EPIC Final Report

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Administrator	**San Diego Gas & Electric Company**
Project Number	**EPIC-1, Project 4**
Project Name	**Demonstration of Grid Support Functions of Distributed Energy Resources (DER)**
Project Focus	**Module 1, Pre-Commercial Demonstration and Value Assessment**
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Attribution

This comprehensive final report documents the work done in this EPIC project.

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EXECUTIVE SUMMARY

The objective of EPIC-1, Project 4, Demonstration of Grid Support Functions of Distributed Energy Resources (DER) was to demonstrate grid support functions of DER, which can improve distribution system operations. The chosen sub-projects and modules quantified the value of specific grid support functions in specific application situations and provided a basis for San Diego Gas & Electric Company (SDG&E) to determine which functions it wants to pursue commercially in the development of its smart grid. This project consists of three modules: value assessment of grid support functions of DER, communication standards for grid support functions of DER, and demonstration and comparison of the Electric Power Research Institute (EPRI) and SDG&E DER hosting capacity analysis tools. This executive summary addresses the module on value assessment of grid support functions of DER, especially to demonstrate and determine the viability of specific DER functions and to identify that, if any, grid support functions of DER and application situations (use cases) should be pursued in advance distribution system automation.

A distribution circuit that includes renewable energy sources such as photovoltaic (PV) and the energy storage system (ESS) was selected as a demonstration circuit to conduct this assessment. A test device (a bi-directional ESS inverter) was interfaced with the Real Time Digital Simulator (RTDS®) in the control and power hardware-in-the-loop (PHIL) experiments. The rating of the test device was 50 KVA, which was scaled up in the RTDS to 1 MW in the distribution circuit. This additional DER was interfaced in the circuit in such a way that it could be moved and connected at different locations. A grid simulator and a battery/load emulator was used to supply AC and DC power to the inverter. The test circuit and device were tested in a variety of scenarios, based on the location of the DER in the system with different operating modes on the inverter under different system conditions. This report presents the recommendations on operating the DER systems in different functional modes under different conditions and discusses their benefits and success in meeting the grid support objectives and challenges.

The DER grid support functions are summarized as follows:

1. The volt-VAR control provides seamless voltage regulation in the event of an under-voltage and overvoltage in the system. This function effectively provided the grid support during disturbances by injecting more reactive power into the system. With proper coordination among capacitor banks and voltage regulators, the ESS can provide fast, seamless voltage regulation.
2. The frequency-watt control provides seamless frequency regulation in the event of an under and over-frequency in the system created by events such as load switching. The frequency droop and the dead-band settings should be coordinated if multiple DER are operating in parallel to control the contribution from each DER. The hysteresis characteristics of the function provides stability and prevents oscillations or hunting.
3. The advanced, multifunction inverters could be implemented with a function to black start an island or a microgrid, providing voltage and frequency support in addition to feeding the load. Black start functionality enables the formation of an island (microgrid) in the event of distribution system loss, once the island is sustained, additional generation and/or storage resources can be brought online.
4. The load leveling function provides the ESS the ability to follow the load and the generation on the feeder and to maintain the active power import at the point of common coupling (PCC) within a specified range. The peak shaving function supplies the additional load if it goes beyond the peak shaving limit and the base loading function consumes active power during the low loading condition.
5. The volt-watt mode provides the ESS with the ability to curtail the active power output so that it can mitigate the overvoltage condition on the feeder when multiple DER are online. Because of the high penetration of the DER, the overall voltage on the feeder tends to rise beyond a value

that would prevent other DER to come online until the local voltage is within the safe operation limits.

6. The ESS may function in some situations as an efficient and economical alternative to spinning reserve for limited time durations. The ESS can operate in the idle mode for a long time without significant loss of charge. The ESS can supply the peak demand until the generation plant can be brought online, thereby reducing the idle time of the conventional generators.

The increasing penetration of DER in utility power systems has increased the complexity of the design and operation of the power systems. These generation sources are considered mostly as negative loads that are expected to disconnect from the rest of the system, which further aggravates the disturbance. With the implementation of the advanced, multifunction inverter functions, DER can play an active role in supporting the distribution systems operations.

Recommendations

The following recommendations for utilization of different DER functions are made based on the results of pre-commercial demonstrations in the lab.

- Volt-VAR function: In the demonstrations, DER performed voltage regulation successfully in different test scenarios to maintain the system voltage. The DER was a faster device in terms of response time during the disturbance compared to voltage regulating devices such as capacitor banks. This function contributed to the system stability autonomously and helped the grid sustain the disturbance. It prevents frequent operation of the capacitor banks and the voltage regulators by providing the dynamic voltage regulation. In a distribution system, which has multiple DER, this function can efficiently provide voltage stability to the grid. It is recommended to pursue this function commercially in the DER inverters.

- Frequency-Watt function: The frequency-watt function of the DER provided smooth active power regulation for the frequency disturbances during the demonstrations. The DER provided the active power to the system to maintain the frequency. This function is recommended to use in the distribution circuit that has a large amount of intermittent generation. The frequency-watt function mitigates the frequency fluctuations caused by these sources. The location of the DER does not impact the operation of the frequency-watt function. This function complements the volt-VAR function, in that both functions can operate independently at the same time and provide voltage and frequency regulation. It is highly recommended to pursue these grid support functions in the commercial DER inverter.

- Load leveling function: The load leveling function maintained the power import from the PCC within the specified dead band during the demonstrations. During heavy and light loading periods, the DER supplied and absorbed the deficit and surplus power. The DER supported the load fluctuation by keeping the power import at the PCC constant under different scenarios. This function smooths out the load fluctuations on the feeder and makes the load forecasting simpler for distribution system operators. When used with an ESS, this function provides both peak shaving and base loading because the ESS can supply, as well as absorb, active power. It will be beneficial to implement this function in the commercial DER inverter.

- Black start function: The results of this demonstration show the effectiveness of using the ESS to black start the system, just like the conventional generation source, to bring the system online in the increment of loads and generations. Once the grid breaker opens, causing the system to enter a blackout, the ESS enters VSI mode creating reference for voltage and frequency. With the ESS in VSI mode, additional load and generation sources can be connected in the system in the subsequent steps. The DER, like the PV system, needs a voltage reference from the ESS to initiate the startup process to feed the load. It is highly recommended to pursue black start functionality commercially to be used in the distribution system microgrids.

- Spinning reserve function: The results of this demonstrations proved that the ESS is quite effective in sustaining loads during periods of under-frequency, providing voltage and frequency support within a short period. In addition to being a fast spinning resource, the ESS also proves to be more effective in terms of cost and efficiency and better in terms of environmental factors and ease of operation and maintenance. The ESS reacted to the undervoltage and underfrequency in the system during a generation outage by acting as a source of spinning reserve providing voltage and frequency support to feed the local loads in the affected region. It is recommended to implement this function in the commercial ESS inverter. The ESS can run in the idle mode with minimal loss of charge to provide spinning reserve.
- DER monitoring and control function: DER monitoring allows system operators visibility into DER operation, which enables efficient use of the DER. All the important status points should be relayed to the remote management system. For the ESS, information such as state of charge, online/offline status, power output, and so on, is necessary to make control decisions. The availability of this information aids the control actions such as connecting and disconnecting the DER, updating voltage and frequency ride-though settings. The ability of DER to communicate with the remote management system to allow monitoring and control is highly desirable to make informed decisions about system operation. It is recommended that this function be implemented in the DER.
- Volt-Watt function: The volt-watt function curtails the active power output of the DER during the overvoltage in the system. This function has a very narrow applicability in terms of grid support. The voltage regulation is best carried out by the volt-VAR function which provides reactive power support instead of active power. Because of the high penetration of the DER, the overall voltage on the feeder tends to rise beyond a value that would prevent other DER to turn online until the local voltage is within safe operation limits. The volt-watt function curtails the active power output of the online DER so that other DER can be turned on. This function is not recommended to use in the steady state where, to correct the low voltage, the feeder needs the reactive power to be fed into the circuit instead of the active power. This is more useful in the overvoltage scenario that prevents energization of the DER.

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ACRONYMS AND ABBREVIATIONS

AC	Alternating current
DC	Direct current
DER	Distributed energy resource(s)
DFIG	Doubly fed induction generator
DQ	Direct quadrature
EPIC	Electric Program Investment Charge
ESS	Energy storage system(s)
GSC	Grid side control
HMI	Human-machine interface
LHFRT	Low-/high-frequency ride-through
LHVRT	Low-/high-voltage ride-through
PCC	Point of common coupling
PHIL	Power hardware-in-the-loop
PLC	Programmable logic controller
PU	Per unit
PV	Photovoltaic
RSC	Rotor side control
RTDS®	Real-Time Digital Simulator
SDG&E	San Diego Gas & Electric Company
SIWG	Smart Inverter Working Group
SOC	State of charge
VSC	Voltage source converter
VSI	Voltage source inverter
ISO	Isochronous
KVAR	Kilovolt-ampere reactive
kW	Kilowatt

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SECTION 1 INTRODUCTION

PROJECT OBJECTIVE

The objective of EPIC-1, Project 4, Demonstration of Grid Support Functions of Distributed Energy Resources (DER) was to demonstrate grid support functions of DER, which can improve distribution system operations. The chosen sub-projects and modules quantified the value of specific grid support functions in specific application situations and provided a basis for SDG&E to determine which functions it wants to pursue commercially in the development of its smart grid. This EPIC project consists of three modules: value assessment of grid support functions of DER, communication standards for grid support functions of DER, and demonstration and comparison of the EPRI and SDG&E DER hosting capacity analysis tools.

Focus of this report is on the first module where the objectives are to demonstrate and determine the viability of specific DER functions and to identify which grid support functions of DER and use cases should be pursued in advance distribution system automation. Furthermore, this module consisted of pre-commercial demonstration of grid support DER functions: to observe how well specific grid support functions work in specific locational and operational situations; to determine the requirements of the grid support functions for interconnection and interoperability; to identify any gaps in meeting those requirements; and to determine operational requirements for control and dispatch of specific grid support functions in viable application situations.

DER are being widely deployed in California and elsewhere. There is increasing interest in using DER for grid support functions to add value beyond their primary function of being local energy resources. The California Public Utilities Commission (CPUC) is preparing a set of guidelines for implementing the autonomous functions in the inverters for photovoltaic and energy storage systems (ESS), which may provide a regulatory basis to guide adoption of DER grid support functions. However, there remains a void in understanding in which situations these DER functions provide sufficient value to warrant adoption. This EPIC project addresses this knowledge gap. The autonomous functions include volt/VAR, frequency/watt and volt/watt support, among others, that improve the operability of the DER systems. This report presents the approach and results for pre-commercial demonstration of DER grid support functions to assess their value in specific applications situations. The report also presents the findings and recommendations based on the test results and observations.

PROJECT APPROACH

A distribution circuit that includes renewable energy sources such as photovoltaic (PV) and the ESS was selected as a demonstration circuit to conduct this assessment. A test device (a bi-directional ESS inverter) was interfaced with the Real Time Digital Simulator (RTDS®) in the control and power hardware-in-the-loop (PHIL) fashion. The rating of the test device was 50 KVA, which was scaled up in the RTDS to 1 MW in the distribution circuit. This additional DER was interfaced in the circuit in such a way that it could be moved and connected at different locations. A grid simulator and a battery/load emulator was used to supply AC and DC power to the inverter. The test circuit and device were tested in a variety of scenarios, based on the location of the DER in the system with different operating modes on the inverter under different system conditions. This report presents the recommendations on operating the DER systems in different functional modes under different conditions and discusses their benefits and the success in meeting the grid support objectives and challenges.

MAJOR TASKS

During this project, the following major tasks were performed for the pre-commercial demonstrations of grid support function of DER. An RTDS model was developed for a typical distribution circuit to connect the DER inverter for the PHIL demonstration. PHIL testing using a hardware inverter was conducted in the DER lab to demonstrate the response of an actual small-scale inverter in the lab. Different use cases were tested in the PHIL setup to conduct the overall assessment, and the test results, observations, and recommendations were recorded. A final report documenting all the findings, value propositions for each grid support function, and recommendations regarding commercial pursuit of DER grid support functions was submitted to SDG&E as a final deliverable.

REPORT OUTLINE

This report is divided into five sections:

- Section 1 presents the project summary, including the project scope.
- Section 2 describes the modeling of different circuit components of SDG&E's distribution circuit into the RTDS system. The calculations and the assumptions for each component are provided.
- Section 3 presents the results of the power hardware-in-the-loop (PHIL) testing conducted in the DER lab, including the descriptions of the various PHIL tests that were performed along with the scenarios under which they were developed.
- Section 4 contains the summary of results, observations, recommendations and value proposition of each functional test.
- Appendix A presents the test results and findings for the software testing conducted with software simulation of the inverter.
- Appendix B presents the tests results for the PHIL testing conducted on the reduced distribution circuit model with dynamics.

SECTION 2 DEMONSTRATION SYSTEM DEVELOPMENT

This section describes the test circuit modeling in the RTDS. The distribution circuit shown in Figure 2.1 was modeled in the RTDS software to obtain the equivalent model and was validated against the actual model for power flow analysis. The information contained in the following subsections for modeling of this circuit was provided in the form of a Synergi circuit model.

DATA EXTRACTION AND RTDS MODEL DEVELOPED FROM SYNERGI

Figure 2.1 shows a simplified single-line diagram of the distribution circuit. This circuit includes three-phase PV inverters and an energy storage system (ESS). The two single-phase PV inverters in the system are ignored for modeling purposes because of their small ratings. The circuit contains the load and line section information along with the various components, such as the source feeder, capacitor banks, distributed energy resources (DER), and ESS. The fuses in the circuit are ignored in the model, and the open points are modeled as the open circuit breaker points in the circuit. The switches are modeled as individual breakers for each line connected to the switch.

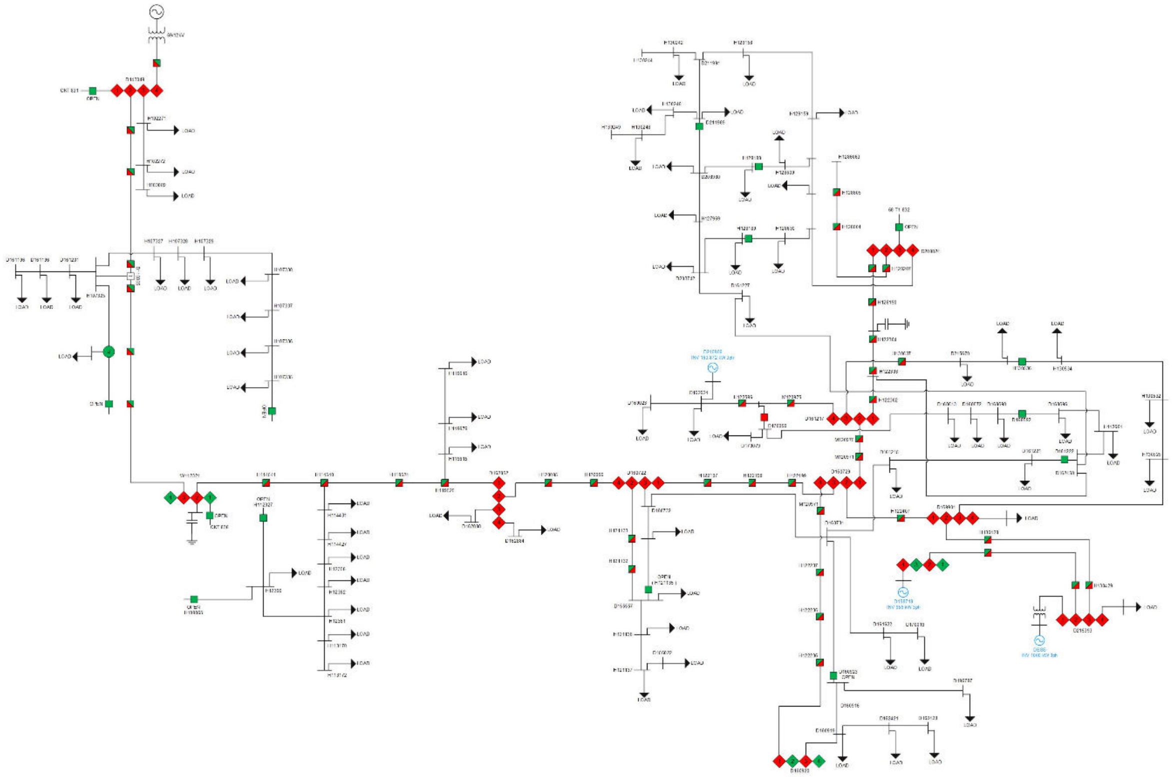


Figure 2.1: Simplified Single-Line Diagram of the Distribution Circuit

EQUIVALENT SOURCE

The source impedance is calculated from the ASPEN model of the reduced SDG&E system [1]. The Synergi model combines the source impedance and the transformer impedance to form a single-source model with equivalent impedance on a 12 kV base.

The per-unit zero- and positive-sequence impedance at 69 kV/100 MVA is calculated as follows:

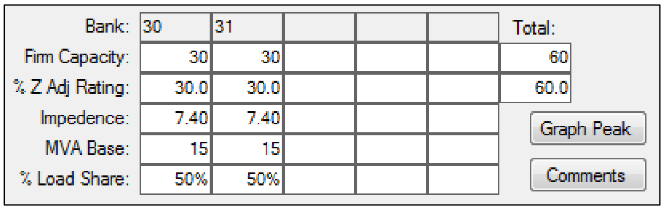
$$Z_{Base} = \frac{(kV)^2}{MVA} = \frac{(69)^2}{100} = 47.62\,\Omega$$

$$Z_1 = (0.00593 + 0.04722j) \bullet Z_{Base} = 2.265\angle 82.84^\circ\Omega$$

$$Z_0 = (0.01703 + 0.14254j) \bullet Z_{Base} = 6.834\angle 83.18^\circ\Omega$$

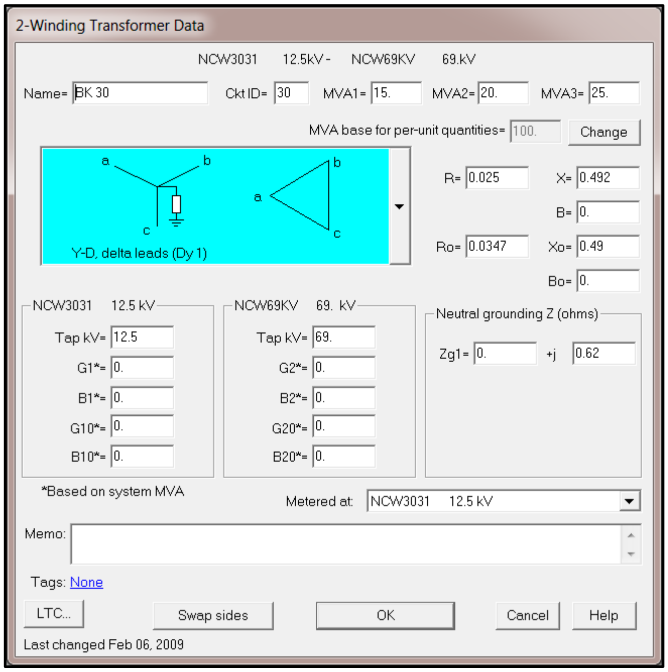
FEEDER TRANSFORMER

The feeder transformer data obtained from the ASPEN model are shown in Figure 2.2 and Figure 2.3.



Bank:	30	31				Total:
Firm Capacity:	30	30				60
% Z Adj Rating:	30.0	30.0				60.0
Impedence:	7.40	7.40				
MVA Base:	15	15				
% Load Share:	50%	50%				

Figure 2.2: Feeder Transformer Information



2-Winding Transformer Data

NCW3031 12.5kV - NCW69KV 69.kV

Name= BK 30 Ckt ID= 30 MVA1= 15. MVA2= 20. MVA3= 25.

MVA base for per-unit quantities= 100.

R= 0.025 X= 0.492

B= 0.

Ro= 0.0347 Xo= 0.49

Bo= 0.

Y-D, delta leads (Dy 1)

NCW3031 12.5 kV
Tap kV= 12.5
G1*= 0.
B1*= 0.
G10*= 0.
B10*= 0.

NCW69KV 69. kV
Tap kV= 69.
G2*= 0.
B2*= 0.
G20*= 0.
B20*= 0.

Neutral grounding Z (ohms)
Zg1= 0. +j 0.62

*Based on system MVA

Metered at: NCW3031 12.5 kV

Memo:

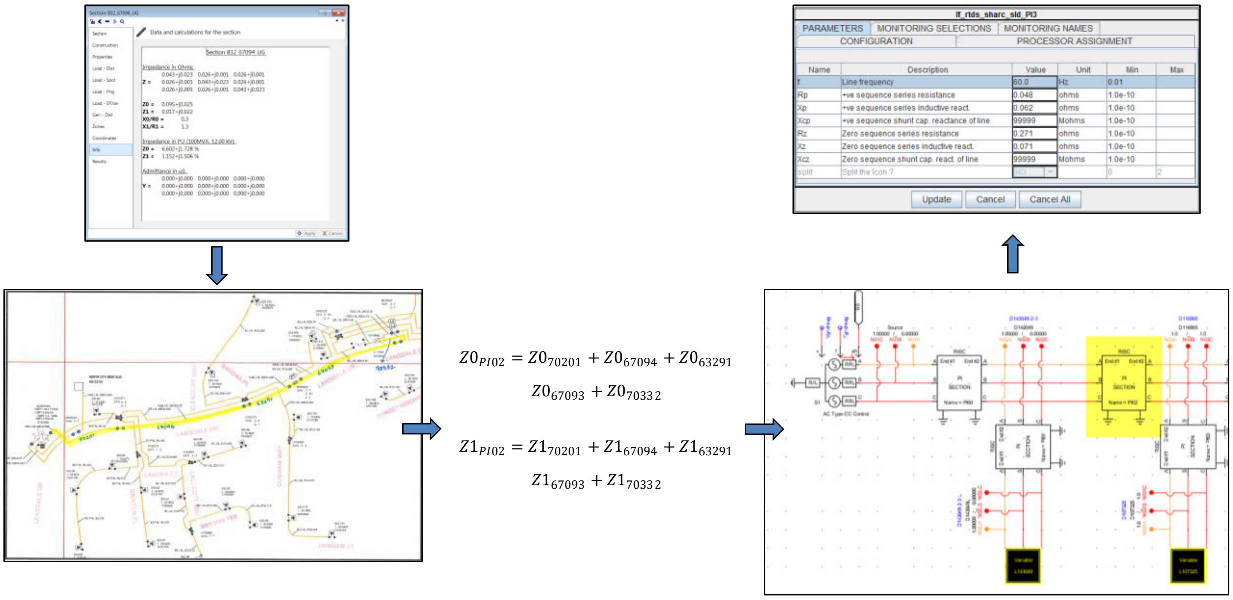
Tags: None

Last changed Feb 06, 2009

Figure 2.3: Feeder Transformer Information from ASPEN OneLiner

DISTRIBUTION LINE MODEL

The RTDS model information for the different line sections was obtained from Synergi by combining multiple small sections to one equivalent PI model to simplify and evaluate the circuit effectively. Single-phase lines leading to individual residences were ignored for modeling purposes, and the net losses from these lines were incorporated into the connected loads to account for them. The various steps taken to covert the Synergi line section data into a PI section model in the RTDS are shown in Figure 2.4.



Data and calculations for the section

Section 832_67094_UG

Impedance in Ohms:
0.043+j0.023 0.026+j0.001 0.026+j0.001
Z = 0.026+j0.001 0.043+j0.023 0.026+j0.001
0.026+j0.001 0.026+j0.001 0.043+j0.023

Z0 = 0.095+j0.025
Z1 = 0.017+j0.022
X0/R0 = 0.3
X1/R1 = 1.3

Impedance in PU (100MVA, 12.00 kV):
Z0 = 6.602+j1.728 %
Z1 = 1.152+j1.506 %

Admittance in uS:
0.000+j0.000 0.000+j0.000 0.000+j0.000
Y = 0.000+j0.000 0.000+j0.000 0.000+j0.000
0.000+j0.000 0.000+j0.000 0.000+j0.000

$$Z0_{PI02} = Z0_{70201} + Z0_{67094} + Z0_{63291}$$
$$Z0_{67093} + Z0_{70332}$$

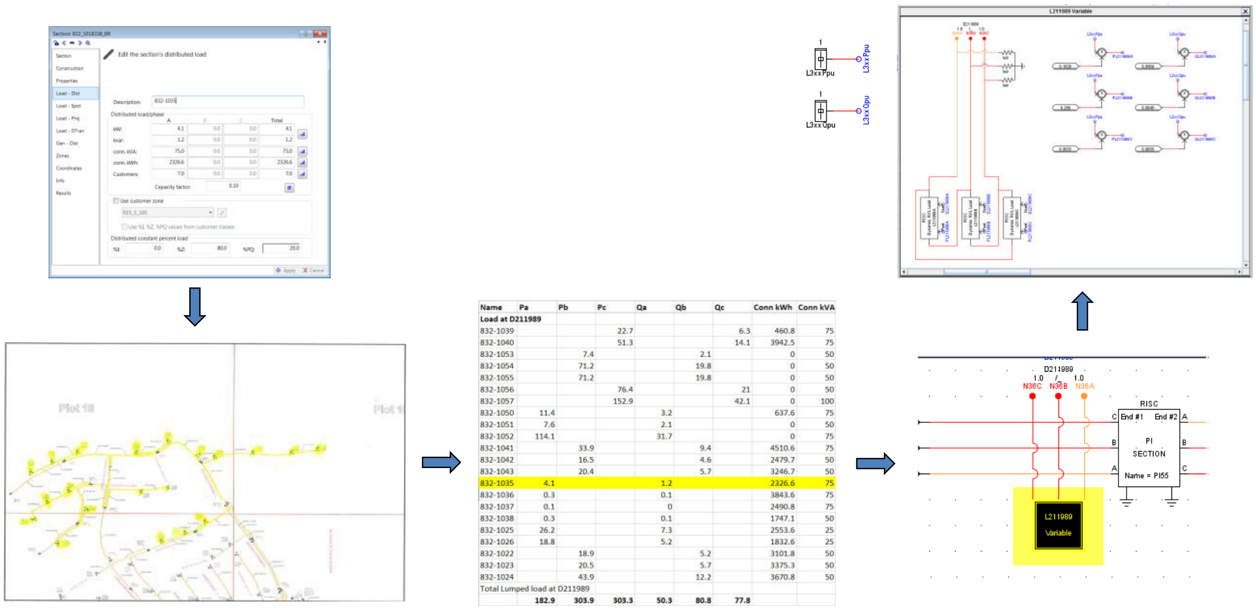
$$Z1_{PI02} = Z1_{70201} + Z1_{67094} + Z1_{63291}$$
$$Z1_{67093} + Z1_{70332}$$

Name	Description	Value	Unit	Min	Max
f	Line frequency	60.0	Hz	0.01	
Rp	+ve sequence series resistance	0.048	ohms	1.0e-10	
Xp	+ve sequence series inductive react.	0.062	ohms	1.0e-10	
Xcp	+ve sequence shunt cap. reactance of line	99999	Mohms	1.0e-10	
Rz	Zero sequence series resistance	0.271	ohms	1.0e-10	
Xz	Zero sequence series inductive react.	0.071	ohms	1.0e-10	
Xcz	Zero sequence shunt cap. react. of line	99999	Mohms	1.0e-10	
split	Split the Icon ?	NO		0	2

Figure 2.4: Conversion of Synergi Section Data into the RTDS PI Model

FEEDER LOADS

The single-phase and three-phase loads across a node were merged into a consolidated three-phase load, which can be dynamically controlled using sliders and/or schedulers to simulate a load demand curve. These connected loads were validated with the load flow to verify the accuracy of the simplification. Figure 2.5 shows the conversion of a load model from Synergi to RTDS.



Description: 832-1035

Distributed load/phase

	A	B	C	Total
kW:	4.1	0.0	0.0	4.1
kvar:	1.2	0.0	0.0	1.2
conn. kVA:	75.0	0.0	0.0	75.0
conn. kWh:	2326.6	0.0	0.0	2326.6
Customers:	7.0	0.0	0.0	7.0

Capacity factor: 0.10

☐ Use customer zone

RES_5_100

☐ Use %I, %Z, %PQ values from customer classes

Distributed constant percent load

%I: 0.0 %Z: 80.0 %PQ: 20.0

Name	Pa	Pb	Pc	Qa	Qb	Qc	Conn kWh	Conn kVA
Load at D211989								
832-1039			22.7			6.3	460.8	75
832-1040			51.3			14.1	3942.5	75
832-1053		7.4			2.1		0	50
832-1054		71.2			19.8		0	50
832-1055		71.2			19.8		0	50
832-1056			76.4			21	0	50
832-1057			152.9			42.1	0	100
832-1050	11.4			3.2			637.6	75
832-1051	7.6			2.1			0	50
832-1052	114.1			31.7			0	75
832-1041		33.9			9.4		4510.6	75
832-1042		16.5			4.6		2479.7	50
832-1043		20.4			5.7		3246.7	50
832-1035	4.1			1.2			2326.6	75
832-1036	0.3			0.1			3843.6	75
832-1037	0.1			0			2490.8	75
832-1038	0.3			0.1			1747.1	50
832-1025	26.2			7.3			2553.6	25
832-1026	18.8			5.2			1832.6	25
832-1022		18.9			5.2		3101.8	50
832-1023		20.5			5.7		3375.3	50
832-1024		43.9			12.2		3670.8	50
Total Lumped load at D211989								
	182.9	**303.9**	**303.3**	**50.3**	**80.8**	**77.8**		

Figure 2.5: Conversion of Synergi Load Data into the RTDS Dynamic Load Model

CAPACITOR BANKS

There are two capacitor banks of 400 kVAR per phase each. These banks are located near the substation and at the far end of the feeder, respectively. The capacitance of these banks is calculated in the next equation to be 22.1 μF per phase. The switching of these capacitor banks is controlled automatically based on the system voltage level. The system voltage levels are maintained between 10.8 kV and 13.2 kV for system stability.

$$C = \frac{(\text{kVAr})}{2\pi f \bullet {V_{1-N}}^2} = \frac{(400\ \text{kVAr})}{2\pi f \bullet \left(\frac{12\ \text{kV}}{\sqrt{3}}\right)^2} = 22.1\ \mu\text{F}$$

DISTRIBUTED ENERGY RESOURCES

PV System Model

The two three-phase PV systems with 471 kW and 485 kW capacities were merged together in the RTDS to form a single three-phase 956 kW PV inverter system for ease of modeling. The two single-phase PV inverters were ignored, and their generation was accounted for in the circuit power flow. The three-phase PV system at Circuit Node D210906 is modeled as a constant current source with a power output of 165 kW. The RTDS model is shown in Figure 2.6.

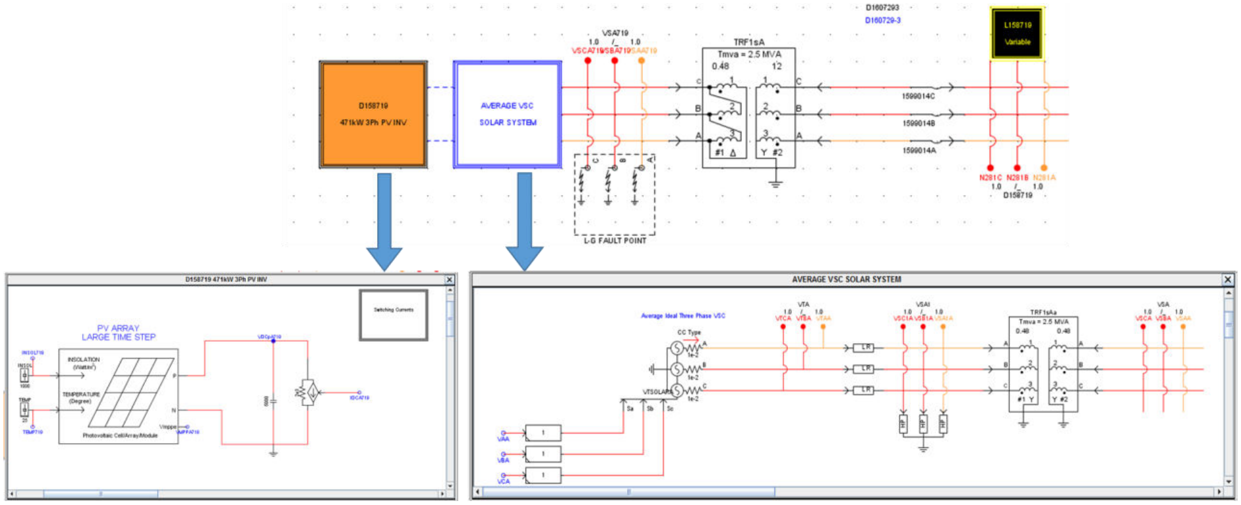


Figure 2.6: PV Inverter Model in the RTDS

The PV system was modeled as an average value model with mathematical control systems. The AC side of the bridge was modeled as a controllable voltage source based on the reference voltage waveform from the controller. The DC side of the bridge was designed as a controllable current source based on the power balance equation on the AC and DC sides. The voltage output can be controlled by defining various parameters and modes.

The flow of control is as follows:

Step 1. Calculate the line current and voltage across the AC side, and change it to a direct-quadrature (DQ) frame using Park's transformation.
Calculate the updated line currents in the DQ frame using the following control operations. The different operational controls on the PV inverter are:

a. Active power output control – This control determines the active power output of the PV inverter based on the radiation (INSOL) and temperature (TEMP) levels. The INSOL and TEMP levels are controlled using sliders in the model.
b. Reactive power dispatch control – This control determines the reactive power output of the PV battery and is controlled by specifying the reactive power directly using a slider in the model.
c. MPPT algorithm – The maximum power point tracking algorithm (MPPT) is either estimated from the PV array indirectly or calculated using the MPPT block in the RSCAD software from the DC voltage obtained from the PV array.
d. Voltage control – The AC voltage can be controlled by regulating the DQ frame reference (DC voltage) of the line voltage and controlling the reactive current (Isq).

Step 2. The updated currents in the DQ frame are converted to A-B-C line voltages and fed into the voltage controlled source on the AC side.

Step 3. The A-B-C frame currents calculated from the DQ frame DC are averaged to obtain the DC reference from the controlled DC source current.

Distributed Energy Storage System Model

The ESS has four 250 kW batteries that are merged to represent one 1 MW battery in the RTDS model. The ESS is modeled similarly to the PV inverter model (Figure 2.7).

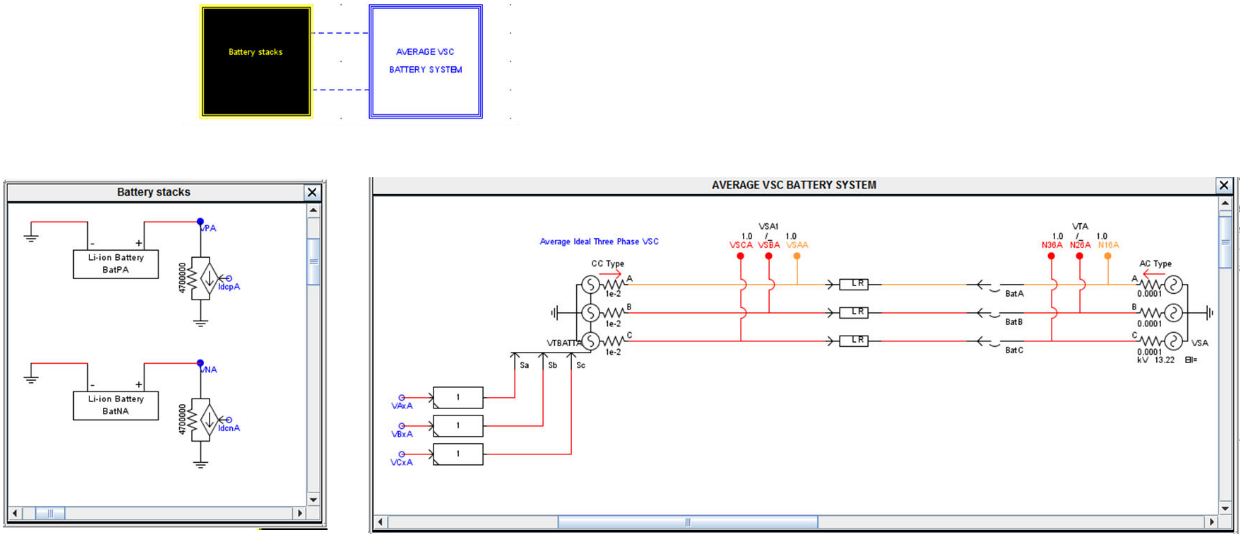


Figure 2.7: ESS Model in the RTDS

The control philosophy of the ESS is like that of the PV system—the AC side of the bridge is modeled as a controllable voltage source based on the reference voltage waveform from the controller. The DC side of the bridge is designed as a controllable current source based on the power balance equation on the AC and DC sides. The real and reactive power outputs of the ESS are controlled using sliders. Both the PV inverter and the ESS have common voltage and frequency ride-through controllers.

Wind Energy System Model

The model has a wind system in the distribution circuit to simulate the effects of wind energy penetration in the grid and the interaction with the test inverter. Thus, a wind energy system is incorporated into the grid with a 2.0 MW capacity as a Type 2 doubly fed induction generator (DFIG) system. The DFIG model is an average value model where the small signal DC-AC converter is replaced by mathematical controls to create a DC link across the bridge.

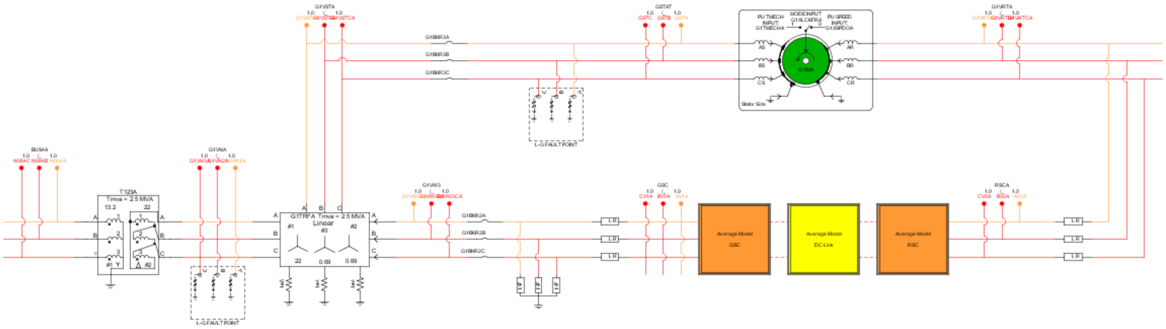


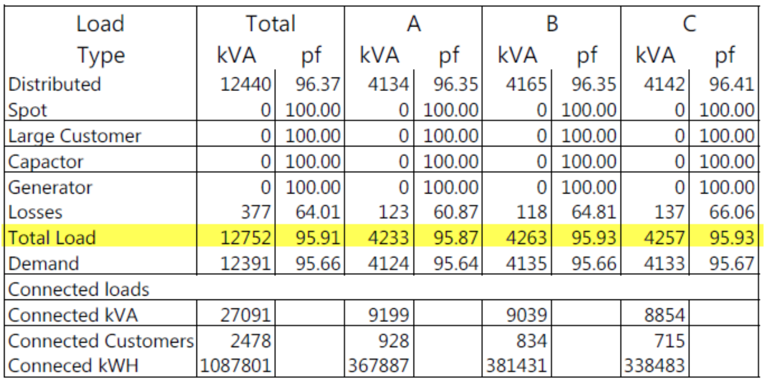
Figure 2.8: DFIG Model on the RTDS

The controls for the DFIG system are divided into four major systems:

- Rotor axis control – The rotor side control (RSC) is modeled using a controllable voltage source on the rotor side that applies voltage to the rotor windings of the DFIG and controls the rotor currents. The control voltage is obtained by converting the three-phase line currents into a DQ frame using Park's transformation. The updated DQ voltages from various control parameters are converted into the three-phase voltage waveforms and are injected into the controllable current source at slip frequency. The reactive power output of the RSC can be controlled using sliders.
- Grid side control (GSC) – The GSC regulates the voltage of the DC bus capacitor and absorbs or generates reactive power for voltage support. The GSC has one control parameter that is the reactive power absorbed from or injected into the grid.
- Rotor and multi-mass control – This block manages the pitch control for the turbine. The mechanical model for the wind turbine is combined with the DFIG and the multi-mass model. Mechanical torque is calculated in the wind turbine and speed in multi-mass and electrical torque is calculated by the DFIG.
- DC link capacitance – This stores the energy between the GSC and RSC and transfers energy across the link. This is the equivalent of the voltage source converter (VSC) bridge modeled mathematically.

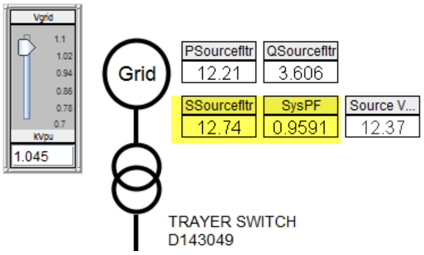
VALIDATION USING SYNERGI MODEL

The RTDS model was validated using the Synergi model for the system power flow. A few changes were made to the connected loads to account for the line losses in the single-phase lines that connect to residences. The changes were usually in the order of ±1 to 2 kW. A comparison of the power flow results on the Synergi model versus the RTDS model is shown in Figure 2.9 and Figure 2.10. The power flows shown in the figures do not consider the generation from the DER and the capacitor reactive power generation.



Load Type	Total kVA	 pf	A kVA	 pf	B kVA	 pf	C kVA	 pf
Distributed	12440	96.37	4134	96.35	4165	96.35	4142	96.41
Spot	0	100.00	0	100.00	0	100.00	0	100.00
Large Customer	0	100.00	0	100.00	0	100.00	0	100.00
Capacitor	0	100.00	0	100.00	0	100.00	0	100.00
Generator	0	100.00	0	100.00	0	100.00	0	100.00
Losses	377	64.01	123	60.87	118	64.81	137	66.06
Total Load	12752	95.91	4233	95.87	4263	95.93	4257	95.93
Demand	12391	95.66	4124	95.64	4135	95.66	4133	95.67
Connected loads								
Connected kVA	27091		9199		9039		8854	
Connected Customers	2478		928		834		715	
Conneced kWH	1087801		367887		381431		338483	

Figure 2.9: Synergi Software Power Flow Results



1.045

PSourcefltr 12.21

QSourcefltr 3.606

SSourcefltr 12.74

SysPF 0.9591

Source V... 12.37

Figure 2.10: RTDS Model Power Flow Results

SECTION 3 PRE-COMMERCIAL DEMONSTRATION OF GRID SUPPORT FUNCTIONS OF DER

This section describes various tests that were conducted on the DER system and provides the test results. The grid support functionalities of the DER (ESS for this demonstration) were tested in various conditions of the circuit including load fluctuations and changes in voltage and frequency. A background on the grid support functions and the PHIL concept is provided before the test result for reference.

INTRODUCTION TO DISTRIBUTED ENERGY RESOURCE GRID SUPPORT FUNCTIONS

The following grid support functions have been demonstrated for their value assessment.

Active Power DER Functions

LIMIT MAXIMUM ACTIVE POWER OUTPUT

This function recommends implementing the maximum limit on the active power of the DER by the grid operator. With this limit in place, DER can operate in any other regulation mode without exceeding active power beyond this limit. The change in the limit occurs at a specified ramp rate. The characteristics for this function is shown in the Figure 3.1 below.

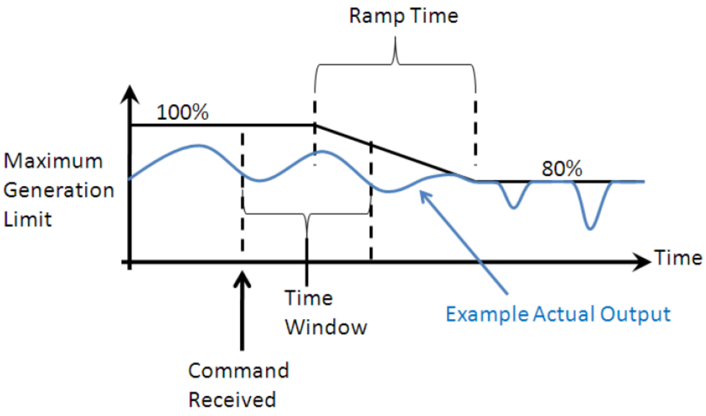


Figure 3.1 Limit Maximum Active Power Output Function

SCHEDULE ACTIVE POWER OUTPUT

This function enables the utility to schedule the output at the PCC during certain times and conditions. This operation establishes the base, or known, generation level on the feeder without the need for constant monitoring, which provides important information about the operational planning and it minimizes the output during low-load conditions, while allowing a higher output during peak load time periods. The power output of the DER is specified to be a constant value. The power grid manages an increase or decrease in load while the power output of the DER remains unchanged.

VOLT-WATT FUNCTION

This function was identified for use as compensation for the voltage variability that results from intermittent renewable sources or other loads. Volt-watt is intended to provide a flexible mechanism through which inverters may be configured to dynamically provide voltage stabilization. This function involves the dynamic production of active power (watts) to resist variations in the voltage at the PCC. The objective is to counter any changes in the voltage by varying the output power. When the DER is set in volt-watt control mode, it tries to maintain the voltage of the system to 1 per unit (pu) by curtailment of the active power output. Figure 3.2 shows the volt-watt function model with a ramp rate.

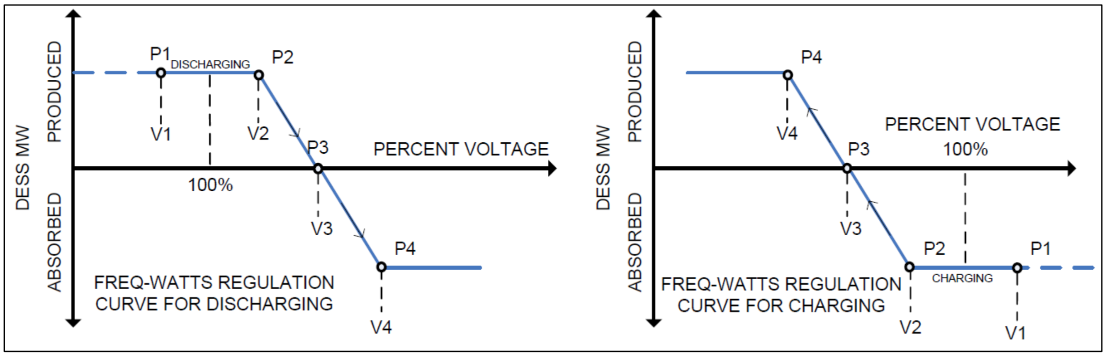


Figure 3.2: Volt-Watt Function

The objective of the tests performed under this section is to study the feasibility of the DER volt-watt function under different locational scenarios and topology.

Reactive Power DER Functions

VOLT-VAR FUNCTION

This function is intended to provide a mechanism through which a DER may be configured to manage its own VAR output in response to a fluctuation in the local service voltage. This function involves the dynamic production of reactive power (VARs) to resist variations in the voltage at the PCC. The objective is to counter any changes in the voltage by varying the output reactive power. When the DER is set in volt-VAR mode, it tries to maintain the voltage of the system to reference value by regulation of the reactive power output. The volt-VAR mode regulates the voltage at specified ramp rate, and the characteristics for this function is shown in Figure 3.3.

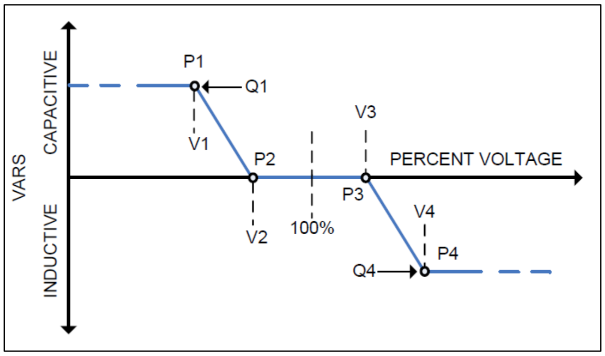


Figure 3.3: Volt-VAR Function

The objective of the tests performed under this section is to study the capability of the DER volt-VAR function under different locational scenarios and topology.

Frequency Support DER Functions

FREQUENCY-WATT FUNCTION

This function is intended to provide a mechanism through which a DER may be configured to manage its own active power output in response to the fluctuations in the system frequency. This function involves the dynamic production of active power to resist variations in the system frequency. The objective is to counter any changes in the frequency by varying the output power. When the DER is in frequency-watt mode, it tries to maintain the frequency of the system to 60 Hz by regulating active power. The characteristics for this function is shown in Figure 3.4.

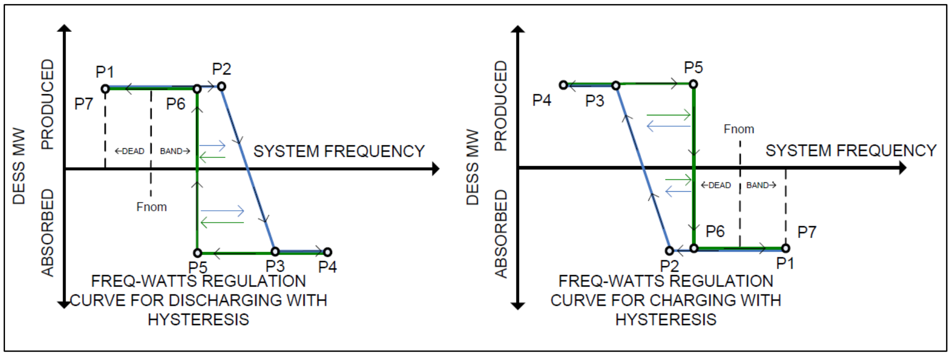


Figure 3.4: Frequency-Watt Function

The objective of the tests performed under this section is to study the capability of the DER frequency-watt function under different locational scenarios and topology.

DER RESPONSE TO EMERGENCIES

These functionalities are part of Phase 3 Rule 21 recommendations by the Smart Inverter Working Group (SIWG). Although not related to the grid supporting DER functions, these functions demonstrate the ability of the DER to respond to different emergency situations or commands from the utility, such as:

- Issue disconnect or reconnect commands to the DER system from the utility.
- Update voltage ride-through curves to change anti-islanding settings.
- Update frequency ride-through curves to change anti-islanding settings.
- Request notification from the DER system about the status of microgrid connection.
- Request notification from the DER system about the spinning reserve.

SPINNING RESERVE

The objective of this test is to assess the benefits of the battery storage system in functioning as a spinning reserve in different system conditions compared to traditional sources, such as diesel generators. The DER system is compared against the traditional backup diesel generator as a source of spinning reserve in terms of response time, standby losses, durability of support, and availability.

BLACK START

The battery storage system can be used to black start the system after complete system outage. The battery can operate in voltage source inverter (VSI) mode to provide voltage and frequency support during the black start. Once the nominal voltage and frequency are established in the island, the loads can be picked up slowly and other renewable generation sources can be brought online to support the load on the feeders.

LOAD LEVELING

The load-leveling function is like peak shaving in that it involves the cycle of charging and discharging during different loading conditions. Therefore, it is most relevant when the DER is a storage device. During the periods of high-load demand, the DER can supply energy into the grid and it can charge while the load is low. This helps reduce the load on less economical peak generating plants. The source level is determined and is limited within the capacity of the DER. The increase and decrease in load is handled by the DER by injecting or absorbing power from the grid. Figure 3.5 shows the characteristics load-leveling function of the DER.

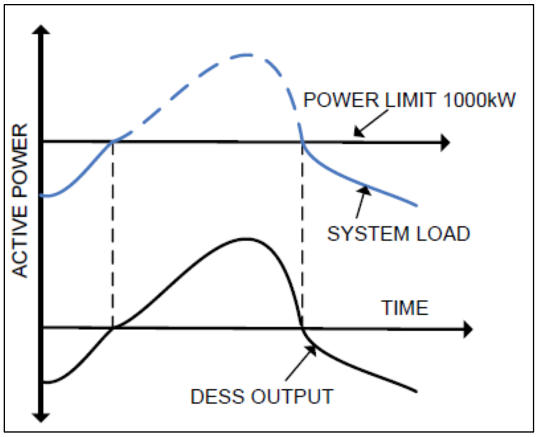


Figure 3.5: Load-Leveling Function

The objective of this test is to assess the economic benefits of using the DER to supply clean and emission-free energy, while reducing the use of less economical generation plants during high-load demands.

POWER-HARDWARE-IN-THE-LOOP (PHIL) TEST SETUP

A hardware inverter was used as a device under test for the assessment of the grid support functions. This hardware device is an additional DER introduced in the distribution circuit for demonstrations purpose. The DER that exist in the circuit presently are modeled in the RTDS simulation as mentioned in Section 2. This section describes the PHIL setup used for the testing in the lab.

Hardware Setup Description

A bidirectional inverter, with grid support functionalities, was installed and commissioned at the DER lab in the PHIL configuration, along with other equipment, such as the grid simulator, battery/load simulator. The PHIL concept brings together software simulation and hardware testing in a closed-loop circuit to evaluate the response of hardware to real-world scenarios in a controlled lab environment. Using the PHIL setup, a small-scale inverter is interfaced with the distribution circuit simulation to produce 1 MW of power at full device rating.

The hardware connection to be implemented is outlined in Figure 3.6. The inverter AC voltage is supplied by the grid simulator, which is controlled by a low-level analog representation of a node voltage in the RTDS model. The power loop is closed by bringing the inverter AC current feedback into the RTDS using low-level voltage signals delivered by current transformer (CT) clamps to the analog input (Giga-Transceiver Analogue Input [GTAI]) card. These current signals are introduced into the simulation using a current injector model, as shown in Figure 3.7. This current injector component can be moved around the circuit to simulate different source penetration points in the system.

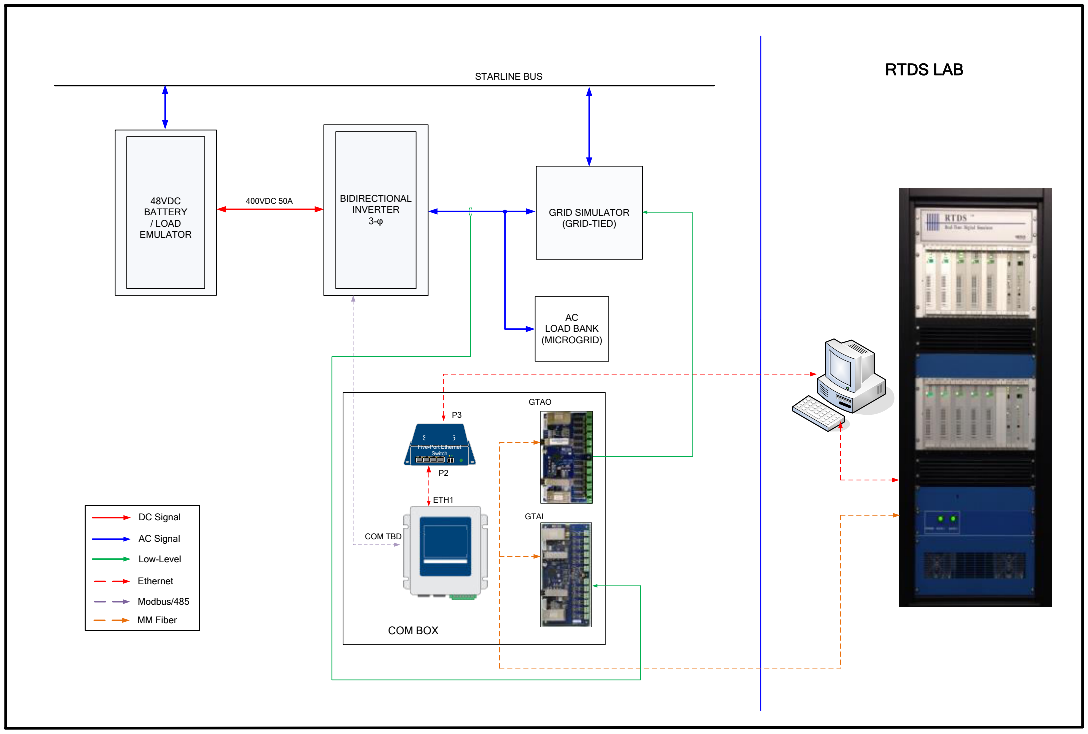


Figure 3.6: Test Circuit Schematic with Inverter at the DER Lab

The typical PHIL test setup modeled in the RSCAD® software is shown in Figure 3.7.

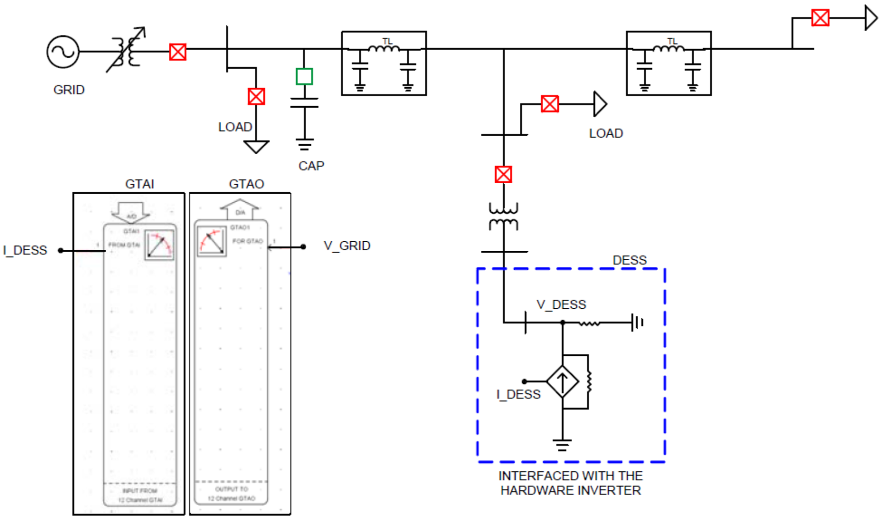


Figure 3.7: PHIL Test Setup Showing Hardware Interface in RSCAD®

RTDS Setup

OUTPUT VOLTAGE SIGNAL

The circuit begins with the translation of the voltage signals from the software model in to the hardware via low-level analog outputs. The software voltage signal is scaled down from the software model level, 12kV for the ESS, to the voltage level of the grid simulator at $277V_{L-N}$. Figure 3.8 shows this process in the RTDS model.

Note: All the signal labels mentioned here are generic names given to the signals in the Figure 3.8 and are not standard acronyms.

Following the signal out through the ESS model.

1. VPCCVA is the label for the voltage at the point of common connection (PCC) between the point in the ESS model being evaluated and the voltage signal sent to the grid simulator. This method allows us to change the PCC location in the model in the future. For the ESS circuit, the PCC is 1MW battery. The line to neutral voltage measured at this point is approximately 6.928kV.
2. Since RTDS base units for voltage are in kV, VPCCVA will come in as 6.928 kV. Point 2 scales this up to be 6928V.
3. Point 3 then scales the voltage down to the $480V_{L-L}$ (or 277 V_{L-N}) level required at the inverter. (12000/25 = 480 or 6928/25 = 277)
4. Point 4 scales 277 V_{L-N} down by the gain of the inverter. The gain was calculated (300/7 = 42.85) as well as verified by measurement. The RS-90 has a maximum output of 300 V_{L-N} and a maximum low-level external input of 7 Vrms. Therefore, the voltage signal at VPA2 = 277/42.85 = 6.46V (for 6.928 kV_{L-N} input). (Note: 7 Vrms at the low level external input of the grid simulator produces 300 V_{L-N} at the output)
5. VPCCLIMA is the voltage signal that is sent through the analog output (GTAO) to the external input of the grid simulator. For 6.928kV input the output is 6.46V. The highlighted symbol is a signal limiter that limits VPCCLIMA to 10 Vpk (7 Vrms) regardless of the signal magnitude of VPA2. If VPA2 is greater than 10 Vpk, the outgoing signal will be clipped to10 Vpk.

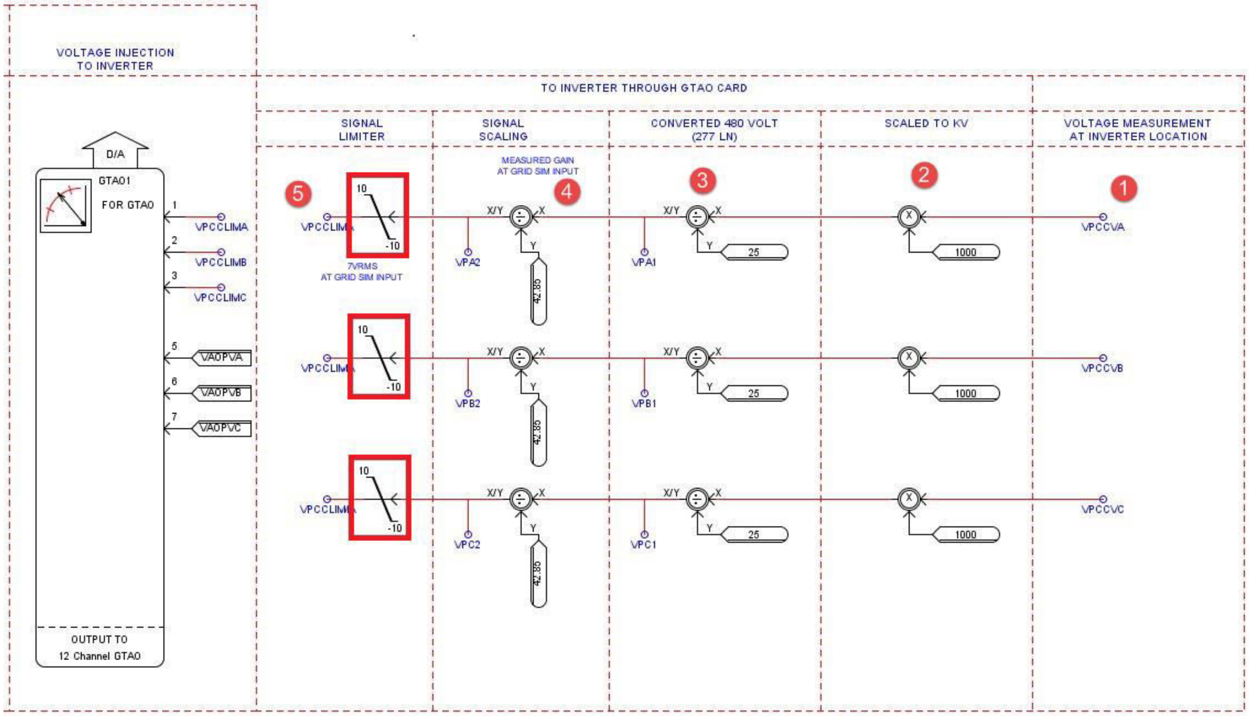


Figure 3.8: ESS RTDS Analog Output

INPUT CURRENT SIGNAL

The feedback loop is closed when the current signal is brought back in to the RTDS model as a low-level voltage signal. The signal brought back in is the current between the grid simulator and the inverter (see Figure 3.9).

Note: All the signal labels with acronyms mentioned here are generic names given to the signals in the Figure 3.9 and are not standard acronyms.

Following the ESS current in from the GTAI:

1. INA is the raw analog signal that is brought in from the CTs through the GTAI card. The CT ratio of the clamps used is 1V input per 10A measured. At 1MW at unity power factor the current is ~60A, this equates to a voltage input of 6V at INA. INA then passes through a low-pass filter with a cutoff frequency of 500Hz and a scalable gain to filter out undesired harmonics introduced by measurement. The gain not only scales up from the CT Ratio but also accounts for magnitude attenuation incurred at the filter. The scaling factor will be chosen to amplify the ESS capacity to 1 MW.
2. The switch PHILON is used to change between open-loop and closed-loop. When PHILON is off, the zero at point A is fed in to the circuit. When PHILON is on INFA is fed in to the circuit. INFA is the filtered and input (INA) that has been scaled back to the original signal magnitude.
3. Another limiter is implemented here to prevent a current signal outside expected values from propagating into the RTDS model and cause circuit instability. (The 85Apk limit corresponds to the 60Arms expected value.)
4. The scaling at point 4 corresponds to the opposite of the down scale at point 2 in the GTAO to account for the change in unit, see Figure 3.9. (1/1000 = .001)
5. The scaling at point 5 corresponds to the opposite of the down scale at point 3 in the GTAO to account for the change in voltage level, see Figure 3.9. (1/25 = .04)
6. A gain setting of 20 was used to scale the inverter (50kVA) to 1 MW for the demonstrations.

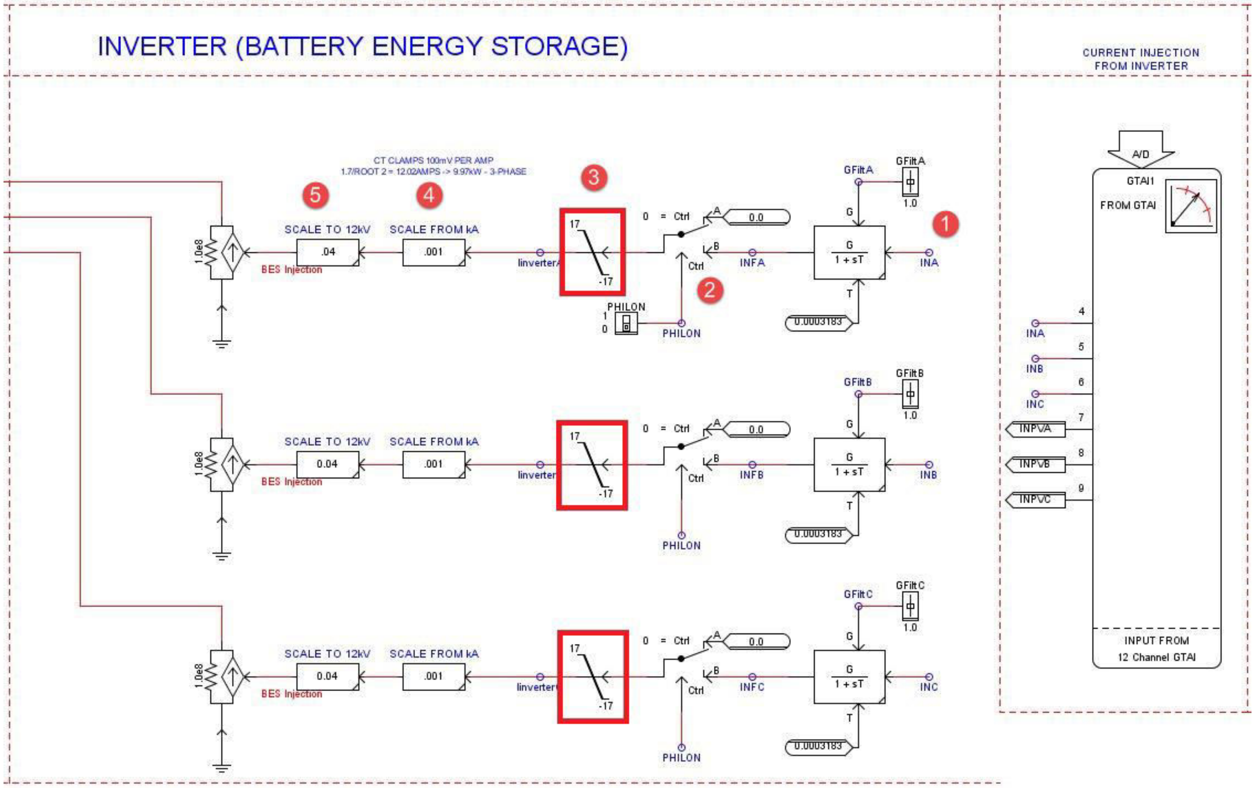


Figure 3.9: ESS RTDS Analog Input

COMMUNICATION WITH THE INVERTER USING THE GATEWAY

The RTDS communicated with the inverter controller using a communication gateway. The RTDS communicates with the gateway using a DNP session. The gateway communicates with the inverter using Modbus session. The register numbers for the various parameters used are mentioned in the inverter manuals. This communication interface is used to control the inverter remotely, to start/stop, to change the modes and set points on the inverter.

TEST SCENARIOS

The components of the DER under test are modeled generically so they can be moved to different locations within the circuit to simulate different source penetration points. The following distribution circuit scenarios are studied for the DER placements.

Scenario 1: DER Close to a Substation

Under this scenario, the DER is placed close to the substation on the low side of the feeder transformer. The Voltage at the substation is set at 1.032pu to have a 1pu voltage at the end of the feeder. This in turn, causes the voltage at the DER to be at 1.025pu. The DFIG system is turned off for studying the effects of the DER on the grid. The capacitor bank is switched on or off using the automatic switching control where they are switched based on the system voltage. Under this scenario, the tests for understanding the functions of the DER are simulated:

Test 1 – Limit the Maximum Power Output
Test 2 – Schedule Active Power Output
Test 3 – Volt-Watt
Test 4 – Volt-VAR
Test 5 – Frequency-Watt
Test 9 – Load Leveling

The simplified circuit of scenario 1 is shown in Figure 3.10.

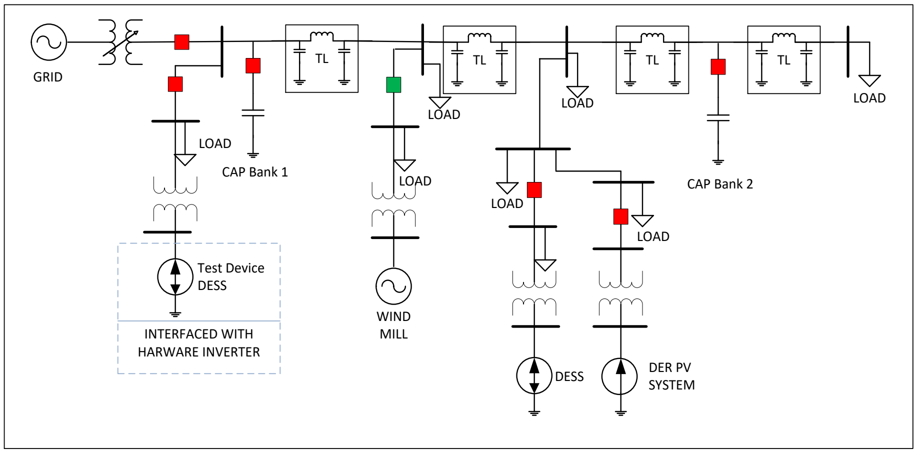


Figure 3.10: DER Close to Substation (Typical)

Scenario 2: DER on a Complex Circuit with a Multitude of Controllable Devices

Under this scenario, the DER under test is placed near the middle of the circuit close to the DFIG system with the DFIG system turned off for the scenario. The Voltage at the DER is at 1.018pu. The DFIG system is turned off for studying the effects of the DER on the grid. The capacitor bank is switched on or off using the automatic switching control where they are switched based on the system voltage. Under this scenario, the tests for understanding the functions of the DER are simulated:

Test 1 – Limit the Maximum Power Output
Test 2 – Schedule Active Power Output
Test 3 – Volt-Watt
Test 4 – Volt-VAR
Test 5 – Frequency-Watt
Test 9 – Load Leveling

The simplified circuit of scenario 2 is shown in Figure 3.11

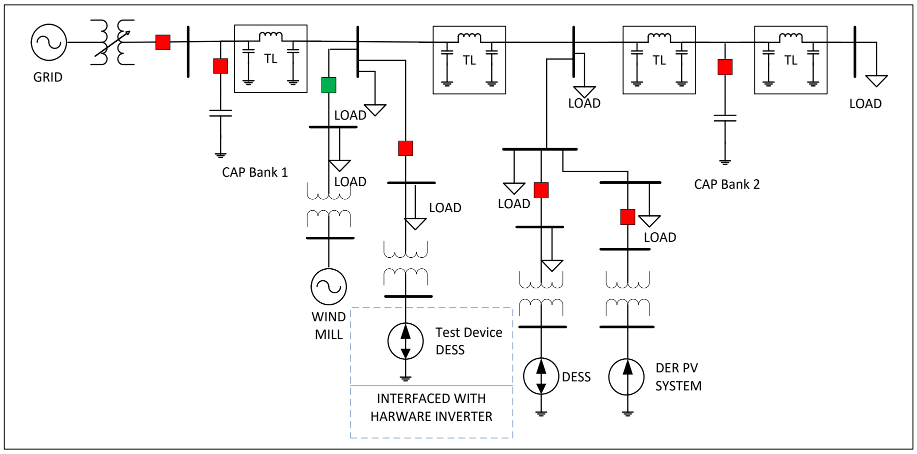


Figure 3.11: DER on a Complex Circuit with a Multitude of Controllable Devices (Typical)

Scenario 3: DER at the End of a Long Feeder

The ESS is placed at the extreme end of the feeder to study the voltage regulation and other functionality of DER under test. The DFIG system is turned off for studying the effects of the ESS on the grid. Under this scenario all the tests except the ESS response to emergencies are simulated. This is because, DER being at the end of feeder, functions effectively for the voltage based tests as the voltage is the lowest at the end of the feeder. The voltage at the Scenario 3 is exactly around 1pu. The capacitor banks are controlled using automatic switching for all the tests except for the black start test where they are turned off. Figure 3.12 shows the simplified circuit of Scenario 3.

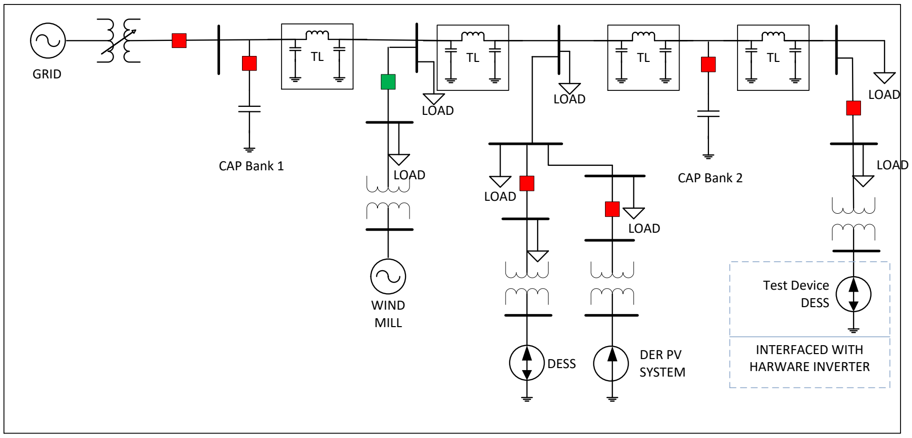


Figure 3.12: DER at the End of a Long Feeder (Typical)

Scenario 4: Multiple Diverse Types of DER on the Same Circuit

Under this scenario, multiple DER are feeding the loads in the system. This scenario is to understand the interaction between the different renewable sources and the DER under test. There is a PV, ESS and a DFIG system in the circuit in addition to the DER under test. The DER is located near the DFIG, like Scenario 2, except that the DFIG is switched on in this scenario to study the interaction. The voltage profile in that case is 1.015pu like the scenario 2. The capacitor banks are switched on or off using the automatic switching control where they are switched based on the system voltage. Figure 3.13 shows simplified circuit of the Scenario 4.

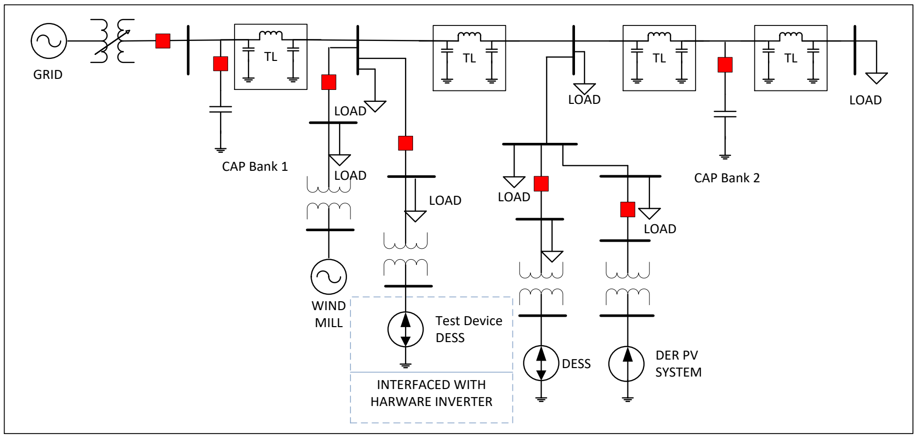


Figure 3.13: Multiple Diverse Types of DER on the Same Circuit (Typical)

TABLE OF TESTS

Table 3.1 lists the DER modes during each of the tests described in the previous sections.

Table 3.1: DER Modes for Demonstrations

Test	Test Name	DER Mode	DER Location	Variable to Change
Test 1	Limit maximum active power output	Active power control mode	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 2	Scheduled active power output	Active power control mode	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 3	Volt-watt	Volt-watt mode	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 4	Volt-VAR	Volt-VAR mode	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 5	Frequency-watt	Frequency-watt mode	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 6	DER emergency response	NA	DER near the substation	Voltage, frequency
			DER on the complex circuit	
			DER at the end of feeder	
			DER with other diverse DER	
Test 7	Spinning reserve	Standby mode	DER at end of feeder	NA
Test 8	Black Start	VSI mode	DER at end of feeder	NA
Test 9	Load leveling	Active power control mode	DER near the substation	Load
			DER on the complex circuit	
			DER at end of feeder	
			DER with other diverse DER	

TEST RESULTS

The performance of the distributed energy resource (DER) was demonstrated under different system topologies, including the various DER locations and the diverse types of DER in the system for each of the following functions. A qualitative analysis has been conducted for the reliability and the economic benefits that each of the functions provides under different situations and is presented in Section 4.

Test 1 – Limit Maximum Active Power Output

Enable the phase 3 function "Limit maximum active power output" of the DER upon a direct command from the controller. In the RTDS model, use the nominal settings for the voltage, frequency, and for the distribution equipment on a typical SDG&E feeder, including tap changers and any capacitor switches, reclosers, and voltage regulators.

The procedure for testing was as follows:

- Issue the command to limit active power output of the DER to a specific value.
- Change the load or other distribution equipment settings to determine if the DER system correctly performs the function.
- Record the circuit measurements, the behavior of the DER system, and behavior of the distribution equipment via a Sequence of Events (SOE) recorder to log all time-stamped results.
- Repeat the previous steps after sending a command for different active power limit values.
- Establish different circuit settings for alternate SDG&E circuit scenarios, so that the value of the function can be judged for different scenarios.
- Record the circuit measurements, the behavior of the DER system, and behavior of the distribution equipment via an SOE recorder to log all time-stamped results.
- Assess the results and determine whether there are any areas of concern.

Table 3.2: DER Maximum Active Power Output Limiting Test Cases

Test	Test Description	Expected Response
Test 1.1	Change the maximum active power limit of the DER from 100% to 50% of its rated capacity with the schedule output set at 70% of rated capacity	DER output decreases to 50% when the limit decreases
Test 1.2	Change the scheduled output of the DER from 50% to 90% of rated capacity with the maximum active power limit set at 80% of its rated capacity	DER output increases to 80% instead of 90% as the limit is set to 80%

This test was conducted only in one scenario (Scenario 1) as the response does not depend on the location on the DER in the circuit.

TEST #1.1 CHANGE THE MAXIMUM ACTIVE POWER LIMIT OF THE DER FROM 100% TO 50% WITH THE SCHEDULE OUTPUT SET AT 70%

On decreasing the maximum active power generation limit to 50% from 100%, the DER active power dispatch reduced from 500kW to 340kW to stay within the generation limit. This caused more active power to be imported across the PCC to compensate for the reduced active power from the DER which increased the active power generation from the source as well. The reactive power output of the DER did not get affected which resulted in the reactive power across the PCC and the source to remain the same. The system voltage and frequency remained unaffected by the change.

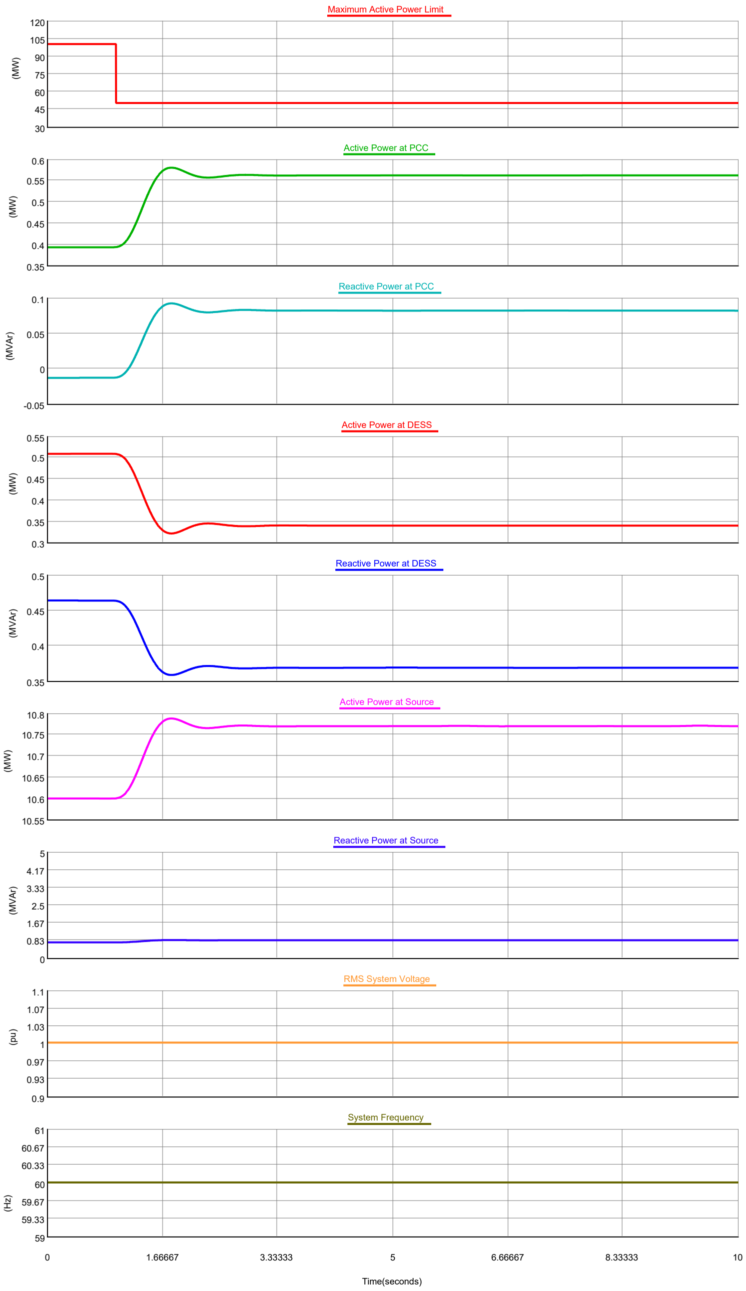


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Figure 3.14: System Response for Test 1.1

TEST #1.2 CHANGE THE SCHEDULED OUTPUT OF THE DER FROM 50% TO 90% WITH THE MAXIMUM ACTIVE POWER LIMIT SET AT 80%

On increasing the DER active power dispatch from 50% to 90%, the DER output was limited at 80% due to the generation set limit at 80%. Because of this limit, the DER output did not increase beyond 600kW even though the DER set point is at 900kW. The active power dispatch of the source decreased by 300kW to compensate for the generation by the DER and this reduced the active power import across the PCC. The reactive power across the DER, PCC and the source got affected marginally. The system voltage and frequency did not get affected by the changes in the DER active power dispatch.

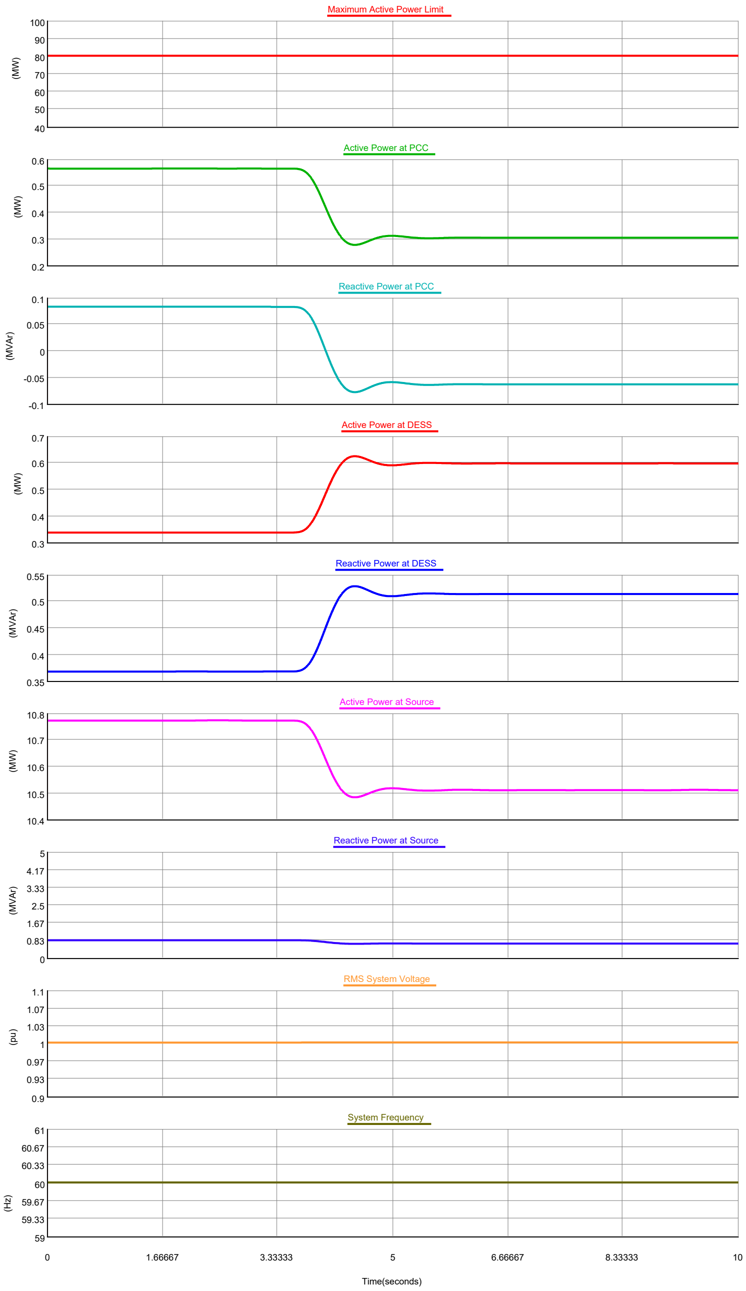

Figure 3.15: System Response for Test 1.2

Test 2 – Schedule Active Power Output

Enable the Phase 3 function "Schedule active power output at the PCC." In the RTDS model, use the default settings for the nominal voltage and for the distribution equipment on a typical SDG&E feeder, including tap changers and any capacitor switches, reclosers, and voltage regulators.

The procedure for testing was as follows:

- Send a schedule of different active power output values (ensuring the DER system can meet those values).
- Change the load or other distribution equipment settings to determine if the DER system correctly performs the function.
- Record the circuit measurements, the behavior of the DER system, and behavior of the distribution equipment via an SOE recorder to log all time-stamped results.
- Repeat the previous steps after sending a command for different active power limit values.
- Establish different circuit settings for alternate SDG&E circuit scenarios so that the value of the function can be judged for different scenarios.
- Record the circuit measurements, the behavior of the DER system, and behavior of the distribution equipment via an SOE recorder to log all time-stamped results.
- Assess the results and determine whether there are any areas of concern.

Table 3.3 lists the tests that were conducted.

Table 3.3: DER Active Power Output Scheduling Test Cases

Test	Test Description	Expected Response
Test 2. x.1	Mode activation with active power set point of 500 kW scheduled at the PCC	DER dispatches 500 kW at steady state
Test 2. x.2	Change active power set point to 800 kW schedule	DER dispatches 800 kW at steady state
Test 2. x.3	Increase the system load by 500 kW	DER dispatches 500 kW at steady state
Test 2. x.4	Increase the system voltage by 5%	DER dispatches 500 kW at steady state
Test 2. x.5	Increase the system frequency by 0.5 Hz for 1 s	DER dispatches 500 kW at steady state
Test 2. x.6	Increase the system frequency by 0.5 Hz for 5 s	DER dispatches 500 kW at steady state

Note: "x" denotes the scenario under test.

SCENARIO 1: DER CLOSE TO A SUBSTATION

TEST 2.1.1: MODE ACTIVATION WITH 500 KW ACTIVE POWER SET POINT SCHEDULED AT THE PCC

Before the DER was set to schedule active power mode, the DER active power dispatch was set at 0 kW. The initial set point was set at 500 kW at the DER. This caused the power flow to shift in such a way that the DER provided 500 kW of the 900 kW active power load, while the rest was fed by the grid through the PCC. The reactive power at the DER and PCC, the system frequency and the voltage remained unaffected by the change across the PCC.

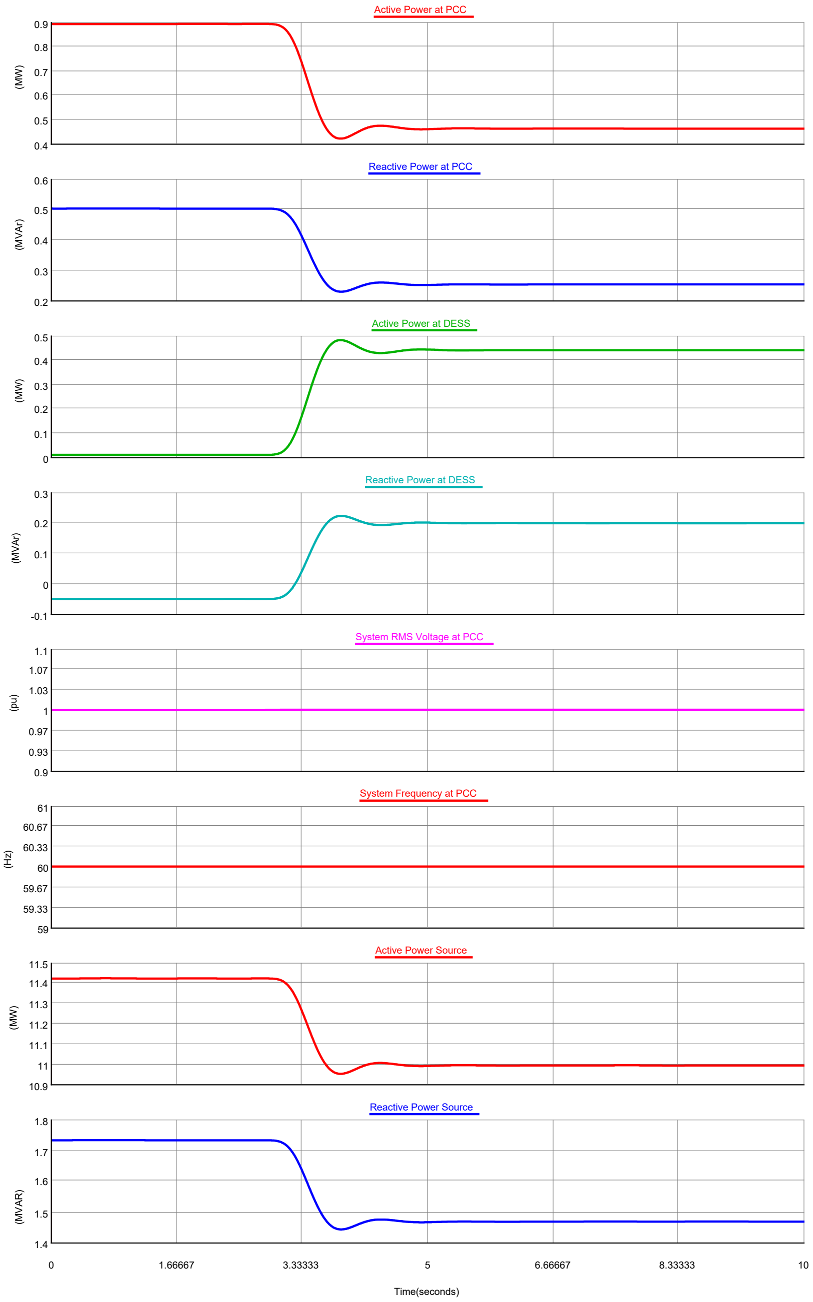

Figure 3.16: System Response for Test 2.1.1

TEST 2.1.2: CHANGE ACTIVE POWER SET POINT TO 800 KW SCHEDULED

On increasing the set point for active power output of the DER to 800 kW, the power import across the PCC reduced to 100 kW, while the active power at the DER settled to 800 kW. The reactive power across the PCC and DER changed marginally, while the system voltage and frequency remained unaffected by the change in the set point.

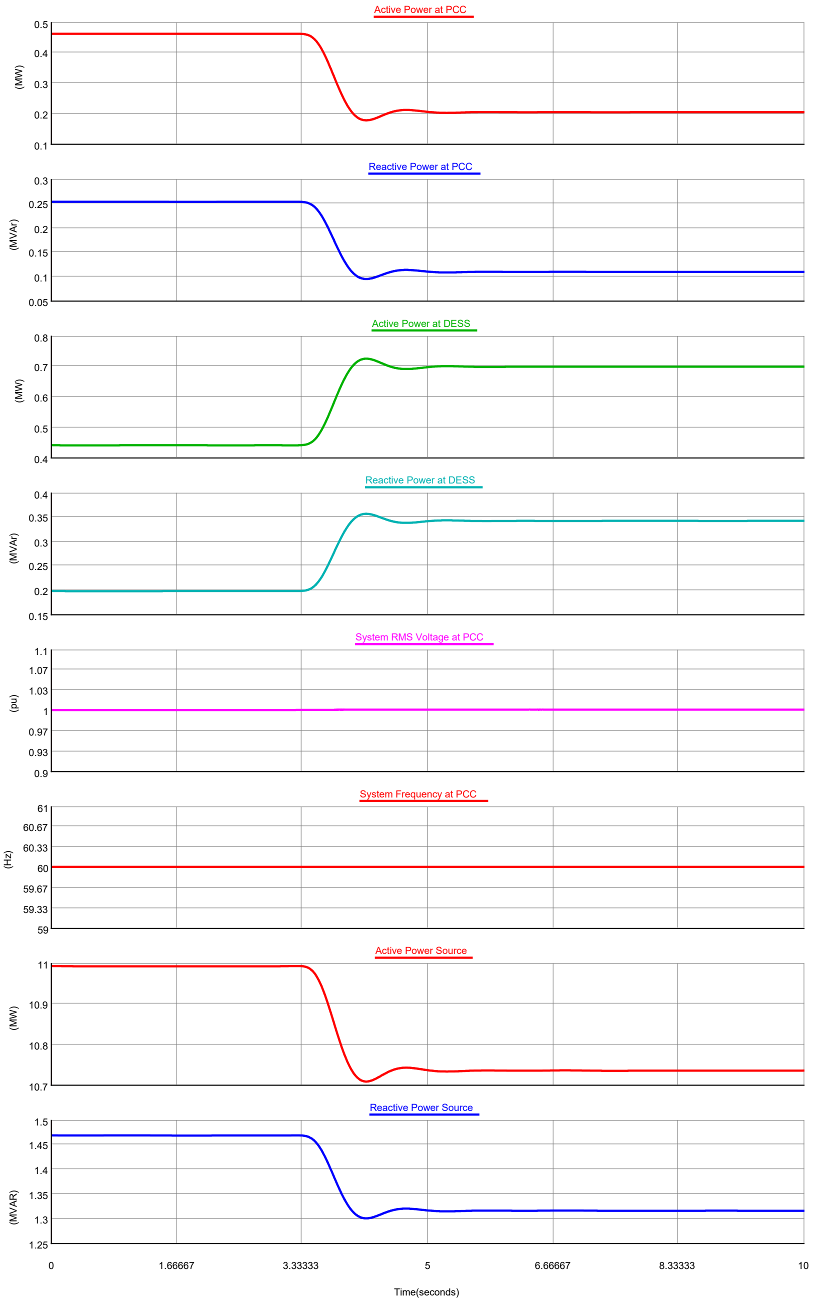

Figure 3.17: System Response for Test 2.1.2

TEST 2.1.3: INCREASE THE SYSTEM LOAD BY 500 KW

The active load connected to the DER was increased from 900 kW to 1400 kW. The DER remained at the prior set point of 500 kW at steady state, while the additional 500 kW was fed by the grid through the PCC. The reactive power, voltage, and frequency remained unaffected by the change in active load.

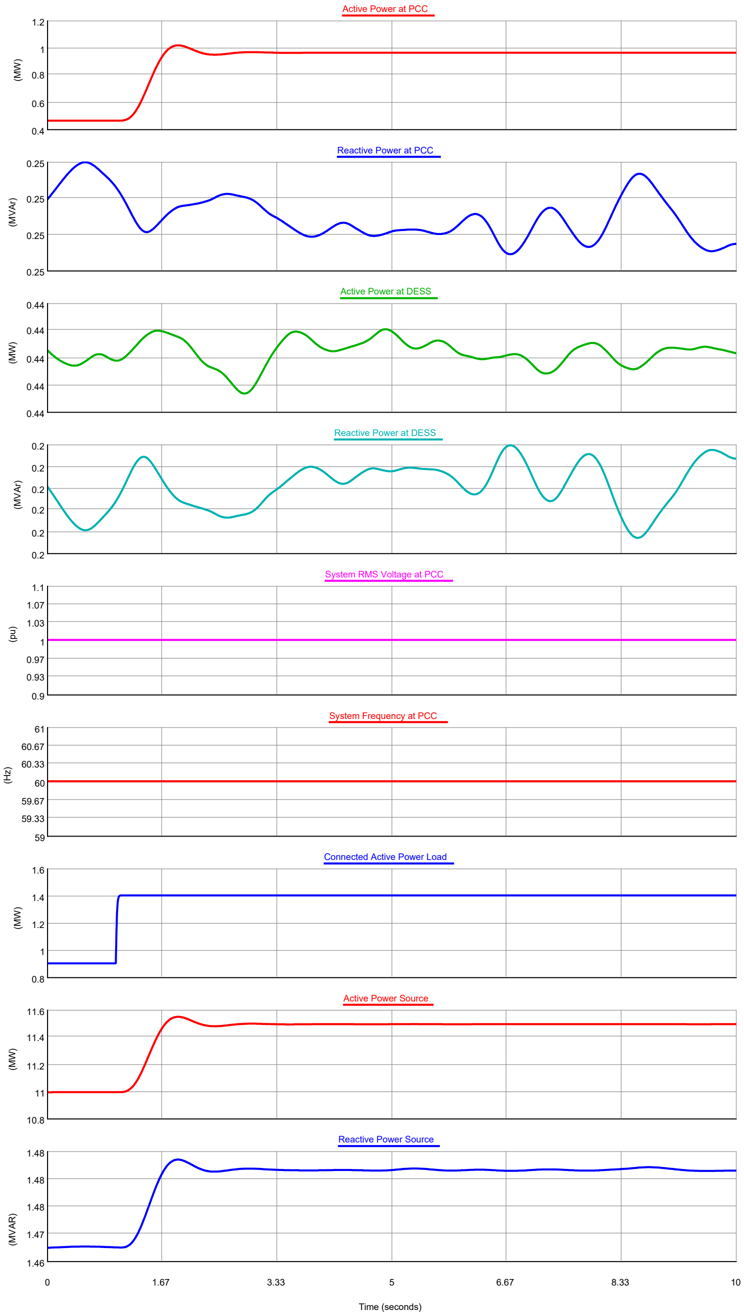

Figure 3.18: System Response for Test 2.1.3

TEST 2.1.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system pu voltage from 1 pu to 1.05 pu, the real power and the reactive power at the DER and PCC rode through the transient phase and settled at its previous set point at steady state. The increase in the reactive power generation by the source was due to the capacitor switching off because of increased voltage. This restricted the voltage at 1.045 pu instead of 1.05pu. The system frequency remained unaffected during this transition.

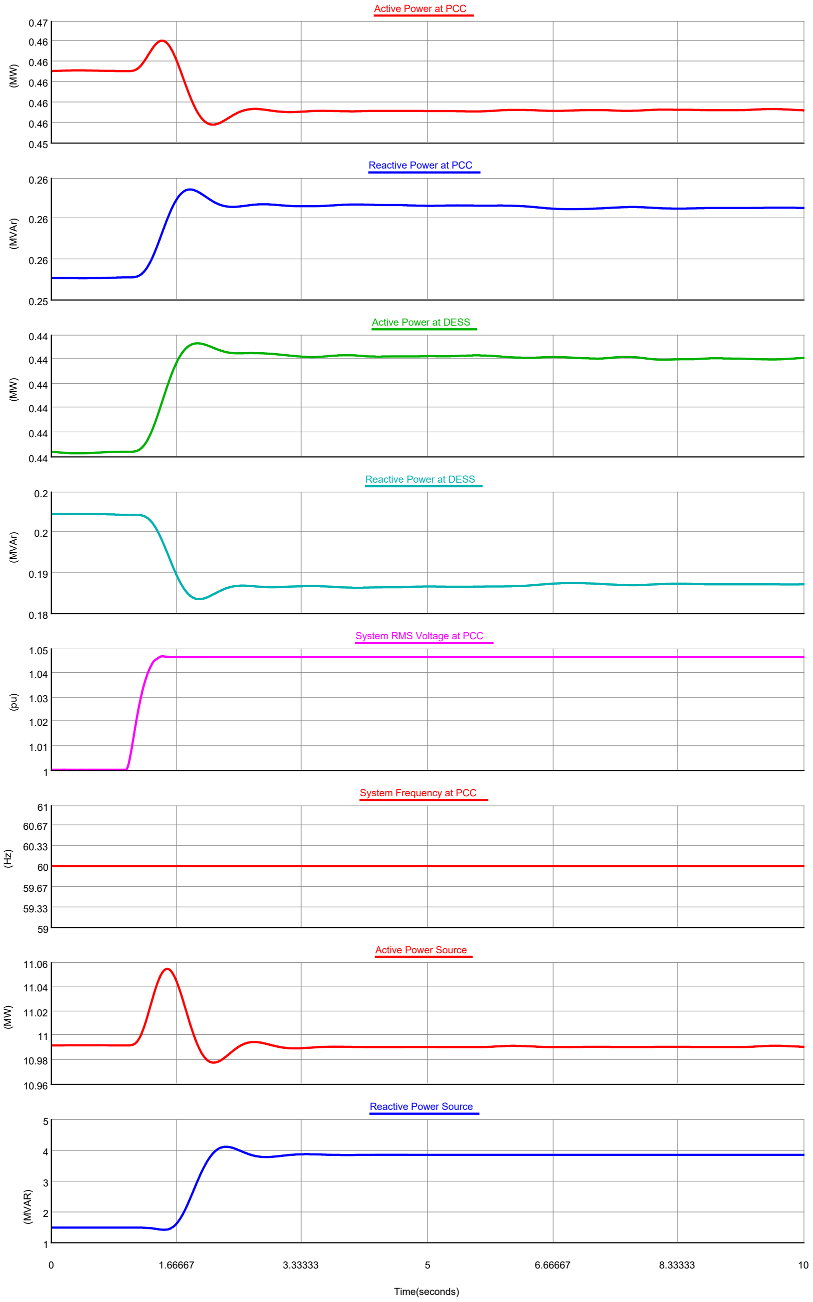

Figure 3.19: System Response for Test 2.1.4

TEST 2.1.5: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flows at the PCC and DER settled at their previous set points. The voltage remained unaffected by the frequency change.

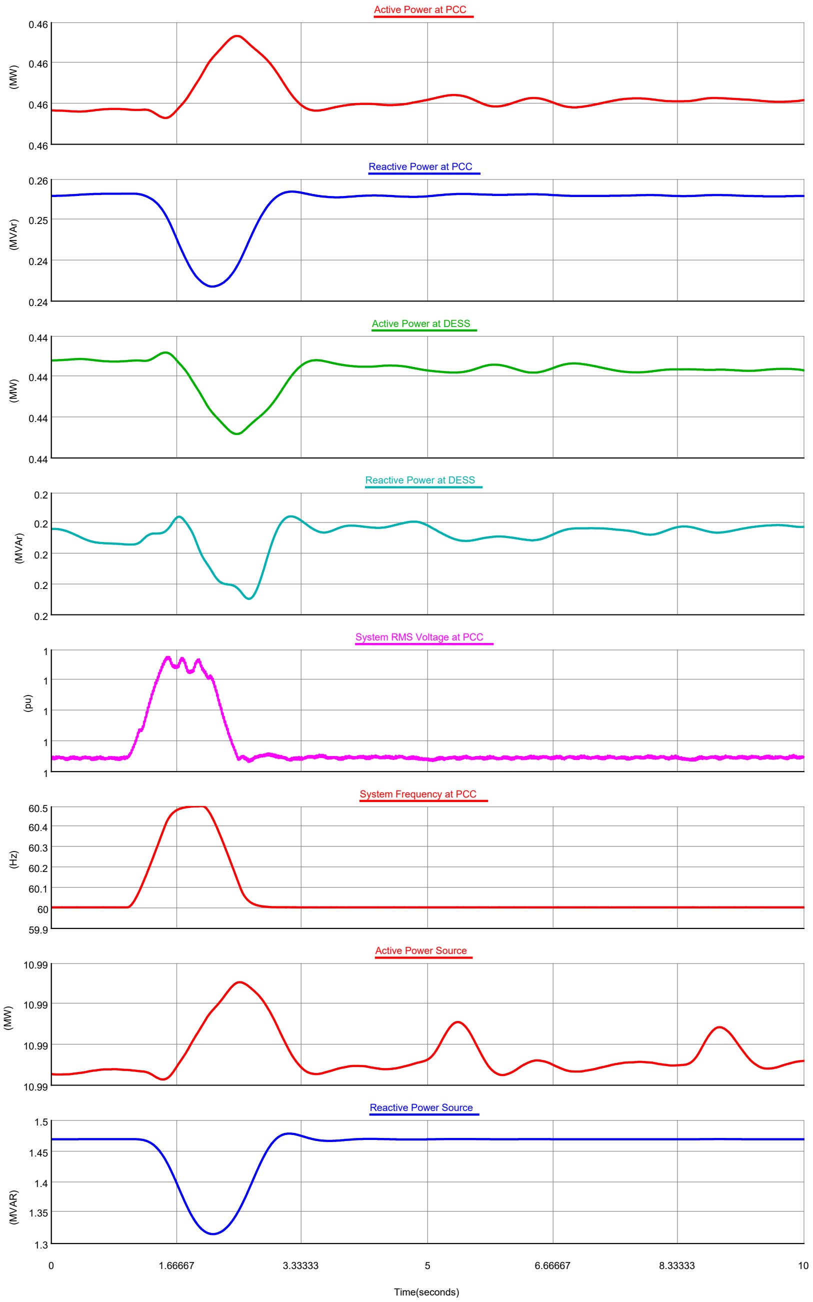

Figure 3.20: System Response for Test 2.1.5

TEST 2.1.6: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ

Like Test 2.1.5, the DER rode through and settled into the previous set point at steady state.

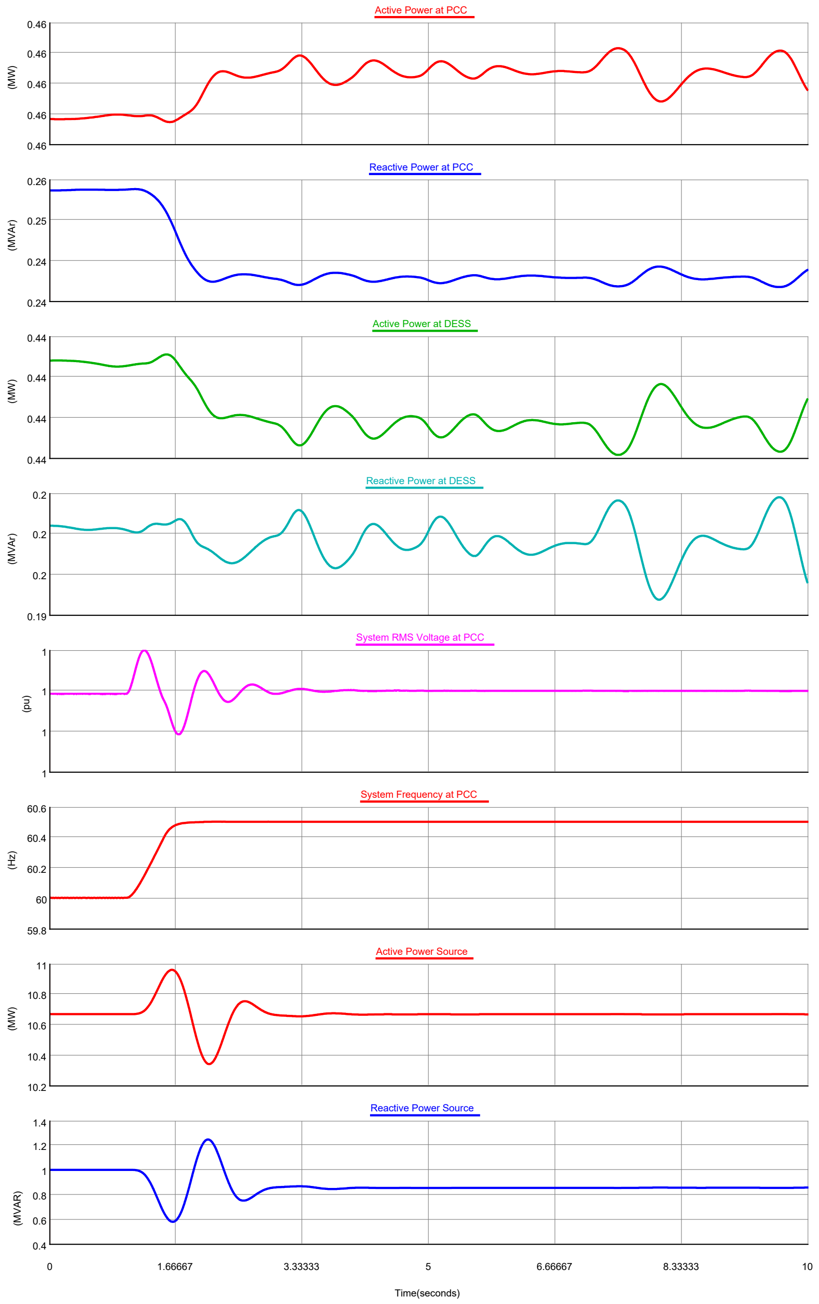

Figure 3.21: System Response for Test 2.1.6

Test 3 – Volt-Watt

This function was identified for use as compensation for the voltage variability that results from intermittent renewable sources or other loads. Volt-watt is intended to provide a flexible mechanism through which inverters may be configured to dynamically provide voltage stabilization. This function involves the dynamic production of active power (watts) to resist variations in the voltage at the PCC.

The objective is to counter any changes in the voltage by varying the output power. When the DER is set in volt-watt control mode, it tries to maintain the voltage of the system to 1 pu by curtailing the active power output.

The procedure for testing was as follows:

Step 1. Vary the system voltage beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER.
Step 2. Change the voltage by changing the load in steps or by changing the grid voltage (the DER should respond in such a way that the system voltage is maintained within the nominal values).
Step 3. Increase the output of the DER to its maximum capacity, which should lead to the voltage increase at the PCC bus (when the DER is put into volt-watt mode at this stage, the system voltage should revert into the nominal band because of the power curtailment by the function).

Compare the results with the baseline case and develop conclusions based on these findings.

Table 3.4 lists the tests that were conducted.

Table 3.4: DER Volt-Watt Test Cases

Test	Test Description	Expected Response
Test 3. x.1	Mode activation with active power set point of 500 kW	DER dispatches 500 kW at steady state
Test 3. x.2	Increase the system load by 500 kW	DER dispatches 500 kW at steady state
Test 3. x.3	Decrease the system load by 500 kW	DER dispatches 500 kW at steady state
Test 3. x.4	Increase the system voltage by 5%	DER decreases active power output to offset voltage increase

Note: "x" denotes the scenario under test.

SCENARIO 1: DER CLOSE TO A SUBSTATION

TEST 3.1.1: MODE ACTIVATION

The system local load was at 900 kW and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profile remained unaffected by the transition.

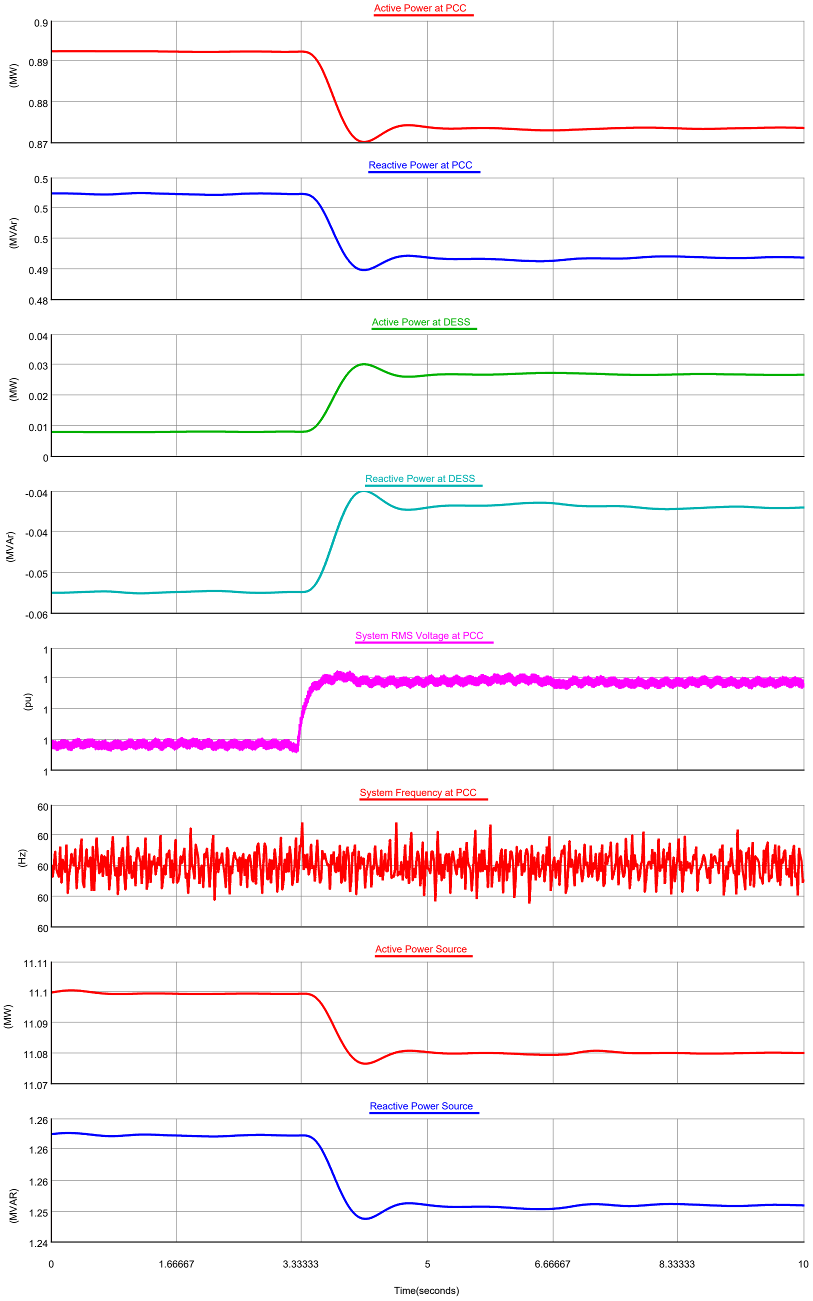

Figure 3.22: System Response for Test 3.1.1

TEST 3.1.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and system voltage and frequency were not affected.

TEST 3.1.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and system voltage and frequency were not affected.

TEST 3.1.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage by 5 percent from 1 pu to 1.05 pu, the active power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition. The increase in the reactive power generation by the source was due to the capacitor switching because of increased voltage, which restricted voltage to 1.045pu.

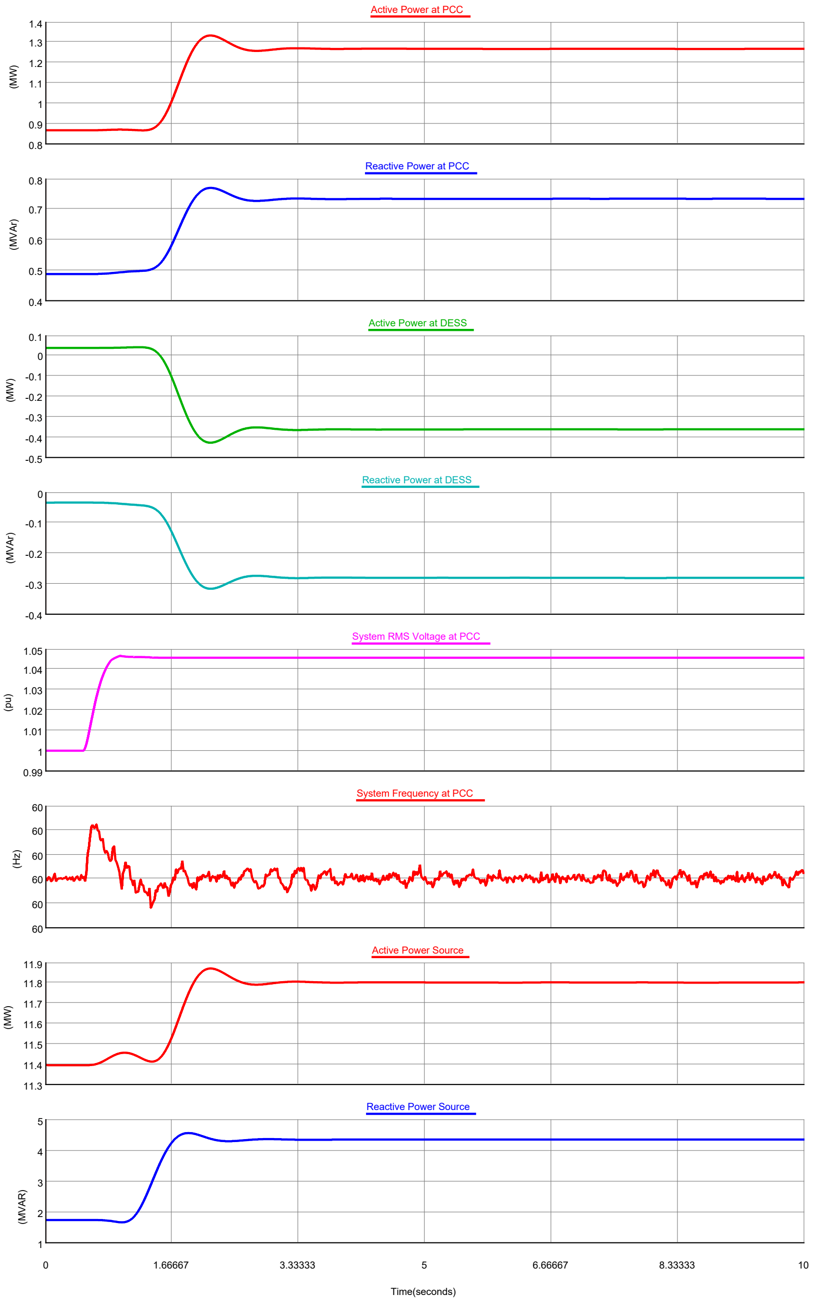

Figure 3.23: System Response for Test 3.1.4

SCENARIO 3: DER AT THE END OF A LONG FEEDER

TEST 3.3.1: MODE ACTIVATION

The system local load was at 900 kV and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profiles remained unaffected by the transition.

TEST 3.3.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power at the DER settled to steady state, while the grid supported the additional load through the PCC. The reactive power flow and the system voltage and frequency were not affected.

TEST 3.3.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power at the DER settled to steady state, while the grid supported the additional load through the PCC. The reactive power flow and the system voltage and frequency were not affected.

TEST 3.3.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage by 5 percent from 0.978 pu to 1.025 pu, the real power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The system frequency remained undisturbed during the transition.

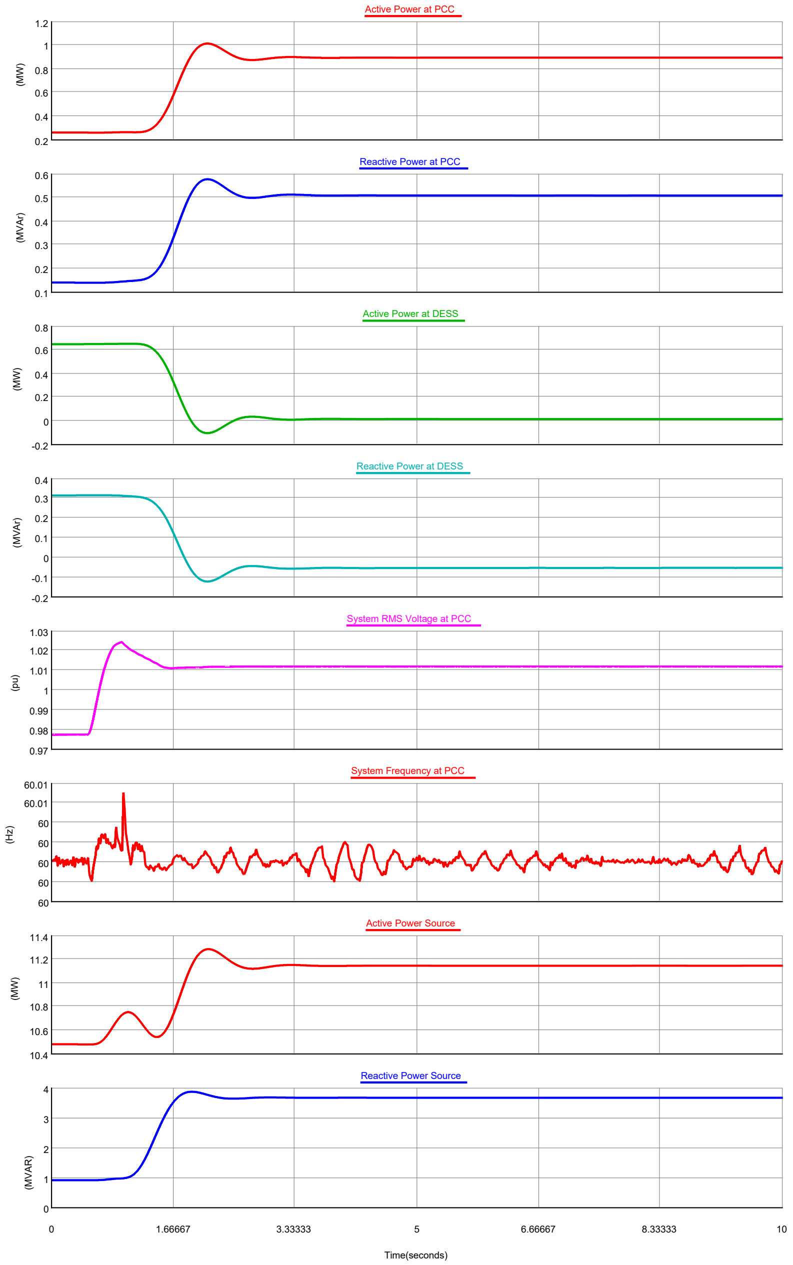

Figure 3.24: System Response for Test 3.3.4

SCENARIO 4: MULTIPLE DIVERSE TYPES OF DER ON THE SAME CIRCUIT

TEST 3.4.1: MODE ACTIVATION

The system local load was at 900 kV and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profiles remained unaffected by the transition.

TEST 3.4.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

TEST 3.4.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

Test 3.4.4: Increase the System Voltage by 5 Percent

On increasing the system voltage by 5 percent from 1.0 pu to 1.05 pu, the real power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition. The increase in the reactive power generation by the source was due to the capacitor switching because of increased voltage, which restricts voltage to 1.045pu.

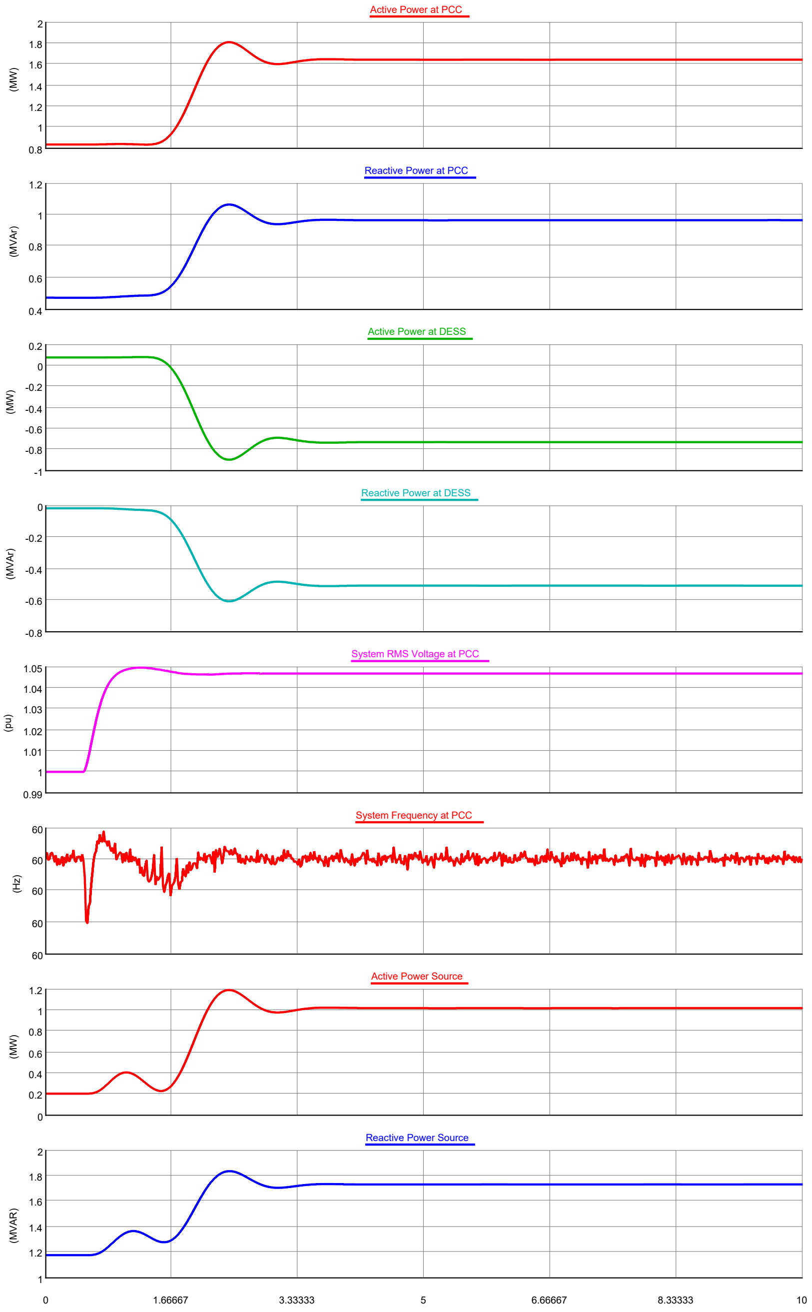

Figure 3.25: System Response for Test 3.4.4

Test 4 – Volt-VAR

This function is intended to provide a mechanism through which a DER may be configured to manage its own VAR output in response to a fluctuation in the local service voltage. This function involves the dynamic production of reactive power (VARs) to resist variations in the voltage at the PCC.

Using the different circuit scenarios, the DER is put into volt-VAR mode. The objective is to counter any changes in the voltage by varying the output reactive power. When the DER is set in volt-VAR mode, it tries to maintain the voltage of the system to 1 pu by regulating the reactive power output.

The procedure for testing was as follows:

Step 1. Vary the system voltage beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER (the DER should respond in such a way that the system voltage is maintained within the nominal values).
Step 2. Change the voltage by changing the load in steps or by changing the grid voltage (when the DER is put into volt-VAR mode, the system voltage should revert into the nominal band because of the DER reactive power regulation).
Step 3. Compare the results with the baseline case and develop conclusions based on these findings.

Table 3.5 lists the tests that were conducted.

Table 3.5: DER Volt-VAR Test Cases

Test	Test Description	Expected Response
Test 4. x.1	Increase the system voltage by 5%	DER decreases reactive power output to offset voltage increase
Test 4. x.2	Decrease the system voltage by 5%	DER increases reactive power output to offset voltage decrease
Test 4. x.3	a) Ramp up the system voltage to 109%, at the rate of 30% per minute, and hold it for 5 s b) Ramp down the system voltage to 90%, at the rate of 30% per minute, and hold it for 5 s c) Ramp up the system voltage, back to nominal voltage (refer to Figure 3.28)	DER decreases its reactive power output to offset voltage increases and following that DER increases its reactive power output to offset voltage decrease. DER settles back at 200 kVAR at steady state.
Test 4. x.4	Increase the system frequency by 0.5 Hz for 1 s	DER dispatches 200 kVAR at steady state
Test 4. x.5	Decrease the system frequency by 0.5 Hz for 1 s	DER dispatches 200 kVAR at steady state

Note: “x” denotes the scenario under test.

SCENARIO 1: DER CLOSE TO A SUBSTATION

TEST 4.1.1: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 1 pu to 1.05 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected. The capacitor switched off during the increase in system voltage due to which the reactive power output of the source increased drastically restricting the system voltage at 1.045pu.

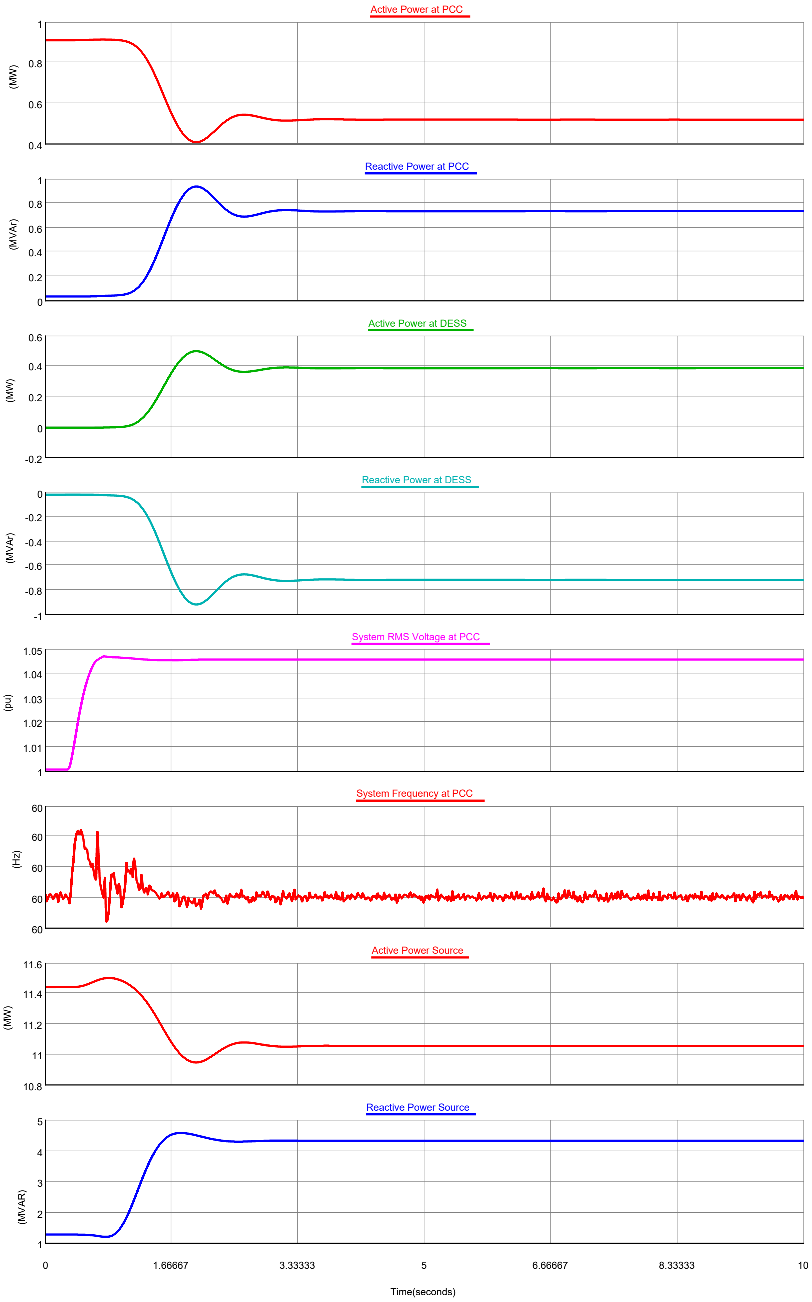

Figure 3.26: System Response for Test 4.1.1

TEST 4.1.2: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 1 pu to 0.95 pu, the reactive power output of the DER increased and produced more reactive power maintain the node voltage at the PCC constant. The frequency remained unaffected by the change at steady state. The active power at the PCC and DER changed due to direction of the power flow.

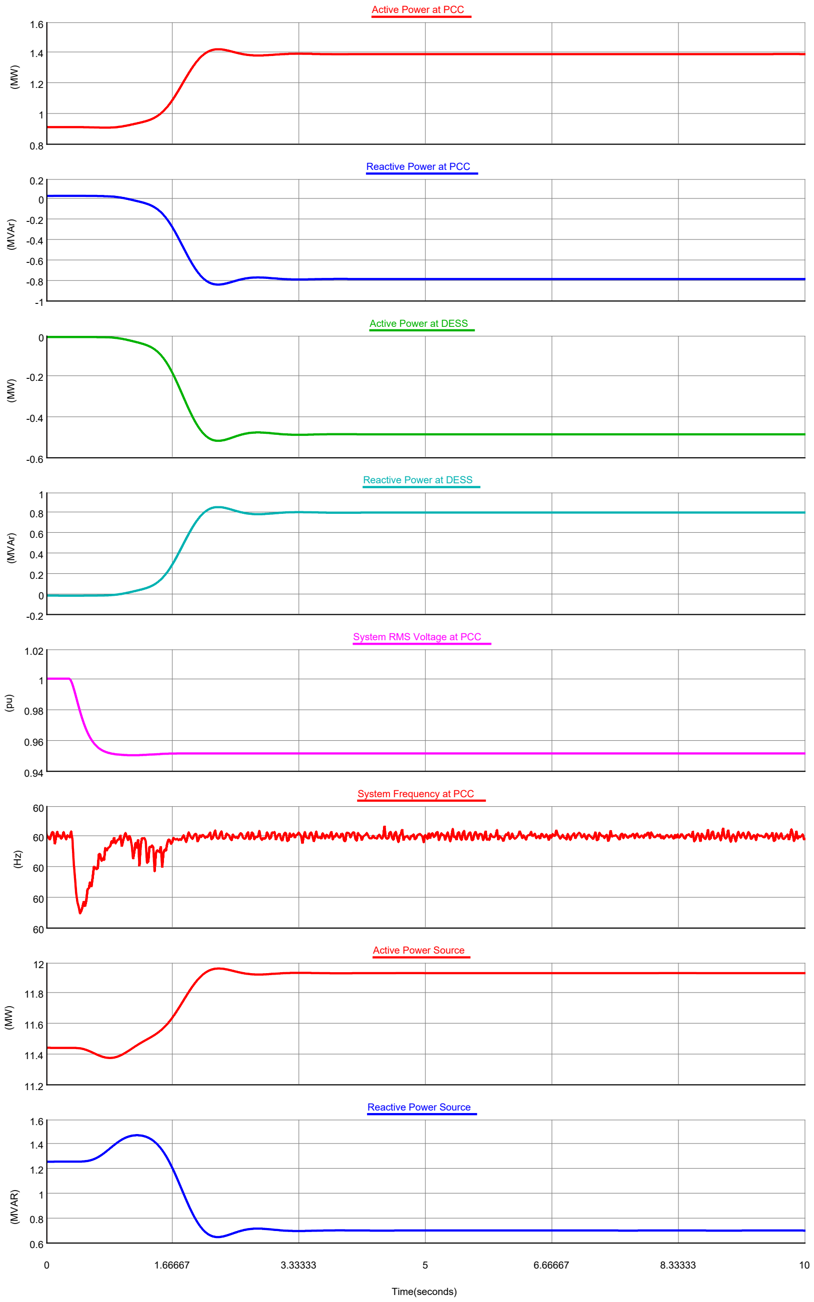

Figure 3.27: System Response for Test 4.1.2

TEST 4.1.3 VARY THE SYSTEM VOLTAGE

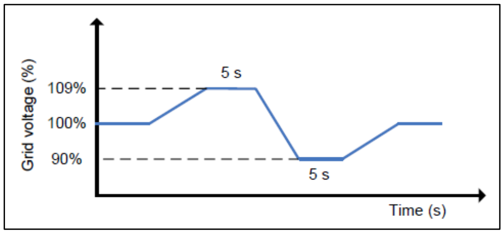

Figure 3.28: System Voltage Profile for Test 4.1.3

The voltage profile at the PCC was changed, as shown in Figure 3.28. On increasing the voltage to 109 percent, the DER reactive power output decreased, while the reactive power import from the grid increased. The increase in voltage caused both system capacitors to turn off during the rising edge of the voltage. This decrease in the DER reactive power output, along with the turning off the capacitor, caused the source reactive power to increase. Once the voltage reached 109 percent, it was held for 5 seconds. Then the voltage dropped from 109 percent to 90 percent, during which the reactive power output of the DER increased to maintain the node voltage constant. The reduction in voltage caused one of the capacitors near the end of the feeder to turn on, which supplemented the reactive power along with the DER, resulting in the reduction of reactive power import from the source. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

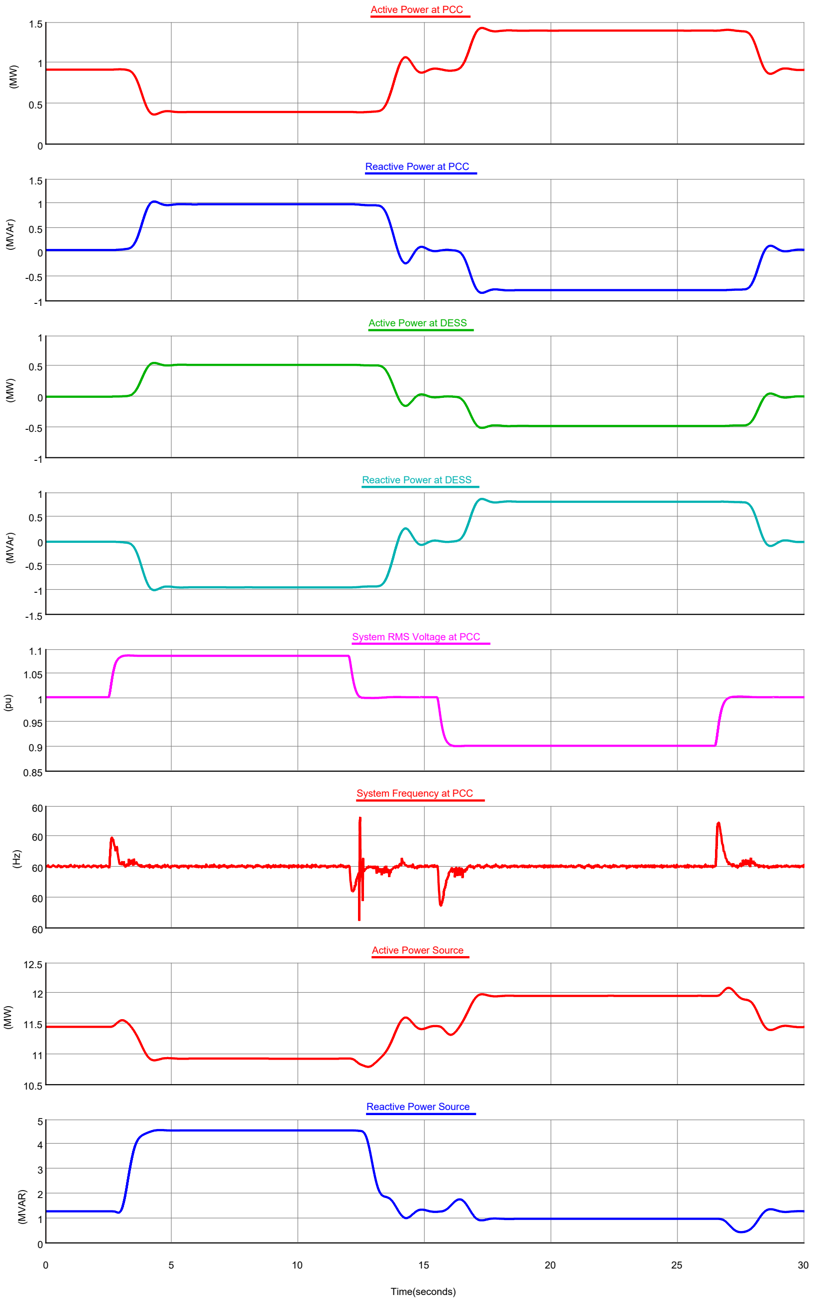

Figure 3.29: System Response for Test 4.1.3

TEST 4.1.4: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flows at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1 pu in steady state.

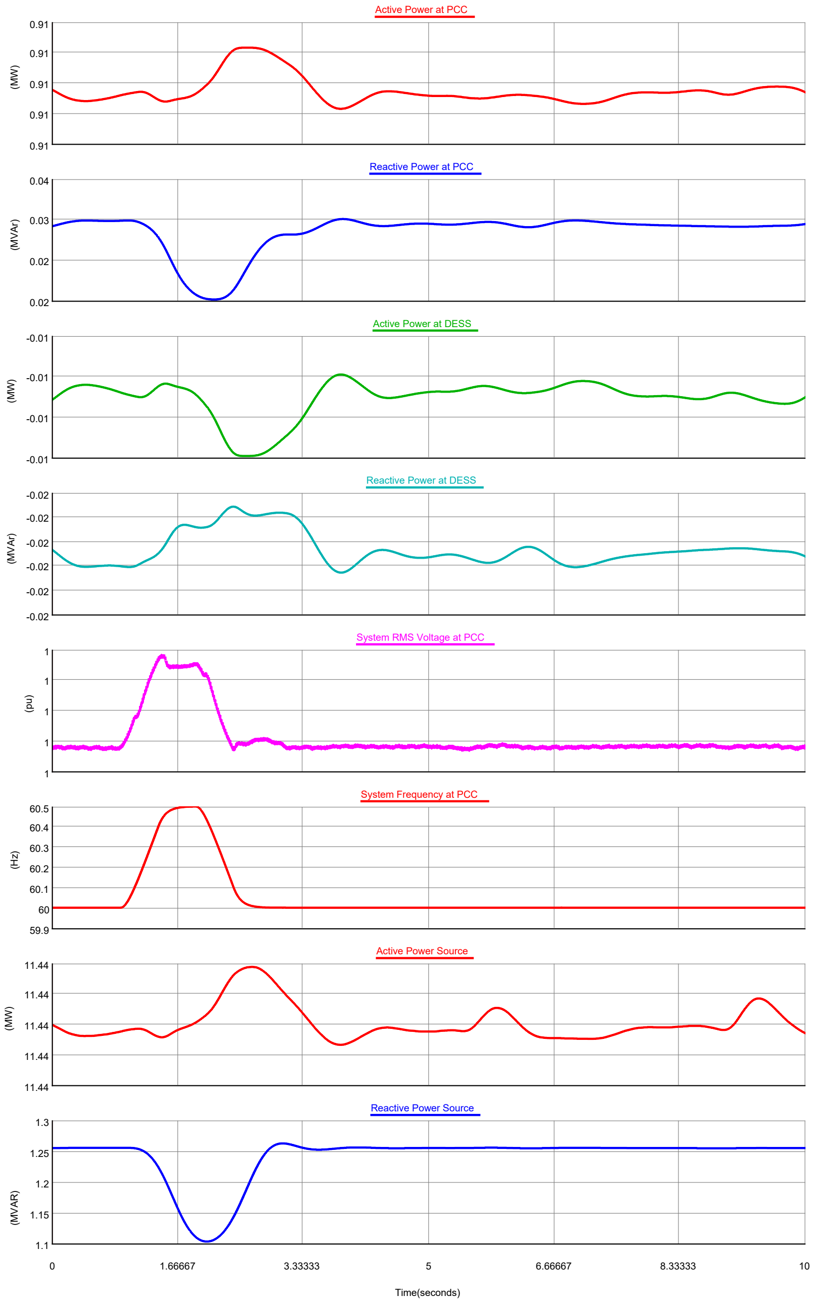

Figure 3.30: System Response for Test 4.1.4

Test 4.1.5: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, it reacted to the change, rode through, and returned to steady state. The real and reactive power flows at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1 pu in steady state.

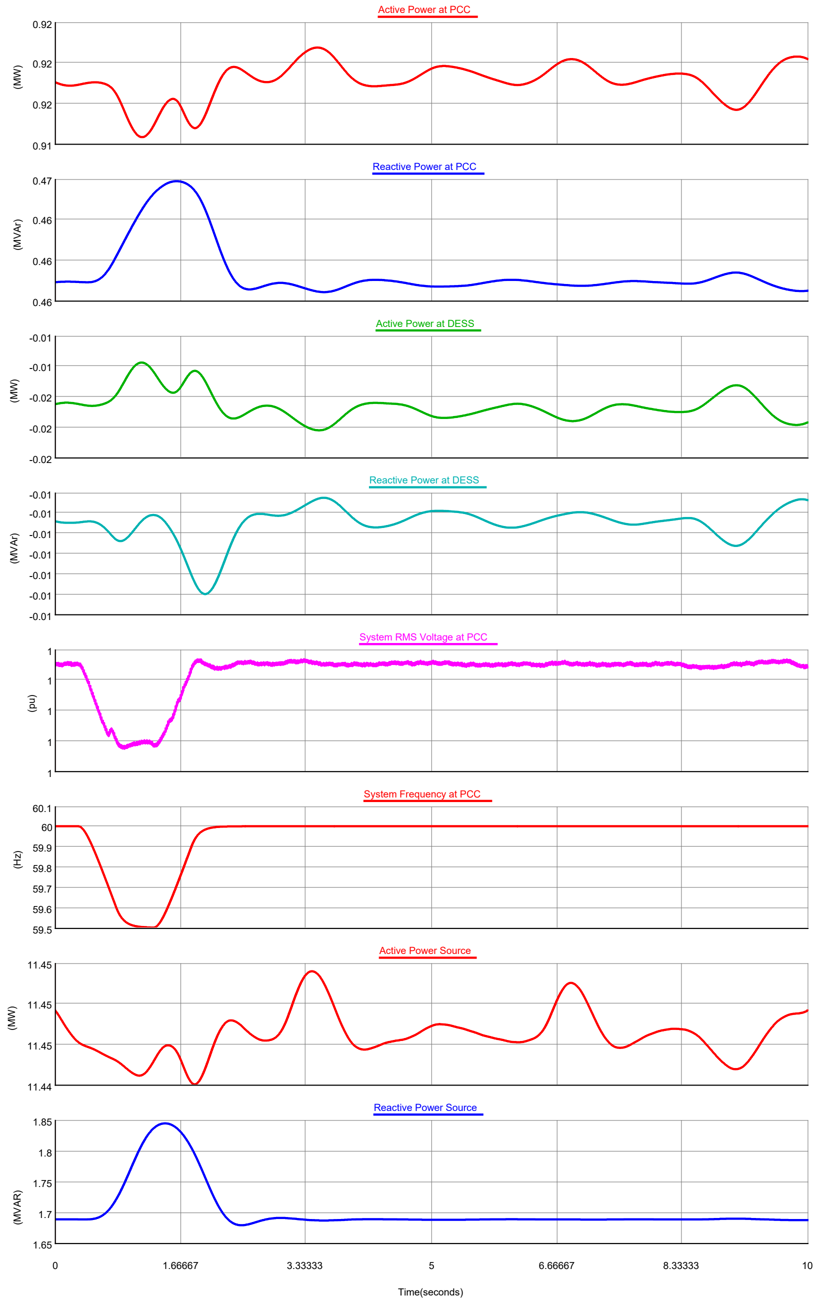

Figure 3.31: System Response for Test 4.1.5

SCENARIO 2: DER ON A COMPLEX CIRCUIT WITH A MULTITUDE OF CONTROLLABLE DEVICES

TEST 4.2.1: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 0.98pu to 1.038 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected by the change. The capacitor switched off during the increase in system voltage due to which the reactive power output of the source increased drastically restricting the system voltage at 1.025pu.

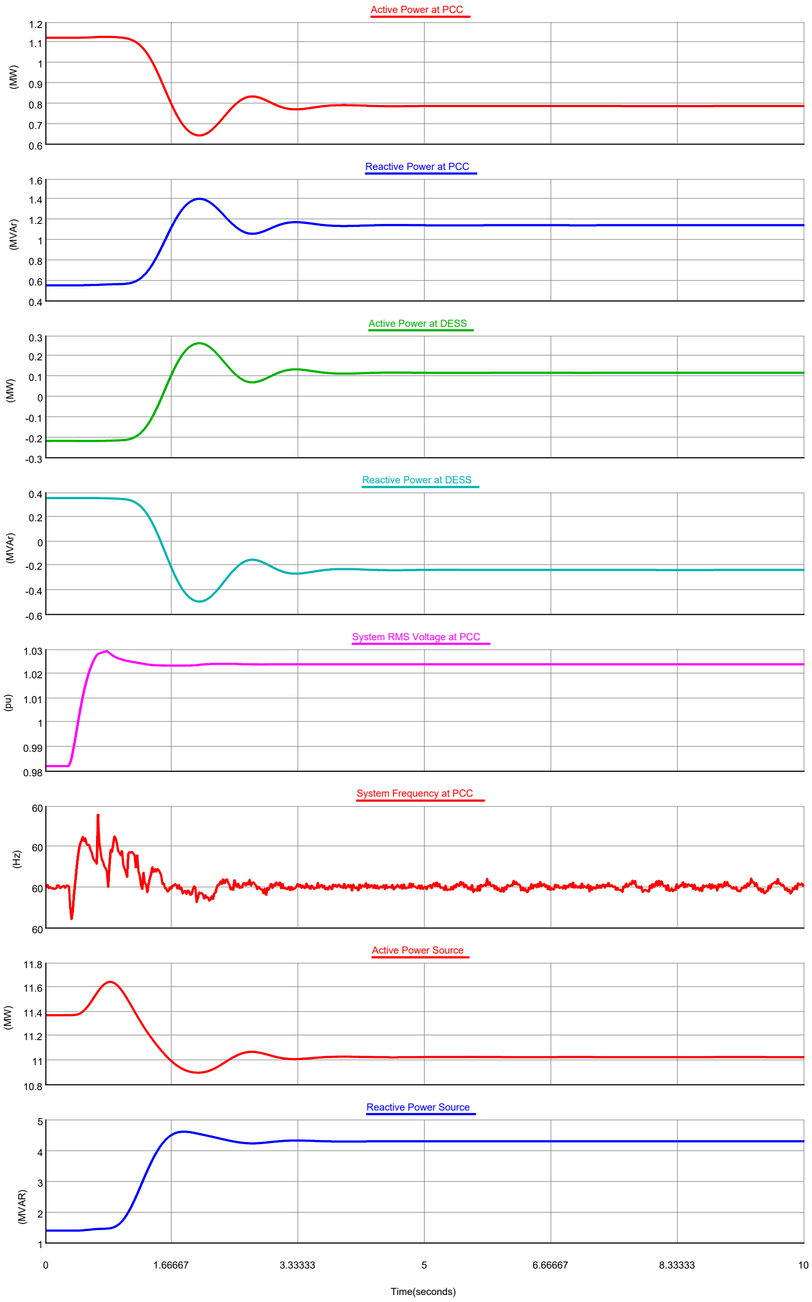

Figure 3.32: System Response for Test 4.2.1

TEST 4.2.2: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 0.98 pu to 0.93 pu, the reactive power output of the DER increased and produced more reactive power to maintain the node voltage at the PCC constant. The frequency remained unaffected by the change at steady state. The active power at the PCC and DER changed due to direction of the power flow.

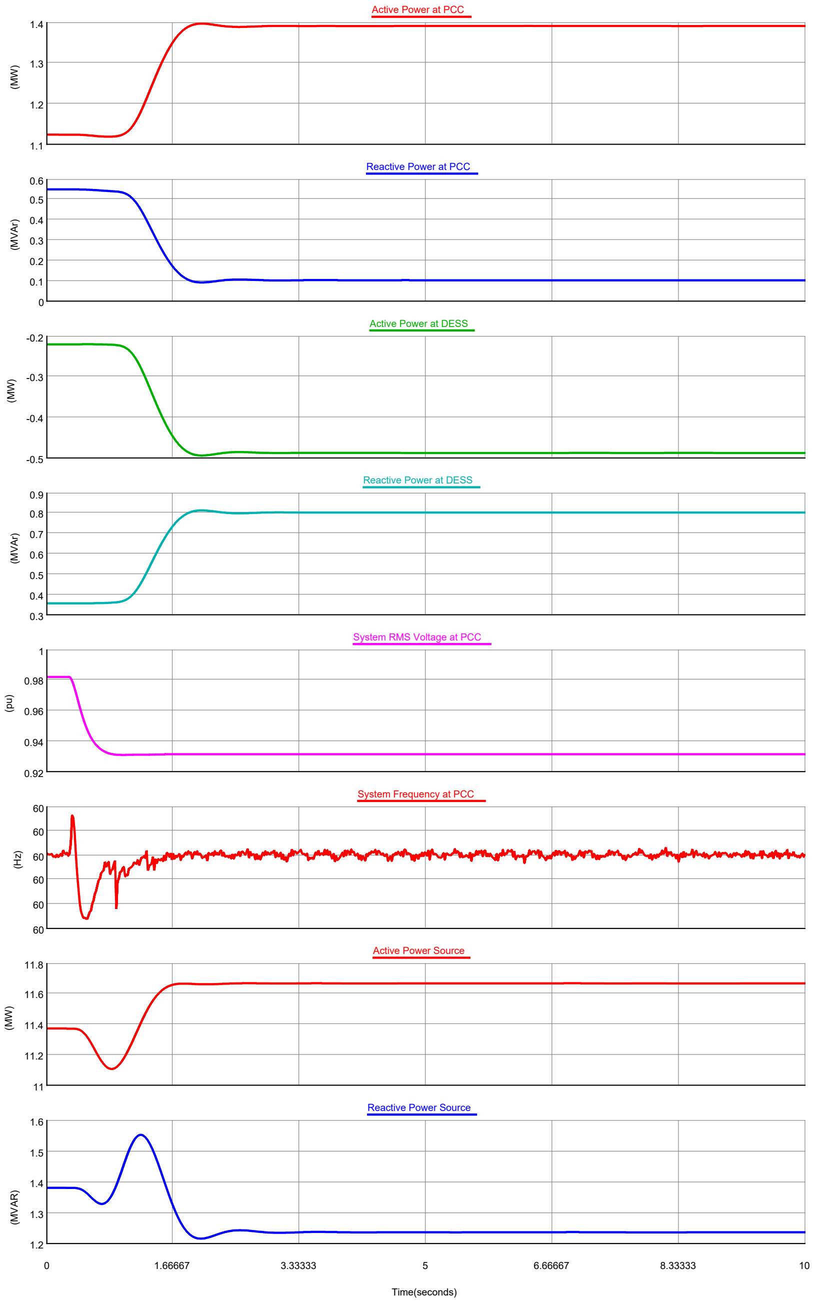

Figure 3.33: System Response for Test 4.2.2

TEST 4.2.3: VARY THE SYSTEM VOLTAGE

The voltage profile at the PCC was varied, as shown in Figure 3.28. The reduction in voltage caused one of the capacitors near the end of the feeder to turn on, which supplemented the reactive power along with the DER, resulting in the reduction of reactive power import from the source. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

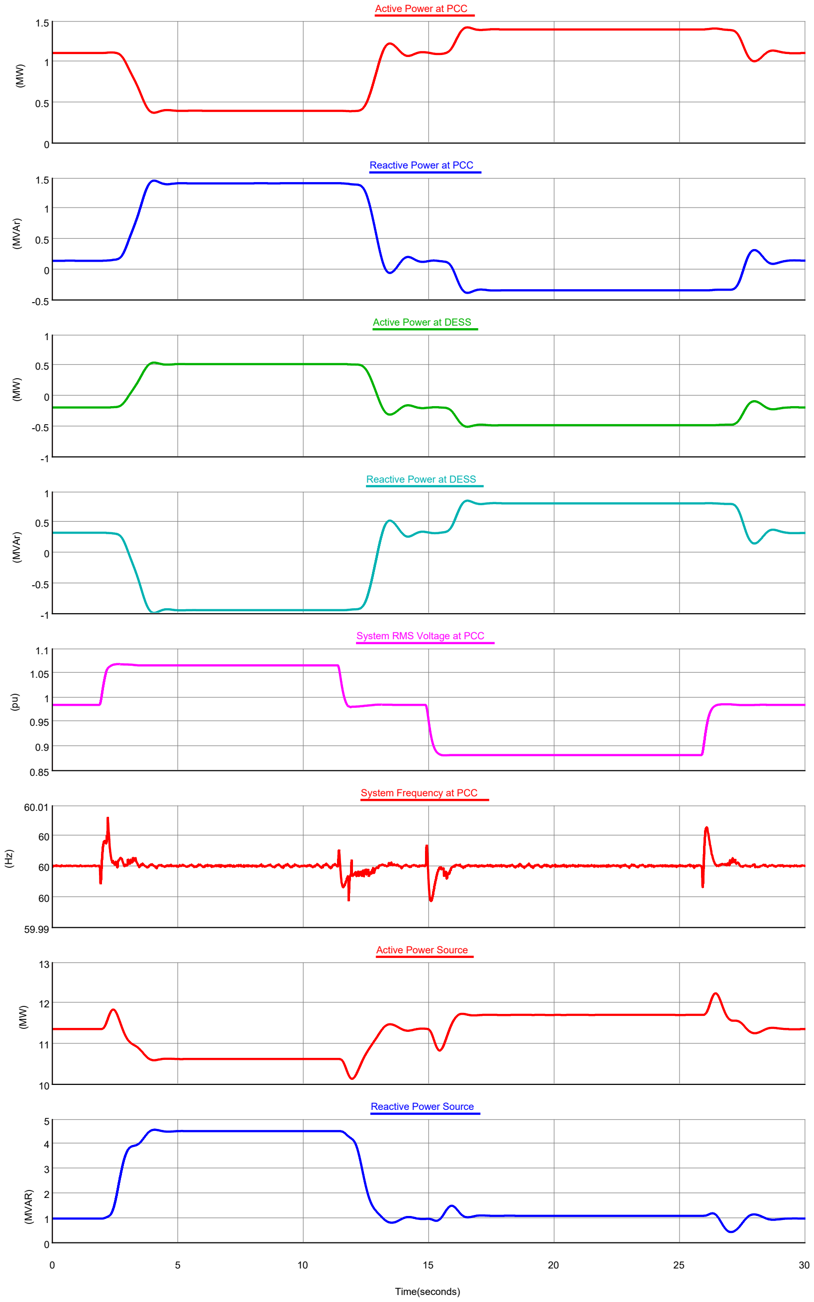

Figure 3.34: System Response for Test 4.2.3

Test 4.2.4: Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, it reacted to the change, rode through, and returned to steady state. The real and reactive power flows at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to the power flow but settled back to 1.018 pu in steady state.

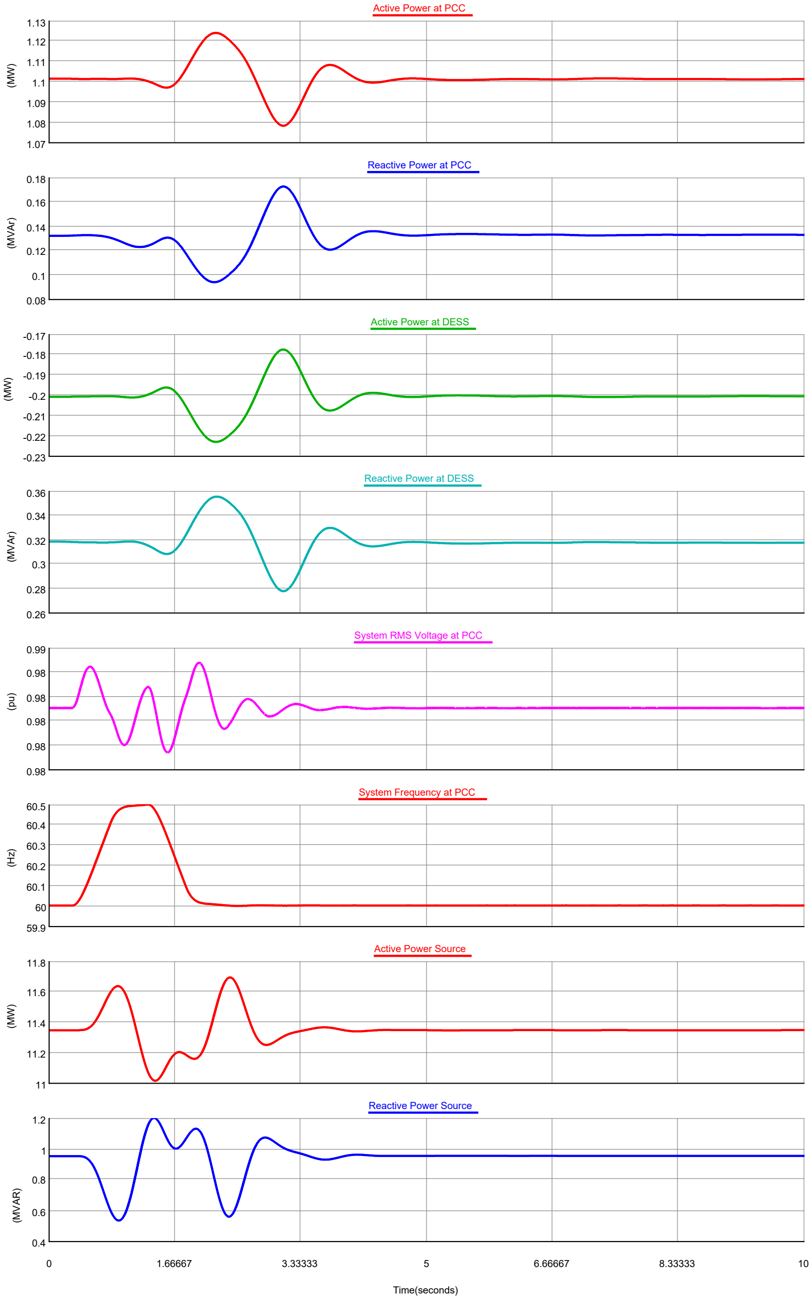

Figure 3.35: System Response for Test 4.2.4

SCENARIO 3: DER AT THE END OF A LONG FEEDER

TEST 4.3.1: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 0.978 pu to 1.025 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and real power at the PCC and DER remained unaffected by the change. The capacitor switched off during the increase in system voltage because of which the reactive power output of the source increased drastically restricting the system voltage at 1.012pu.

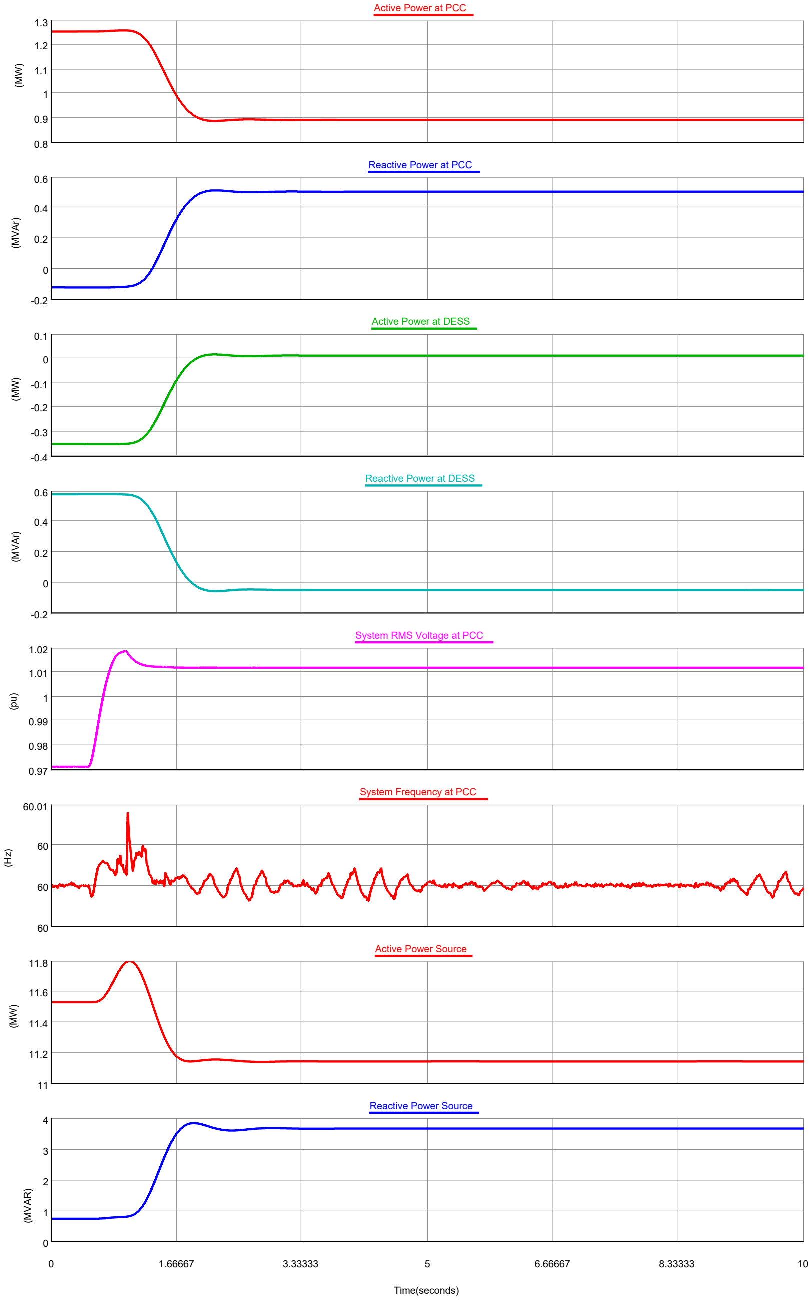

Figure 3.36: System Response for Test 4.3.1

TEST 4.3.2: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 0.978 pu to 0.925 pu, the reactive power output of the DER increased and produced more reactive power maintain the node voltage at the PCC constant. The frequency remained unaffected by the change at steady state. The active power at the PCC and DER changed due to direction of the power flow.

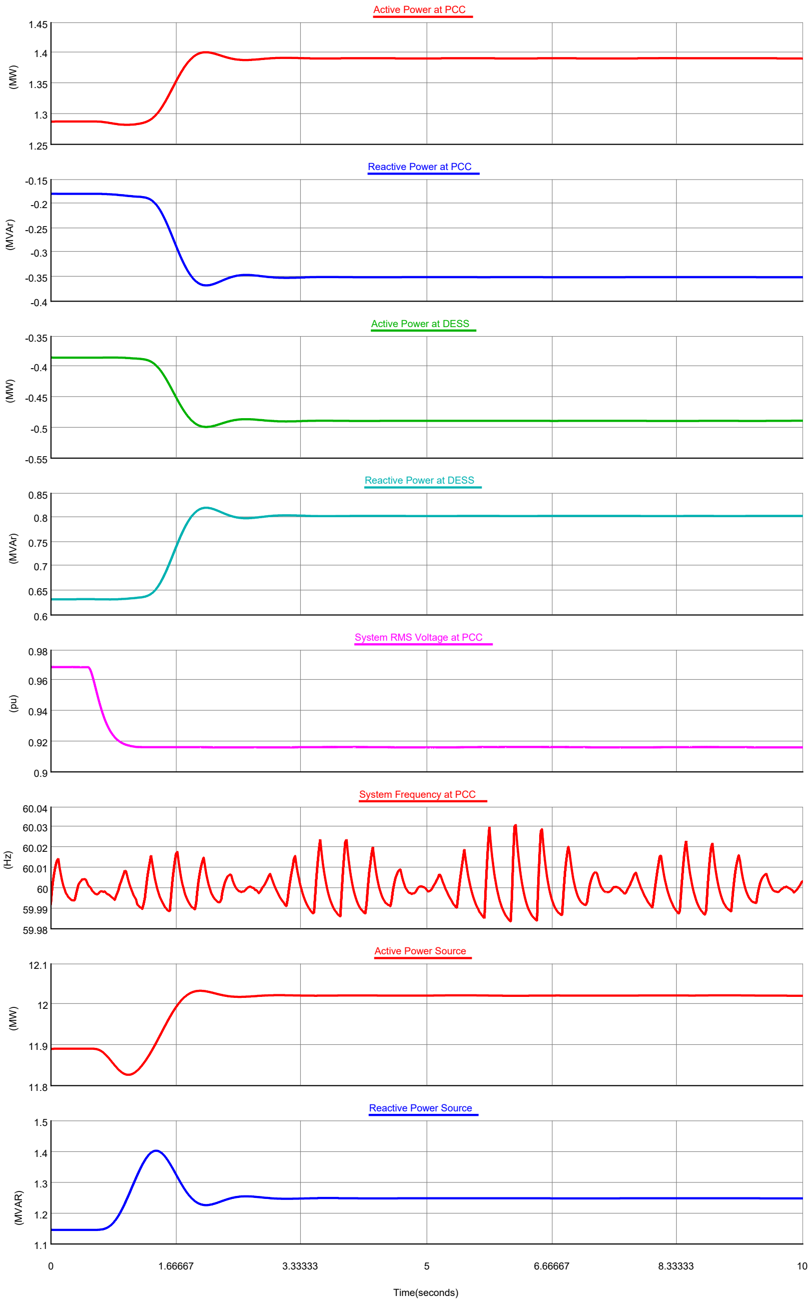

Figure 3.37: System Response for Test 4.3.2

TEST 4.3.3: VARY THE SYSTEM VOLTAGE

The voltage profile at the PCC is varied, as shown in Figure 3.28. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

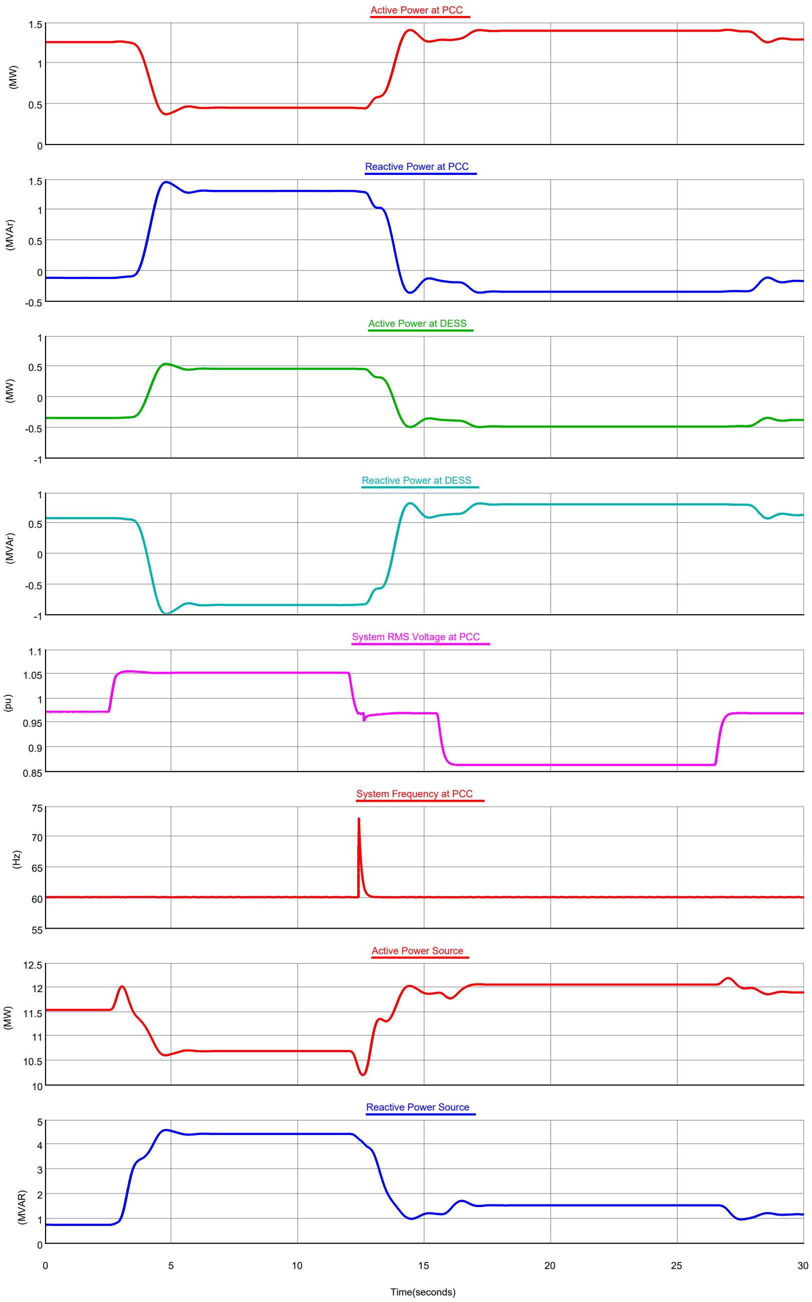

Figure 3.38: System Response for Test 4.3.3

TEST 4.3.4: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flows at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 0.978 pu in steady state.

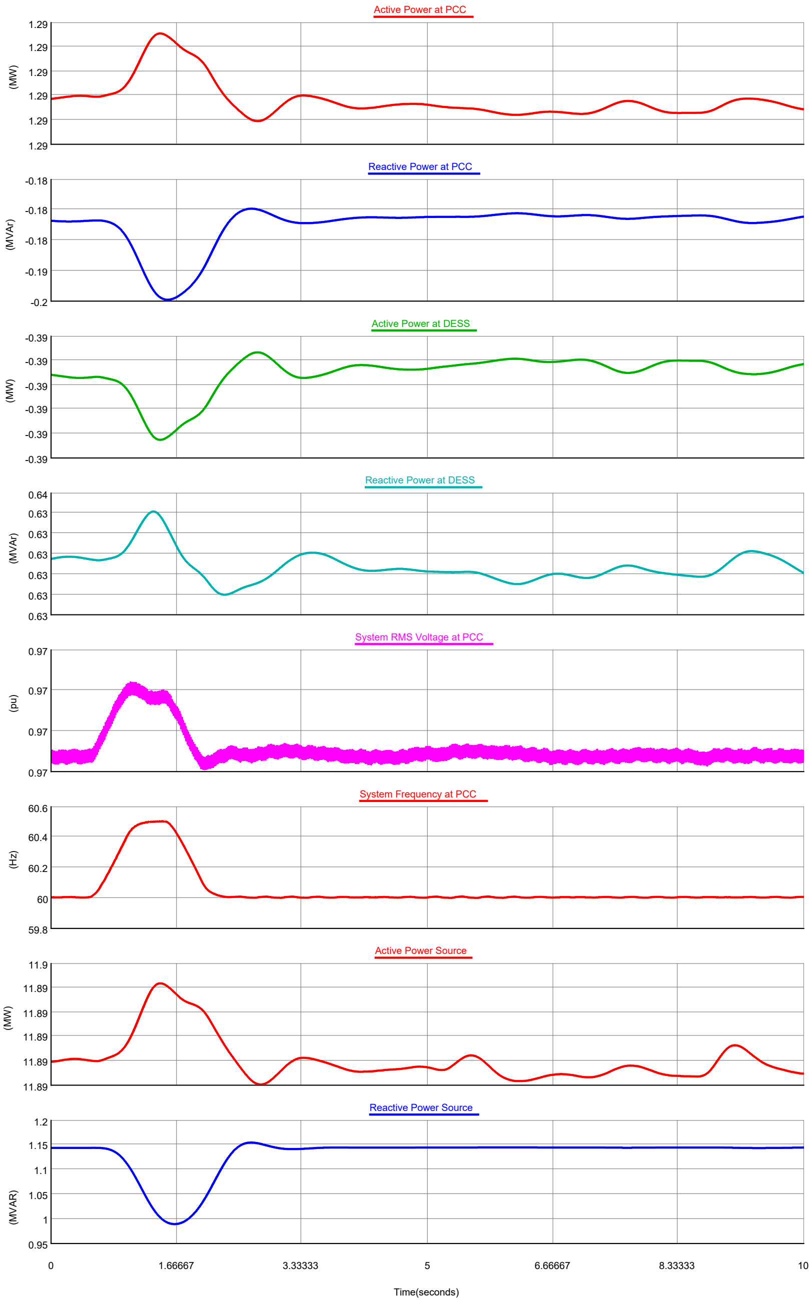

Figure 3.39: System Response for Test 4.3.4

Test 5 – Frequency-Watt

This function is intended to provide a mechanism through which a DER may be configured to manage its own active power output in response to the fluctuations in the system frequency. This function involves the dynamic production of active power to resist variations in the system frequency.

The objective is to counter any changes in the frequency by varying the output power. When the DER is in frequency-watt mode, it tries to maintain the frequency of the system to 60 Hz by regulating active power.

The procedure for testing was as follows:

Step 1. Vary the system frequency beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER (the DER should respond in such a way that the system frequency is maintained within the nominal values).

Step 2. Change the system frequency by changing the load in steps or by changing the grid frequency (when the DER is put into frequency-watt mode, the system frequency should revert to the nominal band because of the DER active power regulation).

Step 3. Compare the results with the base line case and develop the conclusions based on these findings.

Table 3.6 lists the tests that were conducted.

Table 3.6: DER Frequency-Watt Test Cases

Test	Test Description	Expected Response
Test 5. x.1	Increase the system frequency by 0.5 Hz for 1 s	DER decreases active power output to offset frequency increase. DER dispatches 500 kW at steady state.
Test 5. x.2	Decrease the system frequency by 0.5 Hz for 1 s	DER increases active power output to offset frequency decrease. DER dispatches 500 kW at steady state
Test 5. x.3	a) Ramp up the system frequency to 60.5 Hz at the rate of 0.1 Hz per second, and hold it for 5 s b) Ramp down the system frequency to 59.7 Hz at the rate of 0.1 Hz per second, and hold it for 5 s)	DER decreases its active power output to offset frequency increases and following that DER increases its active power output to offset frequency decrease. DER settles back at 500 kW at steady state.
Test 5. x.4	Increase the system frequency by 0.5 Hz for 5 s	DER decreases active power output to offset frequency increase
Test 5. x.5	Decrease the system frequency by 0.5 Hz for 5 s	DER increases active power output to offset frequency decrease

Note: "x" denotes the scenario under test.

SCENARIO 2: DER ON A COMPLEX CIRCUIT WITH A MULTITUDE OF CONTROLLABLE DEVICES

TEST 5.2.1: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settles back to 1.01 pu in steady state.

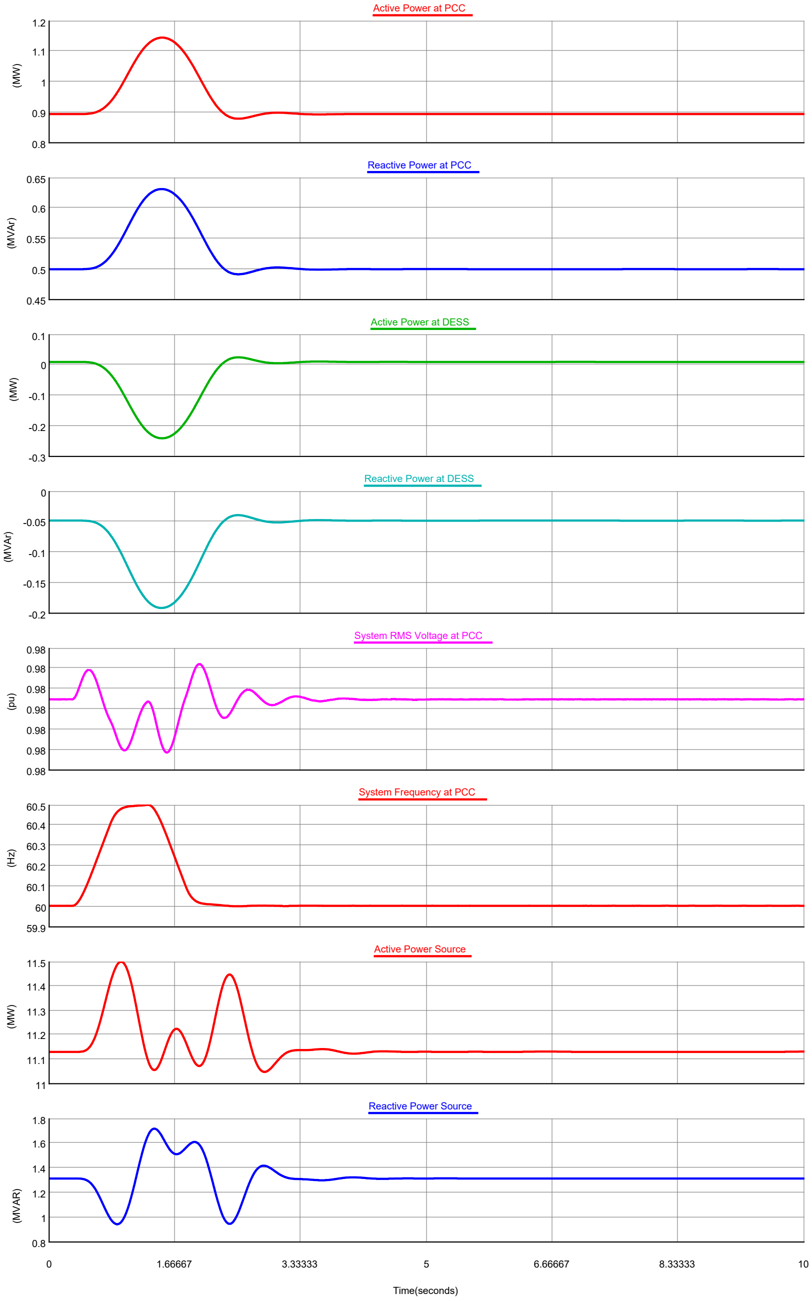

Figure 3.40: System Response for Test 5.2.1

Test 5.2.2: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

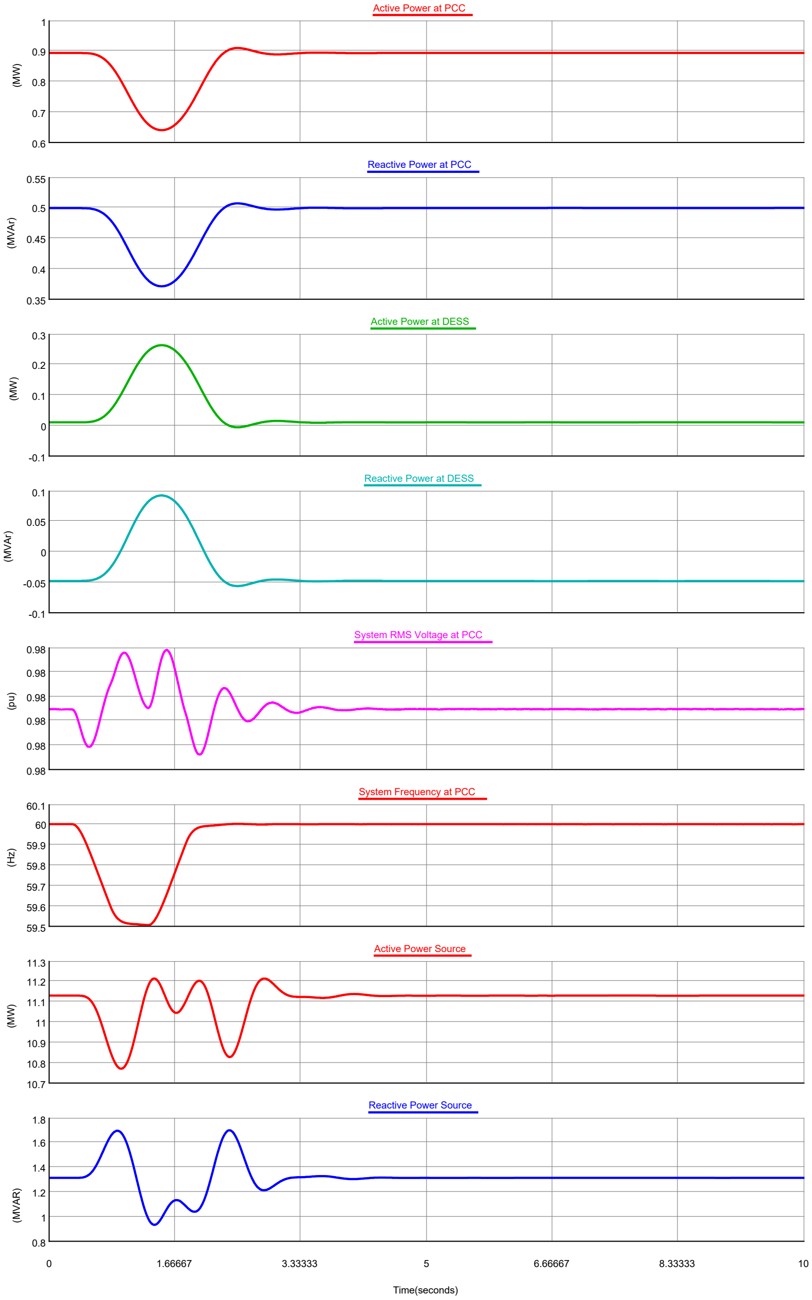

Figure 3.41: System Response for Test 5.2.2

TEST 5.2.3: VARY THE SYSTEM FREQUENCY

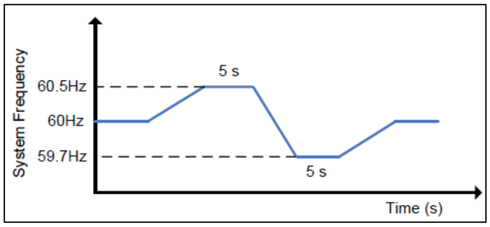

Figure 3.42: System Frequency Profile for Test 5.1.8

On increasing the system frequency to 60.5 Hz at a ramp rate of 0.1 Hz per second (as shown in Figure 3.42), the real power across the DER reduced, while the active power import across the PCC increased. The frequency was held at 60.5 Hz for a period of 5 seconds, during which the active power across the PCC and DER began to settle. Once the frequency started decreasing from 60.5 Hz to 59.7 Hz and was held for another 5 seconds, the active power output of the DER increased and the import across the PCC reduced. The active power settled at its previous set point of 500 kW during steady-state conditions following the disturbances. The reactive power was disturbed during this transition and settled at its previous set point during steady-state conditions. The system voltage was affected during this transition but returned to 1.01 pu during steady-state conditions.

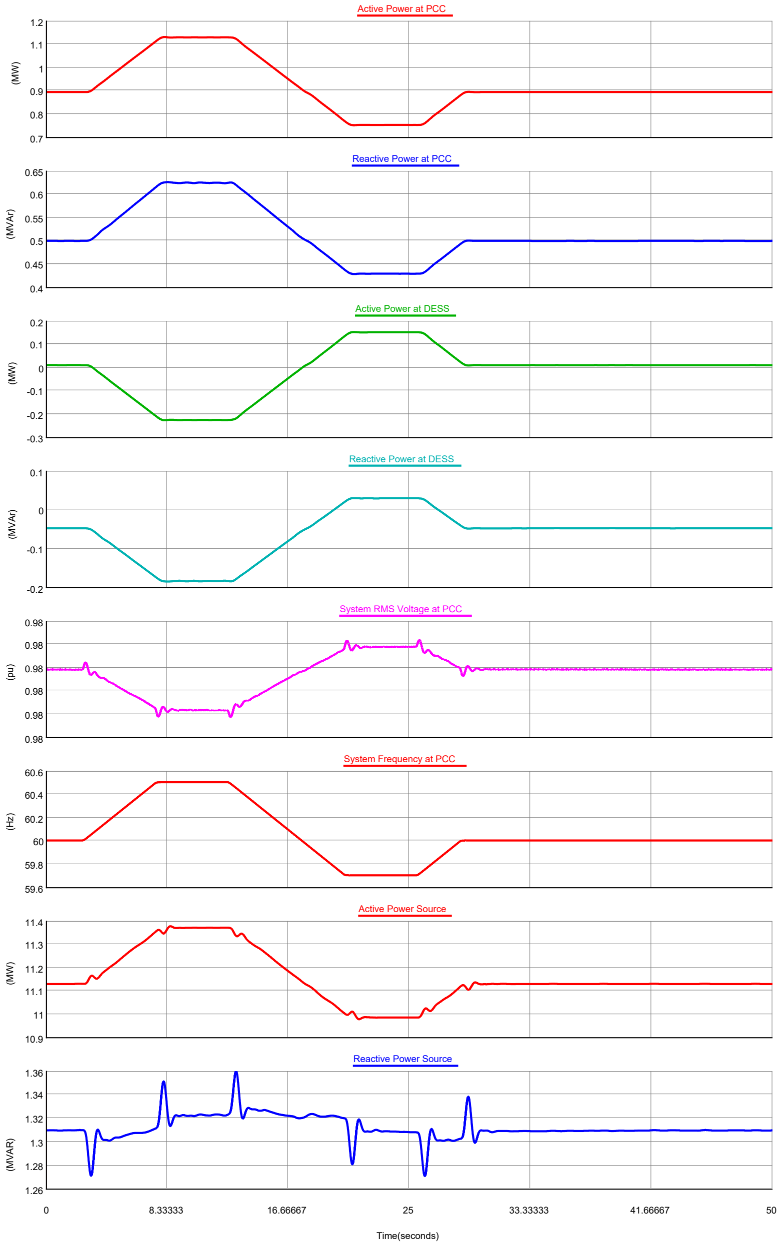

Figure 3.43: System Response for Test 5.2.3

Test 5.2.4: Increase the System Frequency by 0.5 Hz

On increasing the system frequency by 0.5 Hz, the DER responded to the frequency change by reducing its power output and settled at a new set point per the frequency-watt droop of the inverter. This caused more active power to be drawn from the grid. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1 pu at steady state.

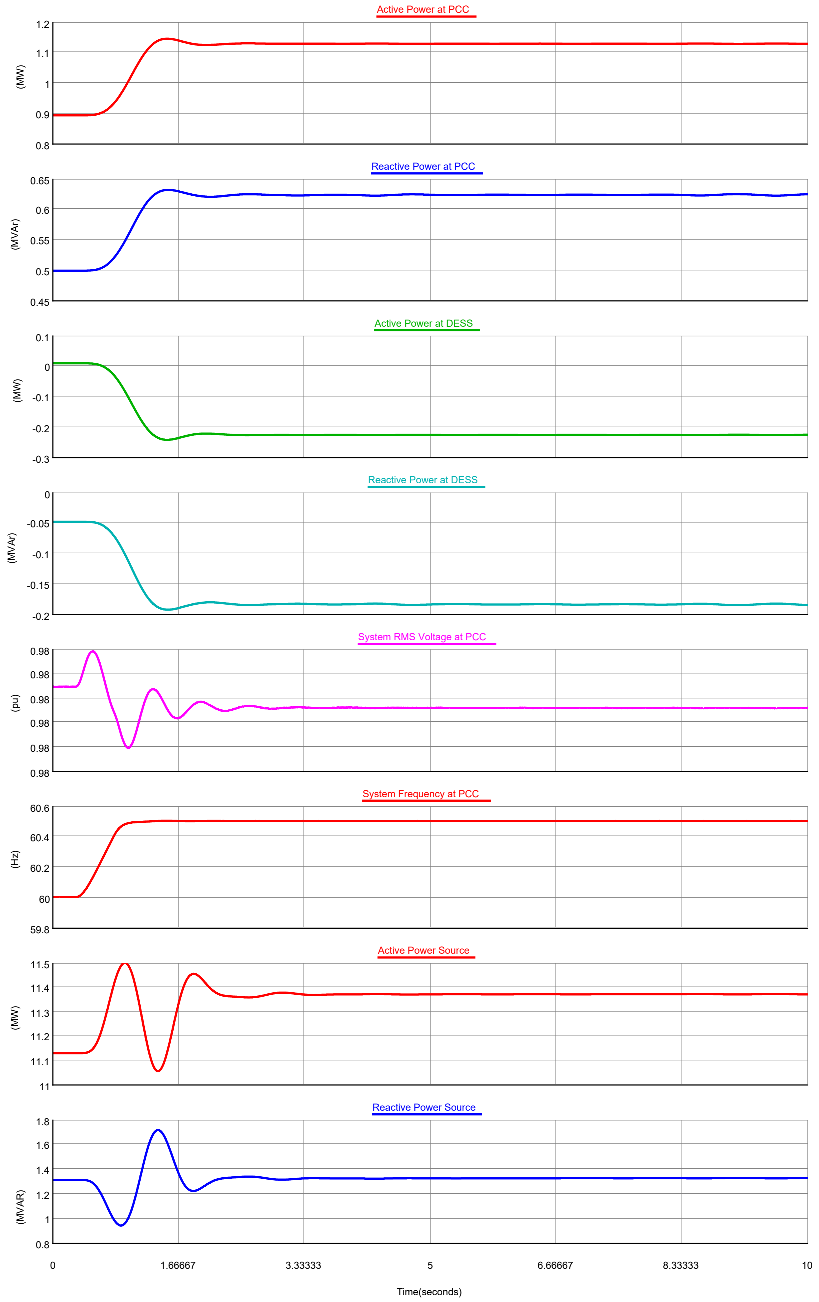

Figure 3.44: System Response for Test 5.2.4

Test 5.2.5: Decrease the System Frequency by 0.5 Hz

On decreasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by increasing its power output and settled at a new set point per the frequency-watt droop of the inverter. This reduced the active power import from the grid through the PCC. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1 pu at steady state.

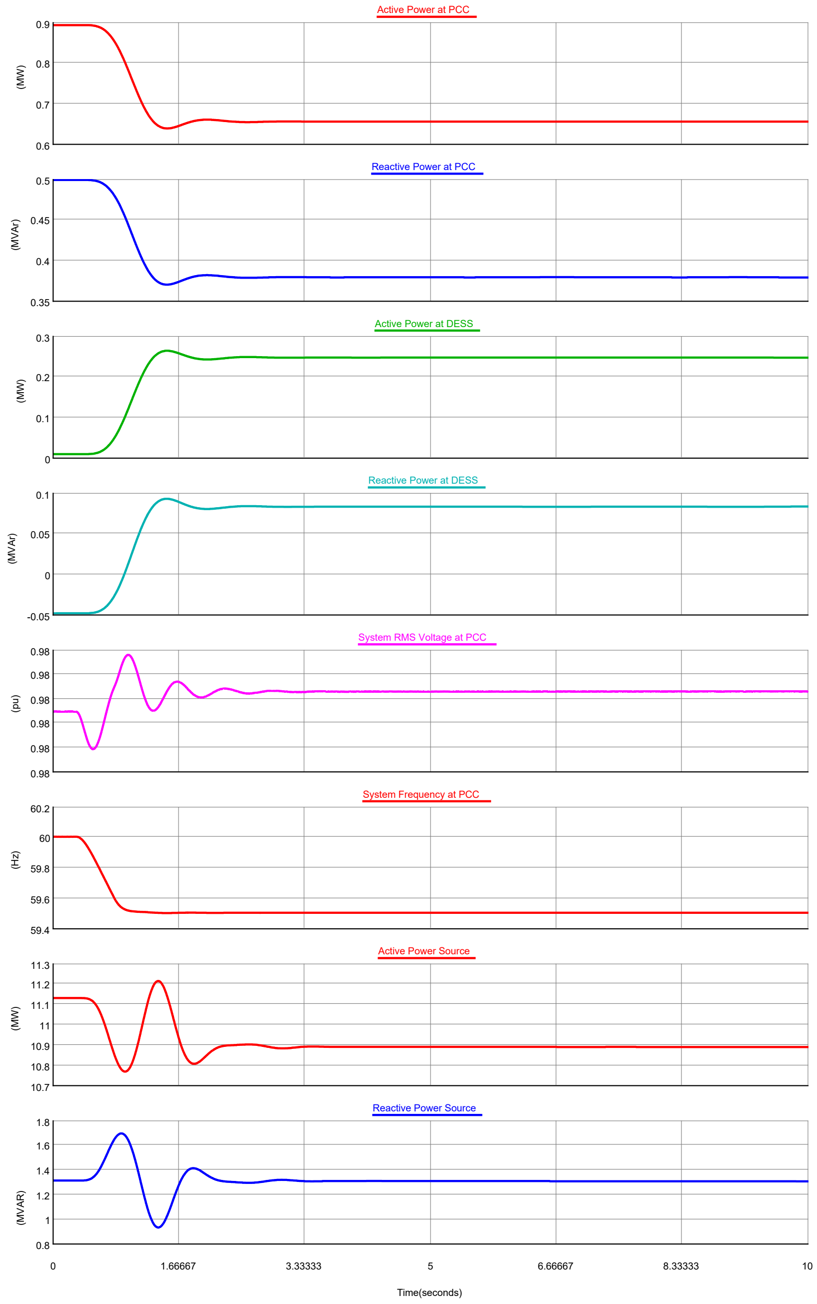

Figure 3.45: System Response for Test 5.2.5

Scenario 3: DER at the End of a Long Feeder

Test 5.3.1: Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 0.978 pu in steady state.

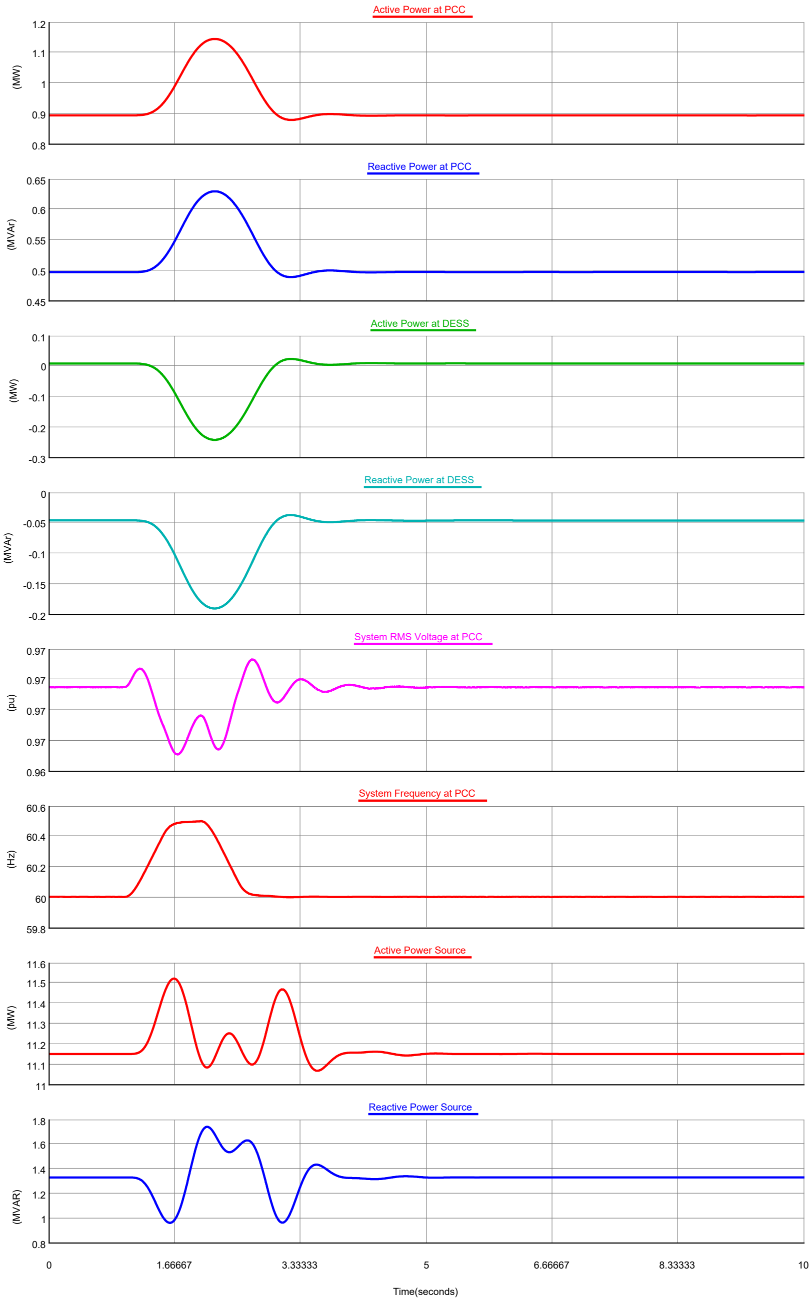

Figure 3.46: System Response for Test 5.3.1

TEST 5.3.2: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 0.978 pu in steady state.

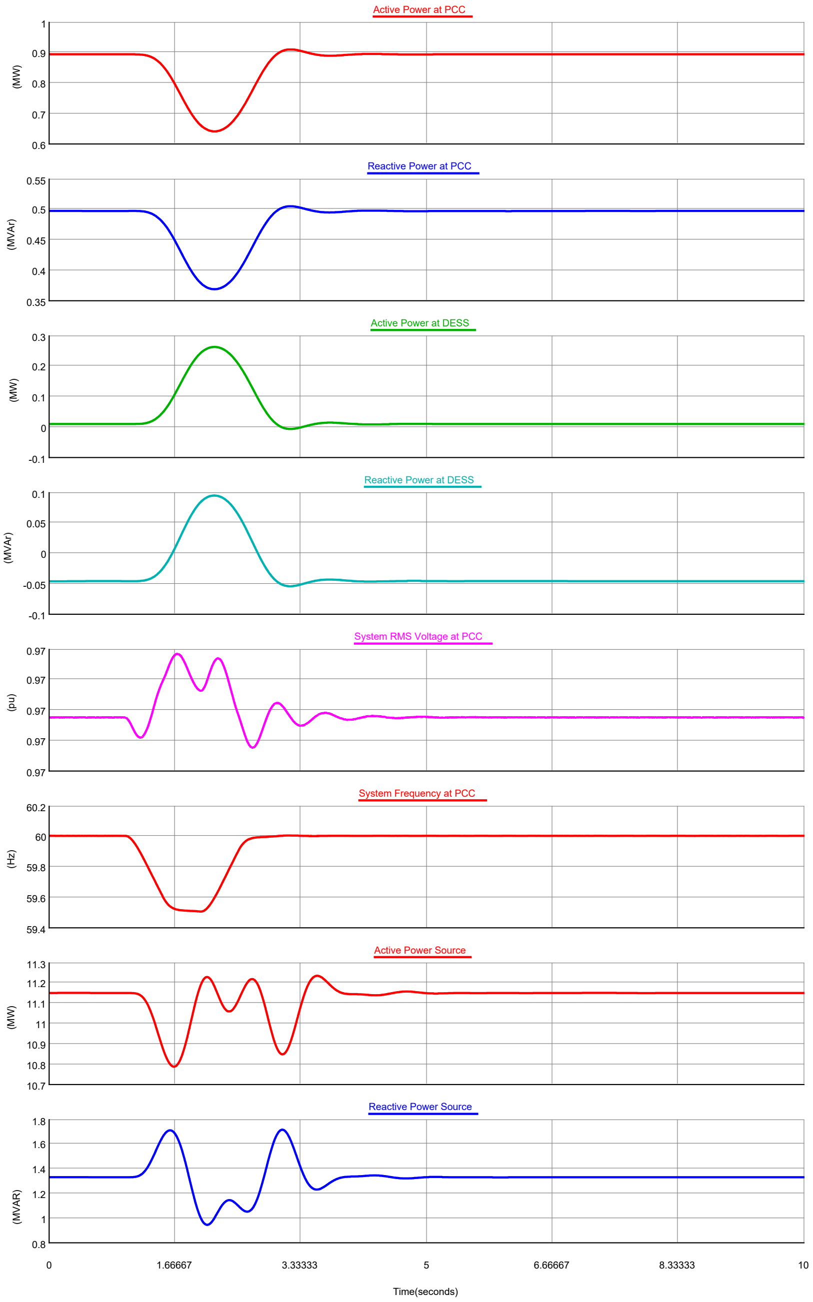

Figure 3.47: System Response for Test 5.3.2

Test 5.3.3: Vary the System Frequency

The system frequency was changed as shown in Figure 3.42. The reactive power is disturbed during this transition and settles at its previous set point during steady-state conditions. The system voltage is affected during this transition but returns to 0.978 pu during steady-state conditions.

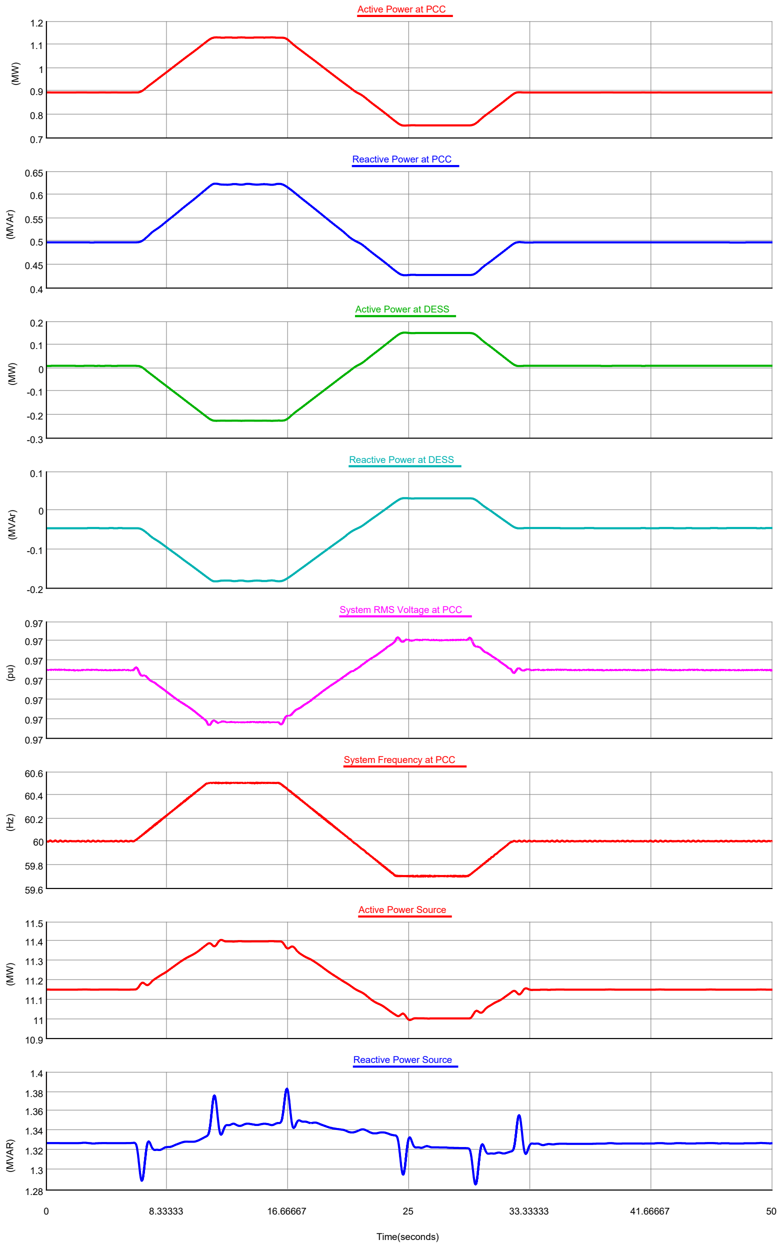

Figure 3.48: System Response for Test 5.3.3

TEST 5.3.4 INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On increasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by reducing its power output and settled at a new set point per the frequency-watt droop of the inverter. This caused more active power to be drawn from the grid. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1 pu at steady state.

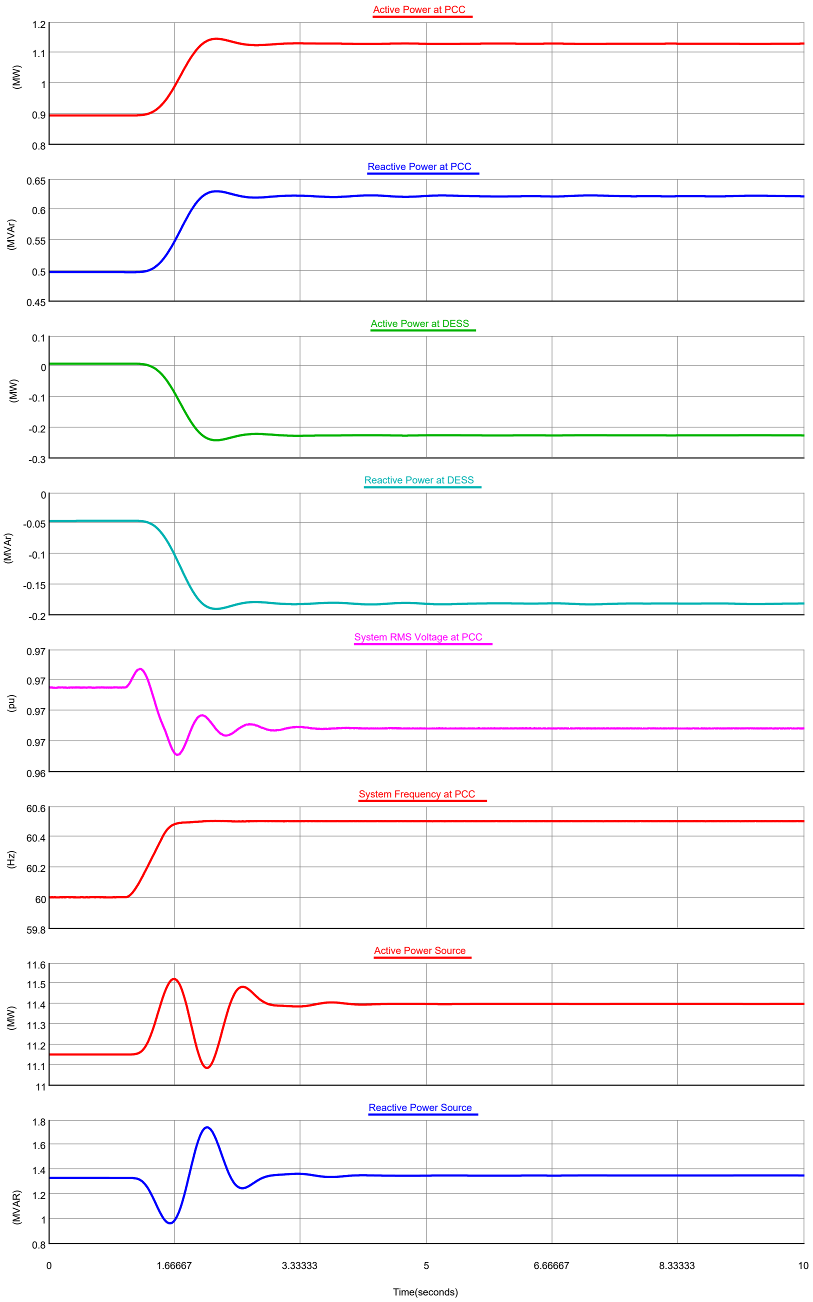

Figure 3.49: System Response for Test 5.3.4

Test 5.3.5: Decrease the System Frequency by 0.5 Hz

On decreasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by increasing its power output and settled at a new set point per the frequency-watt droop of the inverter. This reduced the active power import from the grid through the PCC. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1 pu at steady state.

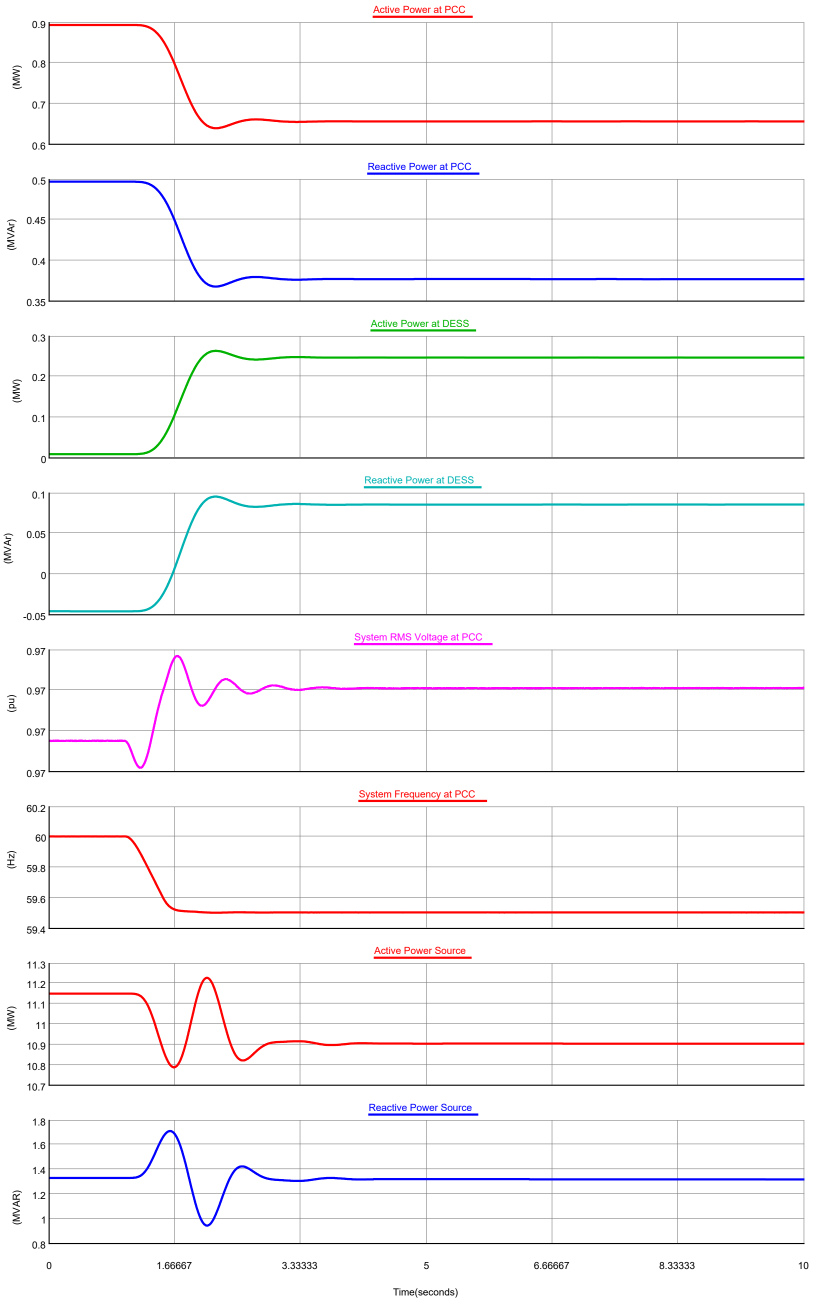

Figure 3.50: System Response for Test 5.3.5

SCENARIO 4: MULTIPLE DIVERSE TYPES OF DER ON THE SAME CIRCUIT

TEST 5.4.1 INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

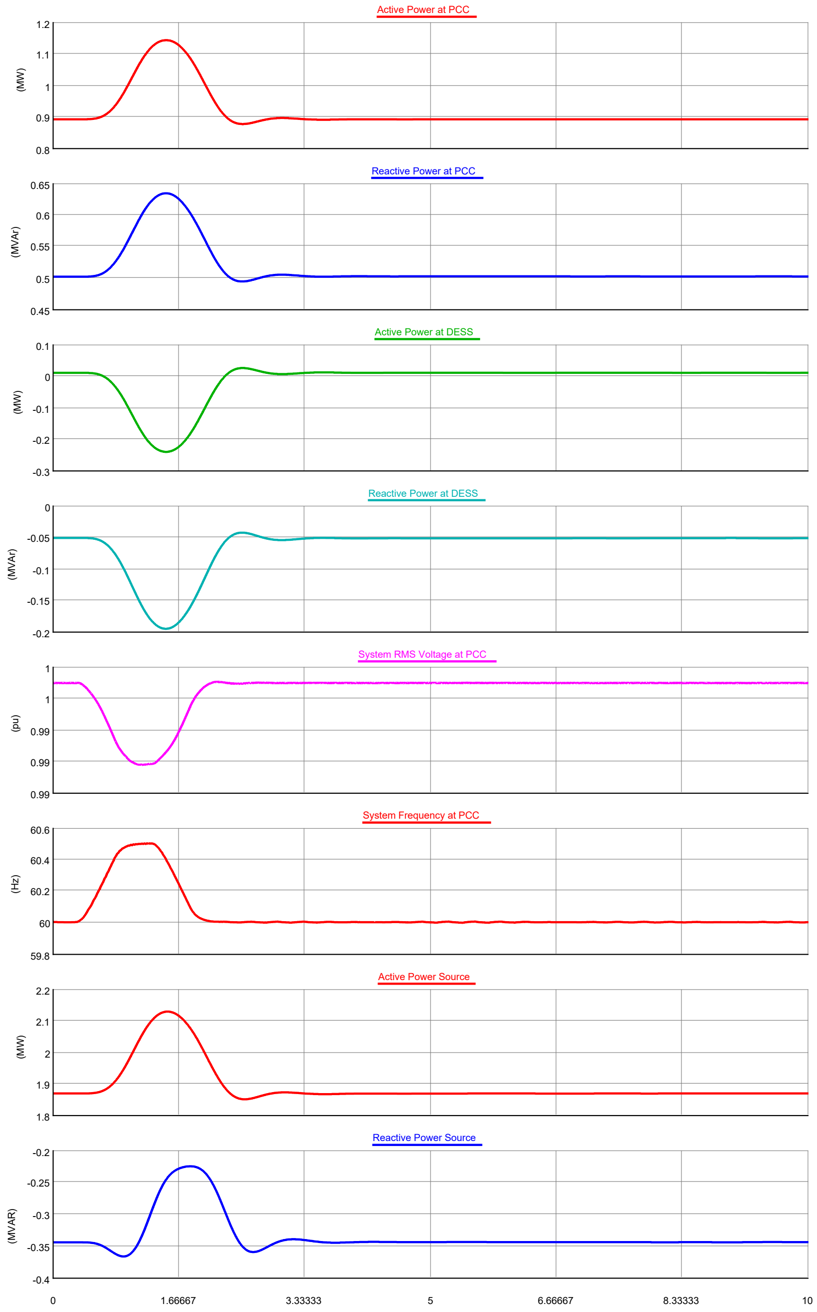

Figure 3.51: System Response for Test 5.4.1

Test 5.4.2: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.0 pu in steady state.

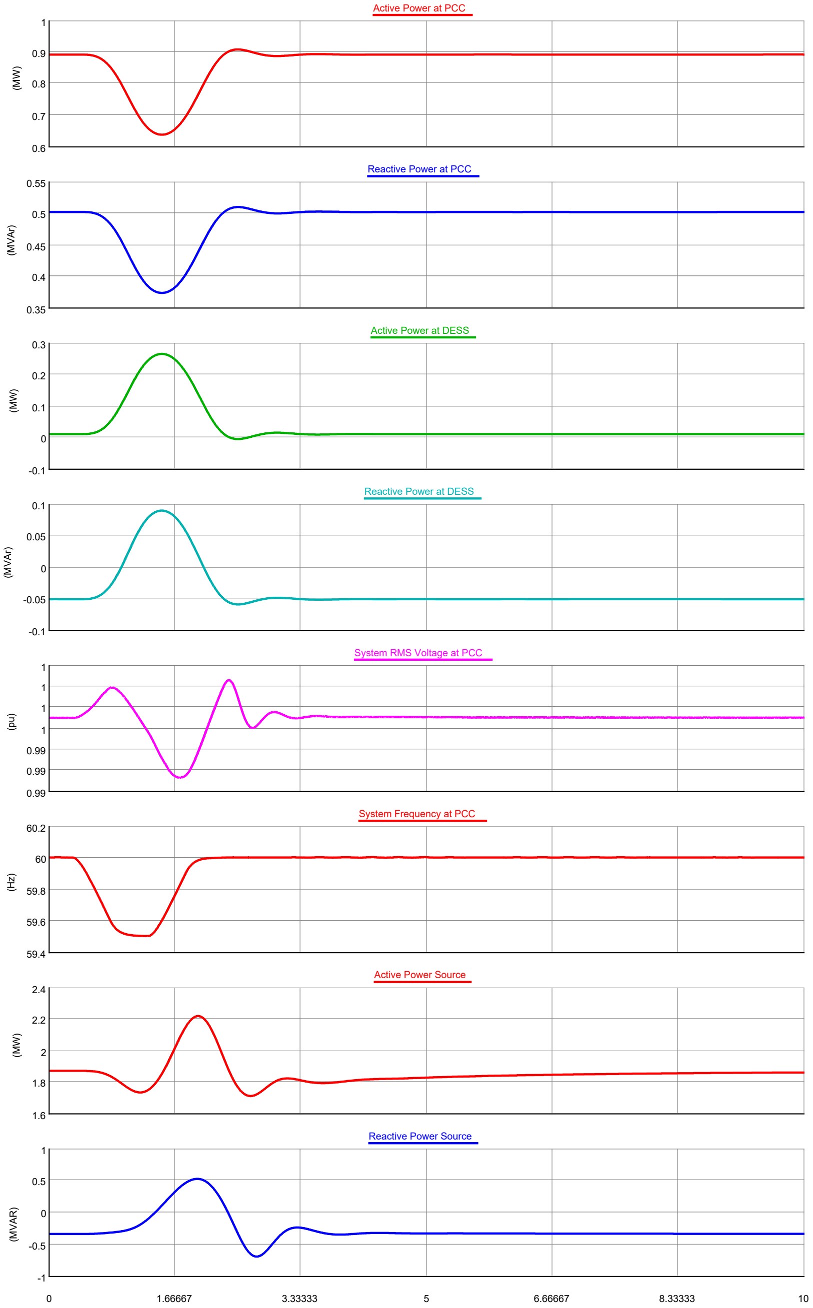

Figure 3.52: System Response for Test 5.4.2

TEST 5.4.3: VARY THE SYSTEM FREQUENCY

The system frequency was changed as shown in Figure 3.42. The reactive power was disturbed during this transition and settled at its previous set point during steady-state conditions. The system voltage was affected during this transition but returned to 1.0 pu during steady-state conditions.

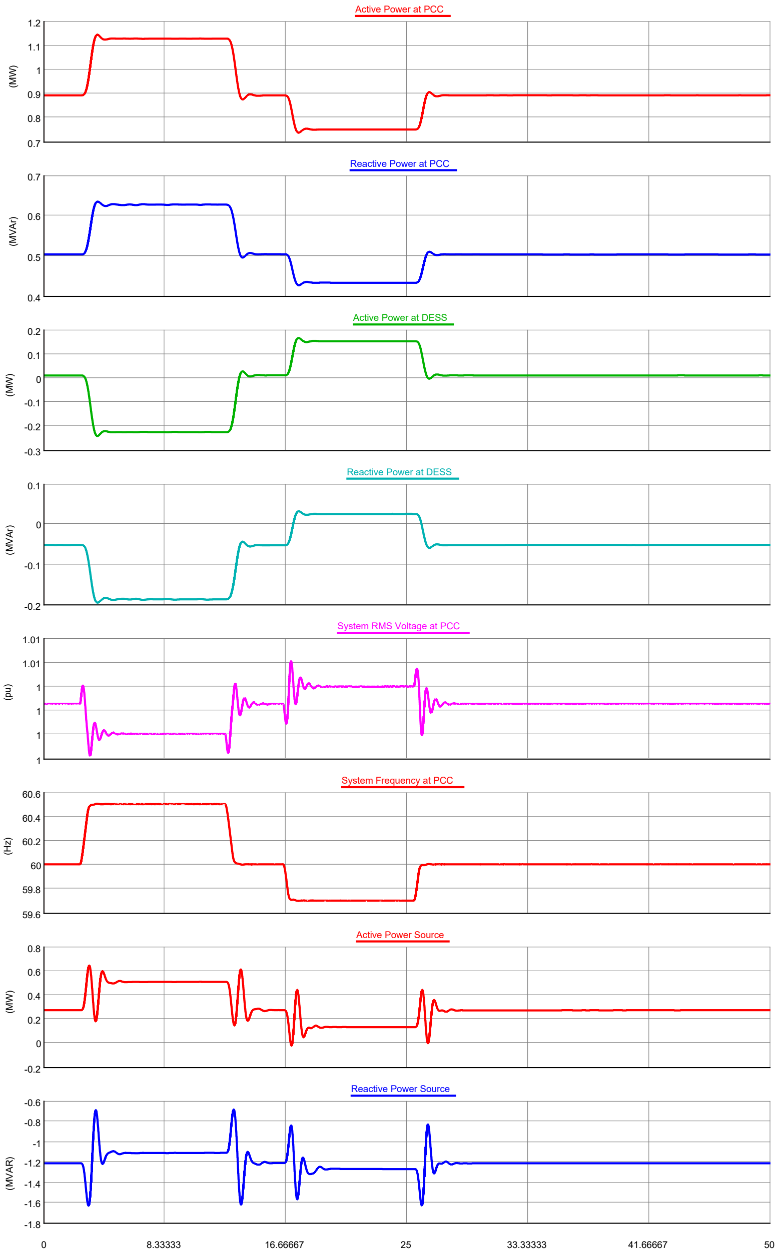

Figure 3.53: System Response for Test 5.4.3

Test 6 – DER Response to Emergencies

In this test, the DER system was subjected to various emergency situations and the action taken by the utility is sending specific commands to the DER. The response of the DER system is recorded for analysis.

The objective of this test was to demonstrate and analyze the operability of the DER system with a utility's DER management system, which performs manual or autonomous functions remotely. The DER system should have the provisions in the inverter to send status signals and respond to the commands and settings from the utility DER management system.

Table 3.7 lists the tests that were conducted.

Table 3.7: DER Emergency Response Test Cases

Test	Test Description	Expected Response	Actual Response
Test #6.1	Issue disconnect or reconnect commands to the DER system from the utility	Connect/ Disconnect	Connect/ Disconnect
Test #6.2	Update voltage ride-through curves to change anti-islanding settings	Update the ride-through curves	Curves are hard set locally
Test #6.3	Update frequency ride-through curves to change anti-islanding settings	Update the ride-through curves	Curves are hard set locally
Test #6.4	Request notification from the DER system about the status of microgrid connection	-	-
Test #6.5	Request notification from the DER system about the spinning reserve	-	-

These tests examined the capability of the inverter to communicate the information with the utility management system for more operational flexibility. Following are some of the emergency commands and requests that are exchanged between the utility and the DER managements system.

- Issue disconnect or reconnect commands to the DER system from the utility.

  A start and stop command can be sent remotely over Modbus to the DER controller for connecting and disconnecting the DER from the system. The startup process took up to 4 seconds after the start command is issued to the controller. Figure 4.6 shows the startup transient during the inverter AC breaker closing. Once the DER is online, different mode commands can be sent with the required active and reactive power set points.

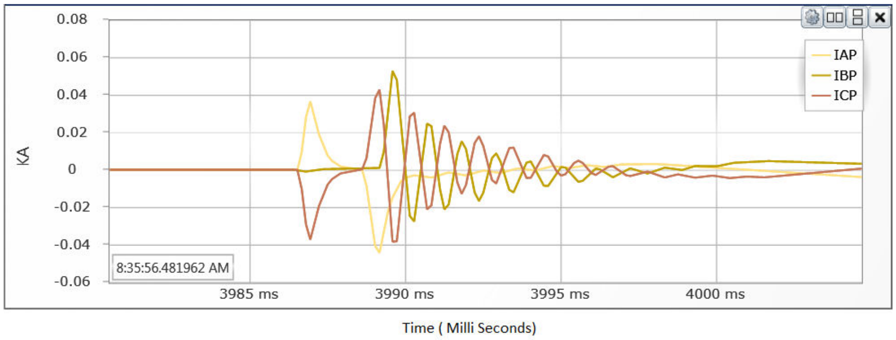

Figure 3.54: Inverter Startup Transients

- Update voltage ride-through curves to change anti-islanding settings.

  The voltage ride-through settings on the tested DER can only be set via the HMI since this setting in not available in the Modbus register.

- Update frequency ride-through curves to change anti-islanding settings.

  The frequency ride-through settings on the tested DER can only be set via the HMI since this setting is not available in the Modbus register.

- Request notification from the DER system about the status of microgrid connection.

  The tested DER continuously broadcast its status to the remote managements system via Modbus, indicating if the DER was online or offline. Along with this status information, the DER also sent the power output information. Based on this information utility operator can take operations decisions during different periods of the day.

- Request notification from the DER system about the spinning reserve.

  The tested DER sent the present state of charge to the remote management system via Modbus, which aids the utility operator with load and generation forecast.

Test 7 – Spinning Reserve

The objective of this test was to assess the benefits of the DER in functioning as a spinning reserve in different system conditions, compared to traditional sources, such as diesel generators. The DER is compared against the traditional backup diesel generator as a source of spinning reserve in terms of response time, standby losses, durability of support, and availability.

The procedure for testing was as follows:

Step 1. Place the DER into the idle mode with the state of charge (SOC) of the battery at the full level.
Step 2. Create a contingency where a source of generation (Grid) is taken offline to simulate an under-frequency situation in the system.
Step 3. Set the DER in to voltage and frequency regulation modes after approximately 5 seconds to produce the deficit active and reactive power to support the rest of the system during this event. Bring the additional backup generation online, in the meantime.
Step 4. Perform a comparative analysis in terms of economic benefits in fuel savings, ease of operation, response time, and reliability.
Step 5. Document the results of the testing for analysis.

To analyze the response of the system more accurately, a reduced dynamic model of the distribution circuit was developed and is described and the results are presented in Appendix B.

TEST 7.1 MODE ACTIVATION

The DER was initiated into the spinning reserve mode by activating the frequency and the voltage regulation functions. This caused the active and reactive to shift to support the system voltage and frequency. This caused the voltage and the frequency to settle down at 1 pu and at 60 Hz respectively.

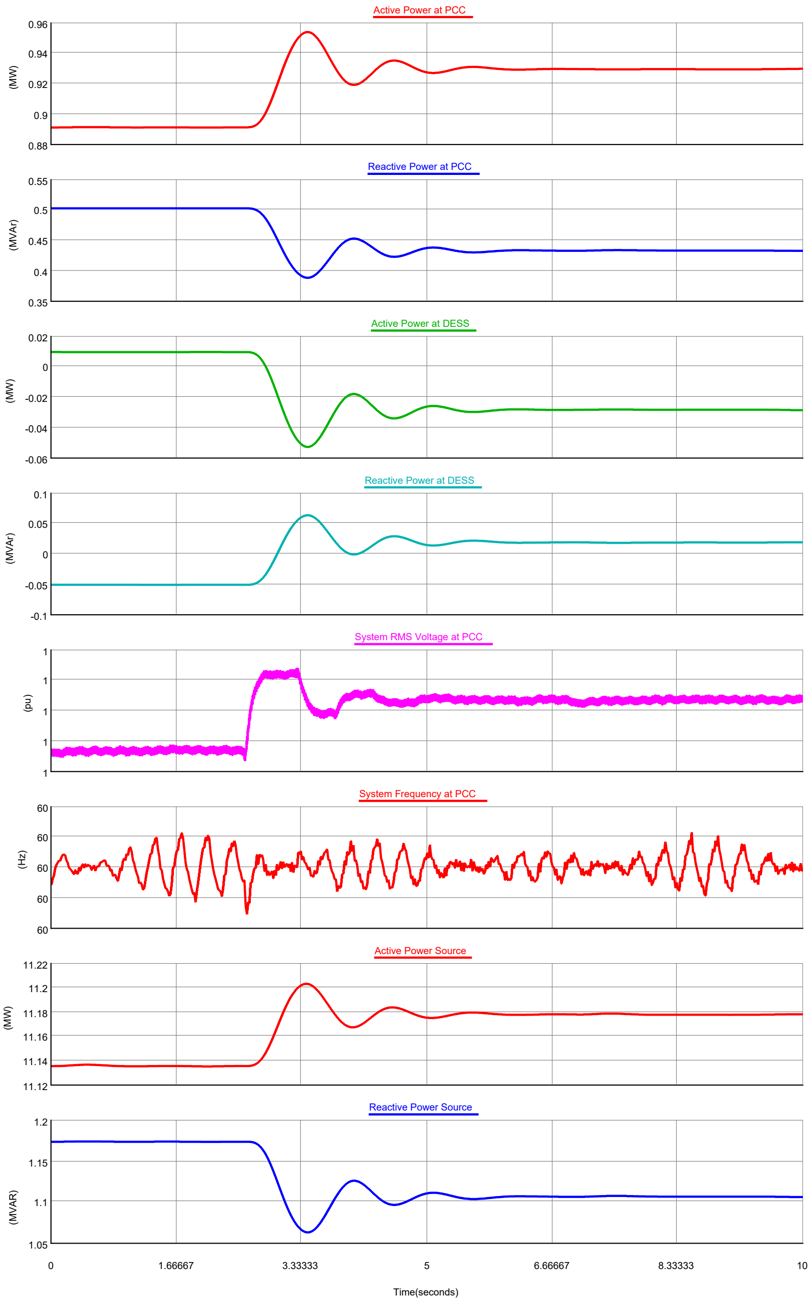

Figure 3.55: System Response for Test 7.1

TEST 7.2 OPENING THE BREAKER ACROSS THE DER

On creating an under-frequency situation by opening the breaker, the generation from the source across the PCC dropped to zero. The DER acted as spinning reserve and picked up/supported the local load. This caused the voltage and frequency to drop temporarily across the terminals of the PCC. The active and reactive power generation from the source dropped as the load across the DER was supported by the DER. The frequency at steady state was lesser than 60Hz because the DER was operating near its maximum capacity.

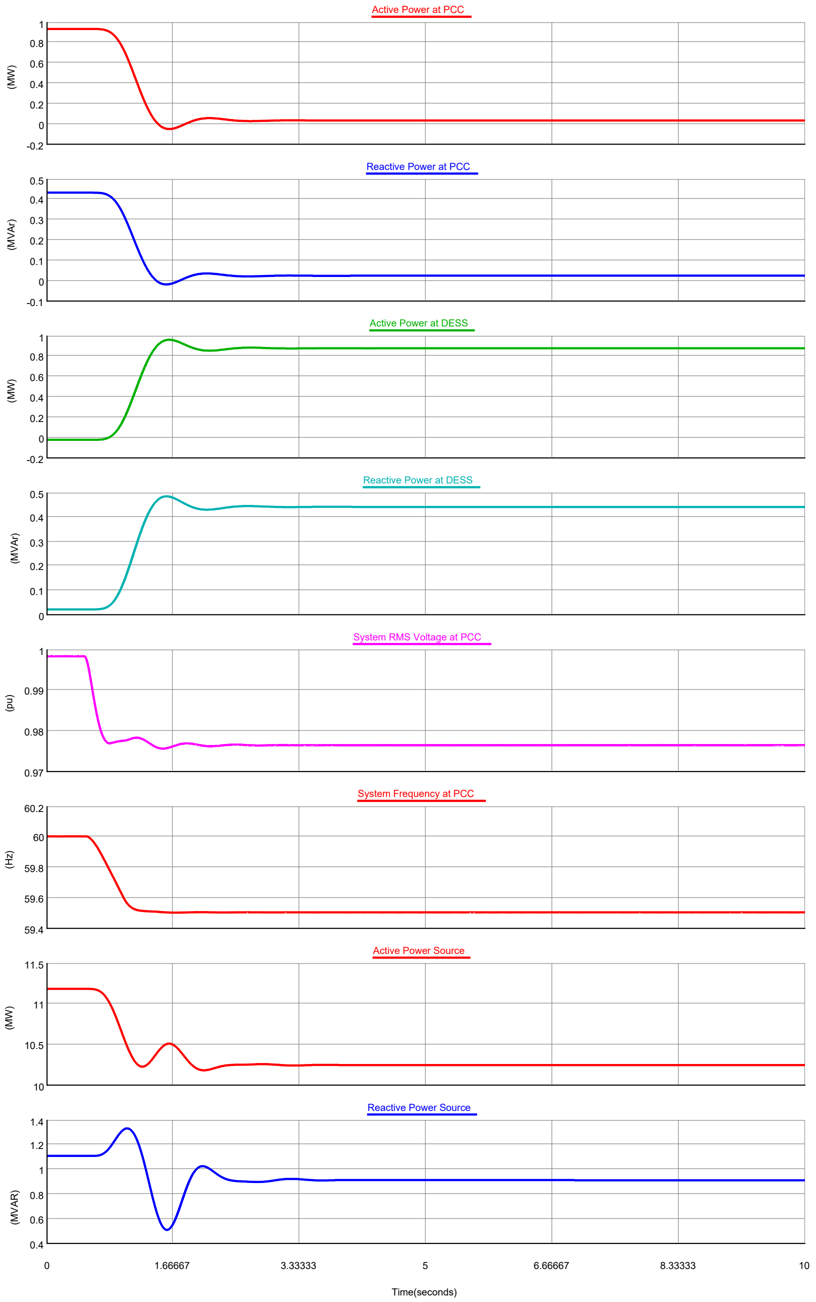

Figure 3.56: System Response for Test 7.2

TEST 7.3 CREATING UNDER-FREQUENCY FOR 1 SECOND

An under-frequency situation was created by decreasing the frequency by 0.5Hz for 1second. On decreasing the frequency, the DER rode through and settled at its prior set point in the steady state.

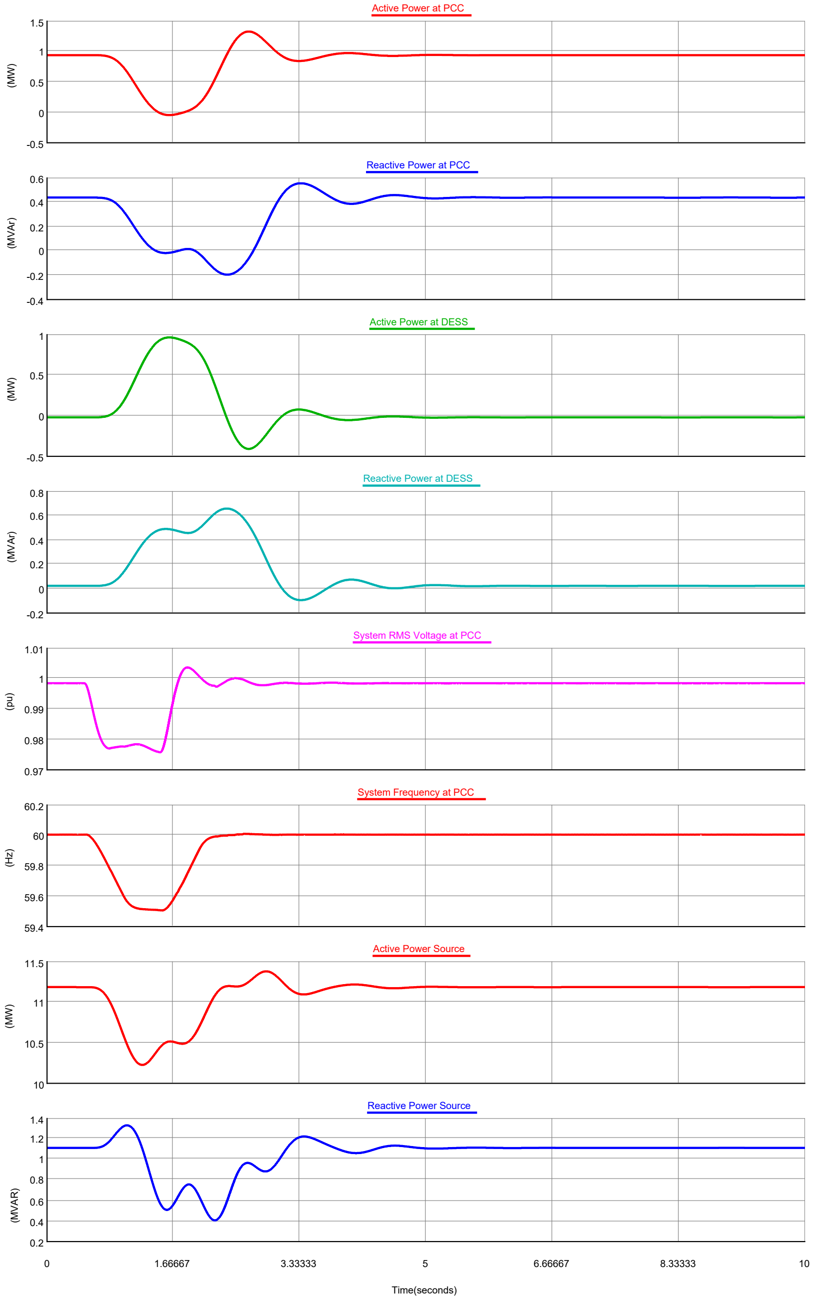

Figure 3.57: System Response for Test 7.3

TEST 7.4 CREATING A TEMPORARY FAULT

Creating a temporary fault caused the DER to react to the transition and return to its steady state once the fault was cleared. The temporary fault caused the voltage to drop and the frequency to increase drastically for which the DER reacted by regulating the active and reactive power output. Once the fault was cleared, the DER returned to its zero value at the steady state.

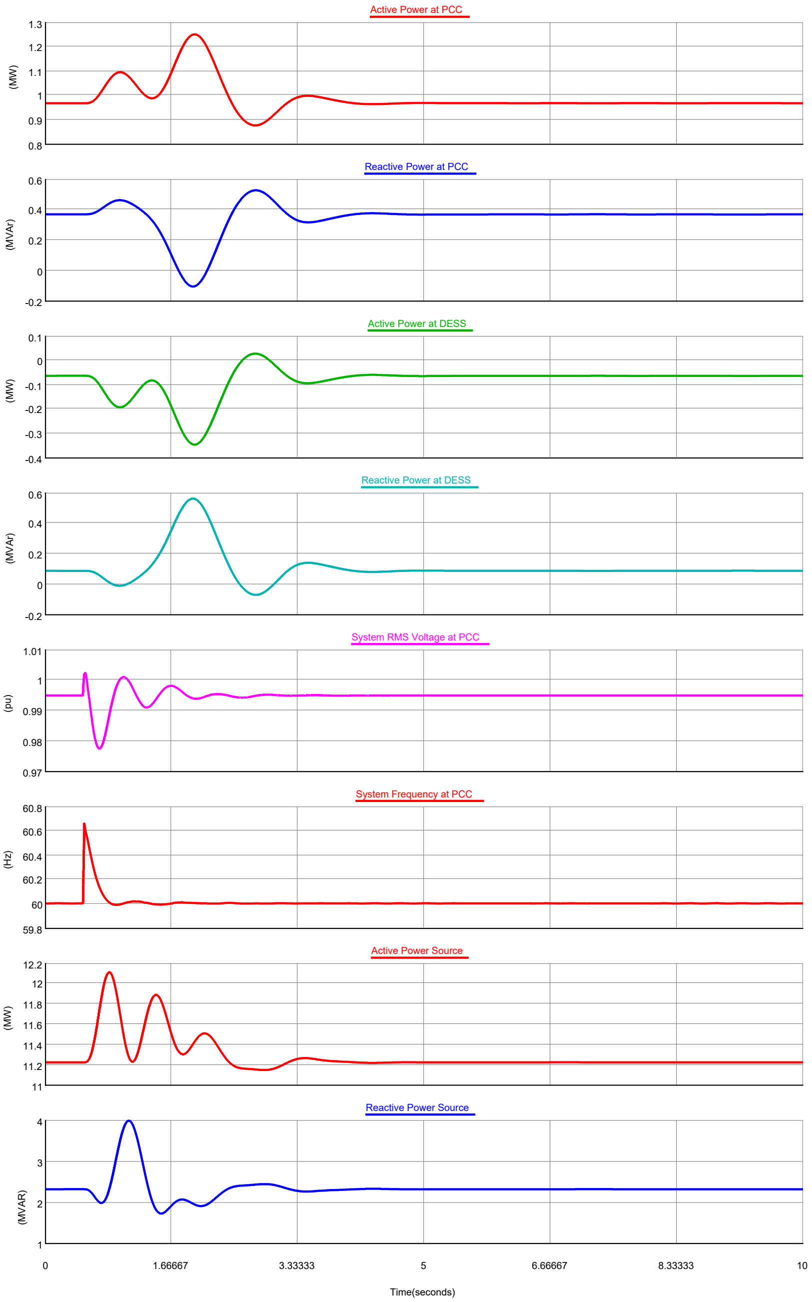

Figure 3.58: System Response for Test 7.4

Test 8 – Black Start

The ESS can be used to black start the system after complete system outage. The DER can operate in VSI mode to provide voltage and frequency support during the black start. Once the nominal voltage and frequency are established in the island, the loads can be picked up slowly and other renewable generation sources can be brought online to support the islanded load on the feeders. For the PHIL testing a load bank was used to connect to the DER to establish an island. The DER in the VSI ISO mode could sustain the island and feed the load bank.

Step 1. Record the system voltage and frequency during the steps performed for black-start operation.
Step 2. Document the black start and load restoration procedure for analysis.

VSI ISO mode regulates the voltage and frequency at the inverter terminals with regards to the voltage and frequency set points but unlike VSI VF does not accept droop set points. The inverter operates like a grid forming generator keeping the grid frequency and voltage as close as possible to the set points. This mode is used for islanded operation when the inverter system is the only source of generation or is the largest source of generation. If the load exceeds the capacity of the ESS the grid parameters will fall out of range.

TEST 8.1A: BLACK START 44 KW

on switching the inverter on in VSI ISO Mode, the inverter provided reference for the voltage and frequency and operates as a primary source. In this mode, once the DER was switched on, the DER supported the active and reactive power load. The frequency was set at 60Hz and the system voltage was set to 400V. The inverter current started flowing when the load was connected.

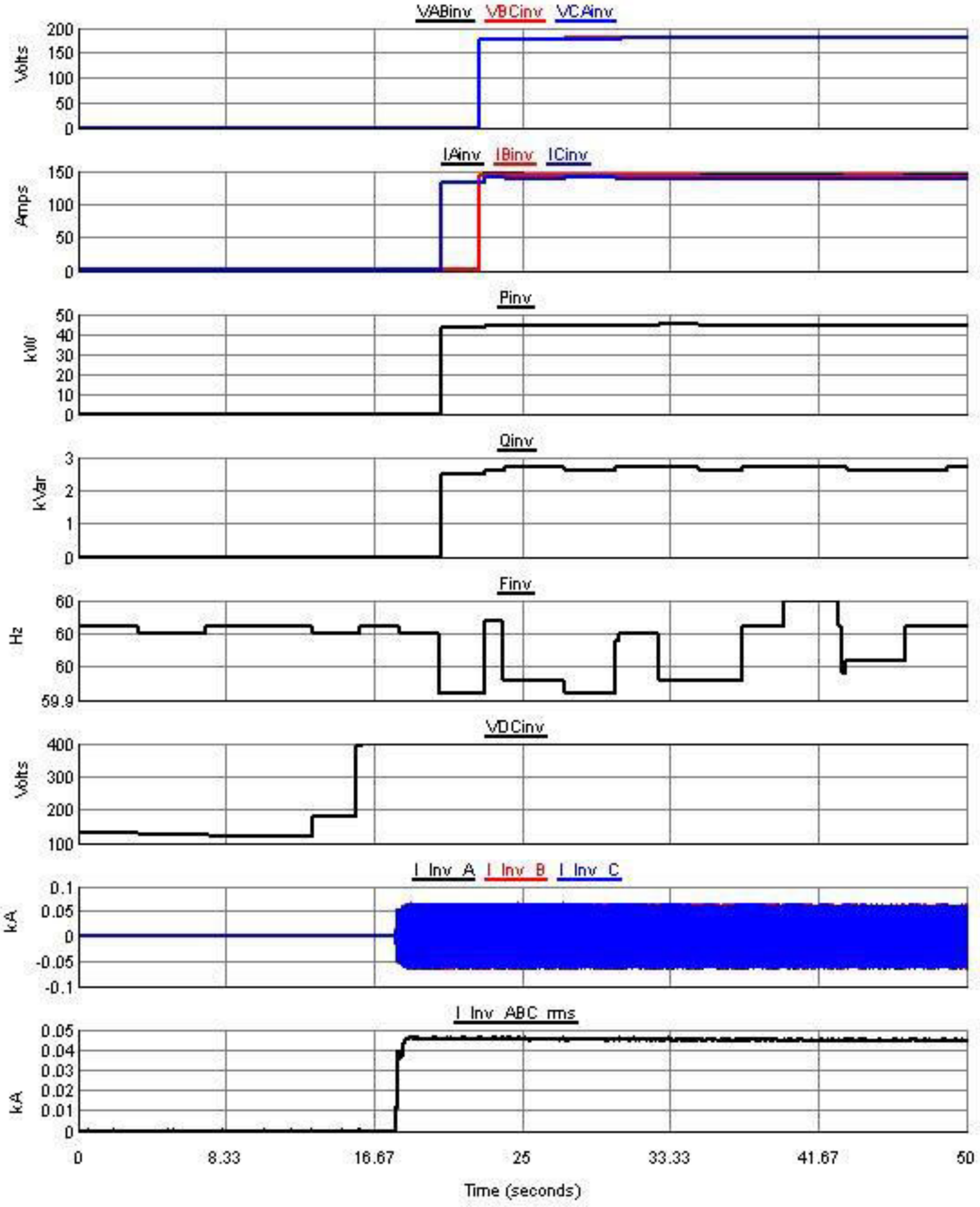

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Figure 3.59: Starting the DER in VSI ISO Mode to support a local load

TEST 8.2A: ISLAND LOAD RAMP

On decreasing the connected load across the terminals of the inverter using a sliding ramp, the DER current reduced and the generated active and reactive power of the inverter reduced as well. The change did not affect the voltage and frequency. The DER current increased with the increasing island load, while the voltage and frequency remained unaffected by the change. The generated active power and reactive power also increased to provide for the local connected load.

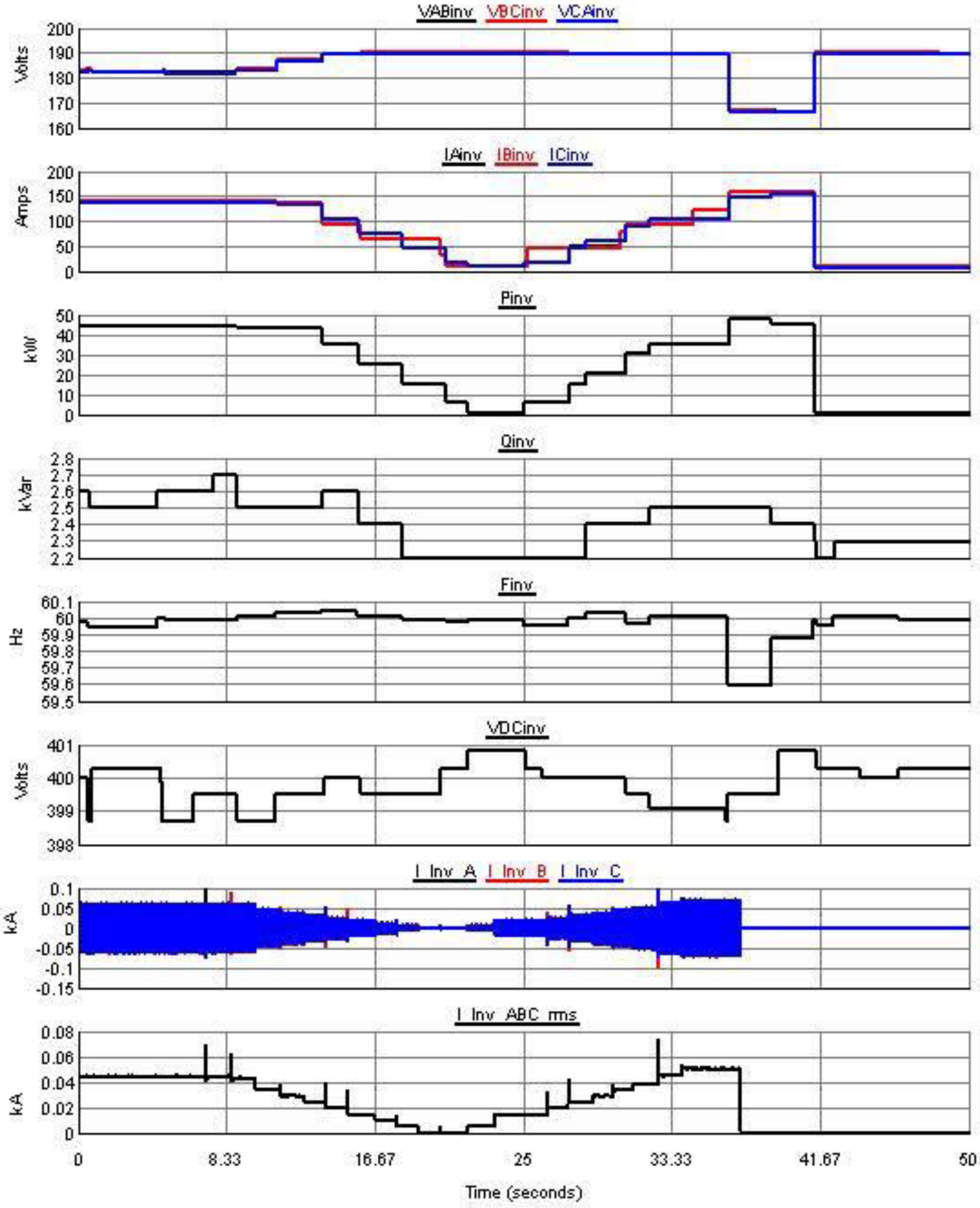

Figure 3.60:Adding a Ramp Load to the Inverter in VSI ISO Mode

TEST 8.3A: ISLAND LOAD STEP

When the DER was connected to a load using step method, the current increased and dropped along with the load. The real power switched to zero right after the step load was removed from the circuit from the inverter. However, due to shift in power flow caused by the increased flow of the current from the inverter, the reactive power of the inverter increased when the inverter supported the load but reduced slowly back to its previous output set point. This change occurred even without any change in the reactive load. The system frequency and voltage remained unaffected during the steady state.

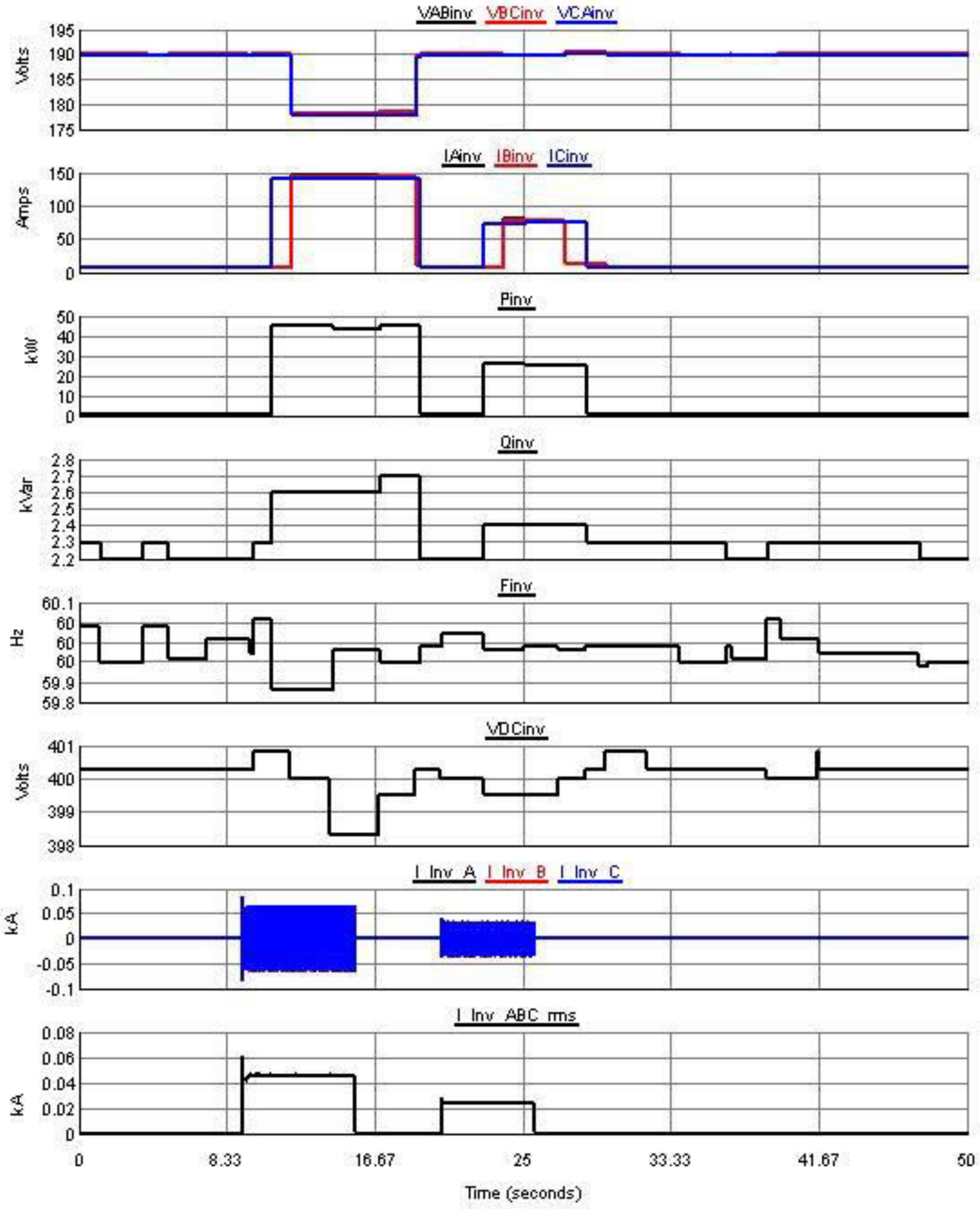

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Figure 3.61:Black Start Application of the DER – Island Load Step

VSI VF MODE

VSI VF mode regulate the voltage and frequency at the inverter terminals per voltage and frequency set points. The response is characterized by the voltage and frequency droops.

TEST 8.1B: BLACK START 44 KW VSI VF

On switching the inverter on in VSI VF Mode, the inverter provided reference for the voltage and frequency and operated as a primary source. In this mode, once the DER was switched on, the DER supported the active and reactive power load. The frequency was set at 60Hz and the system voltage was set to 400V. The inverter current started flowing when the load was connected.

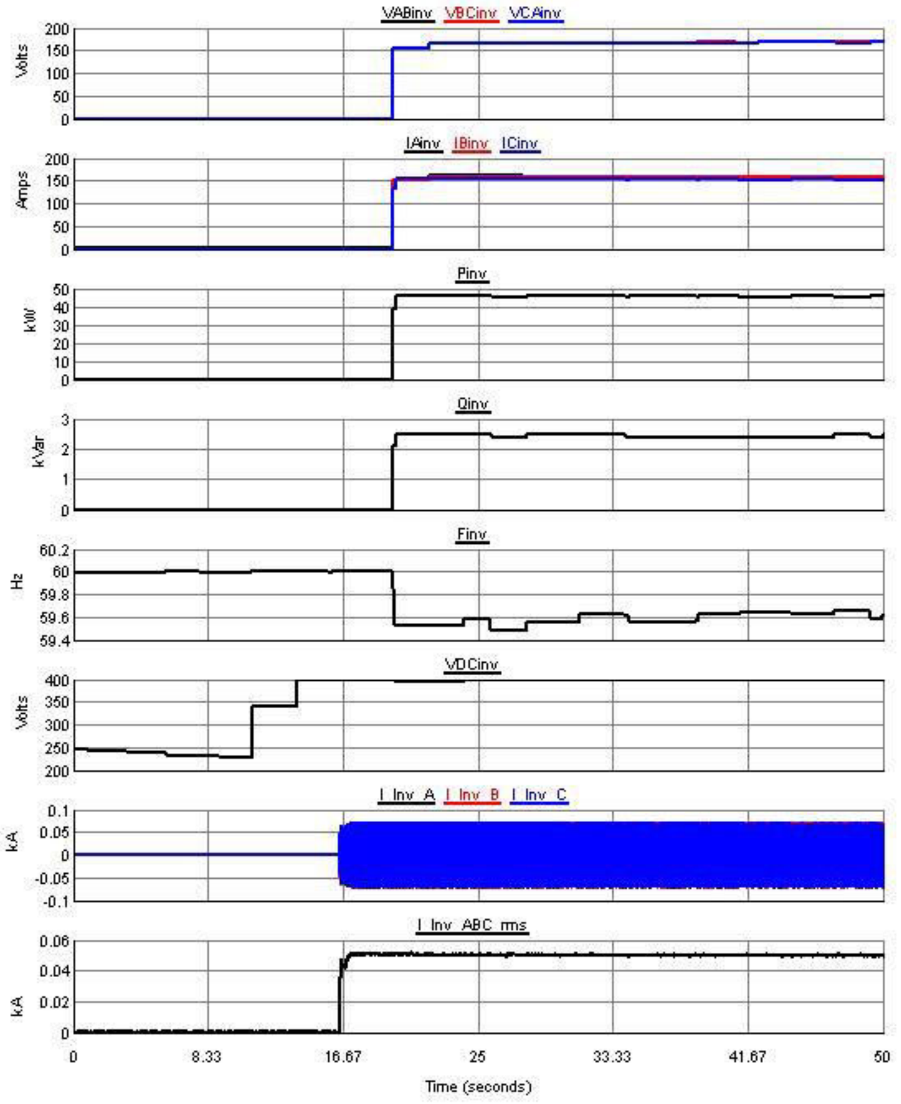

Figure 3.62: Starting the DER in VSI VF Mode to support a local load

TEST 8.2B: ISLAND LOAD RAMP VSI VF

In the VF mode, the inverter responded to the load changes by changing the output voltage and frequency. On decreasing the connected active power load, the DER active power and the reactive power output also reduced, due to the reduction in the current which caused the system frequency to increase (due to a large change in the active power output). The change in voltage was not significant since the reactive power reduces minimally. Similarly, when the active power load increased gradually, causing the system frequency to reduce. The increase in current caused the reactive power to increase, which reduced the system voltage marginally.

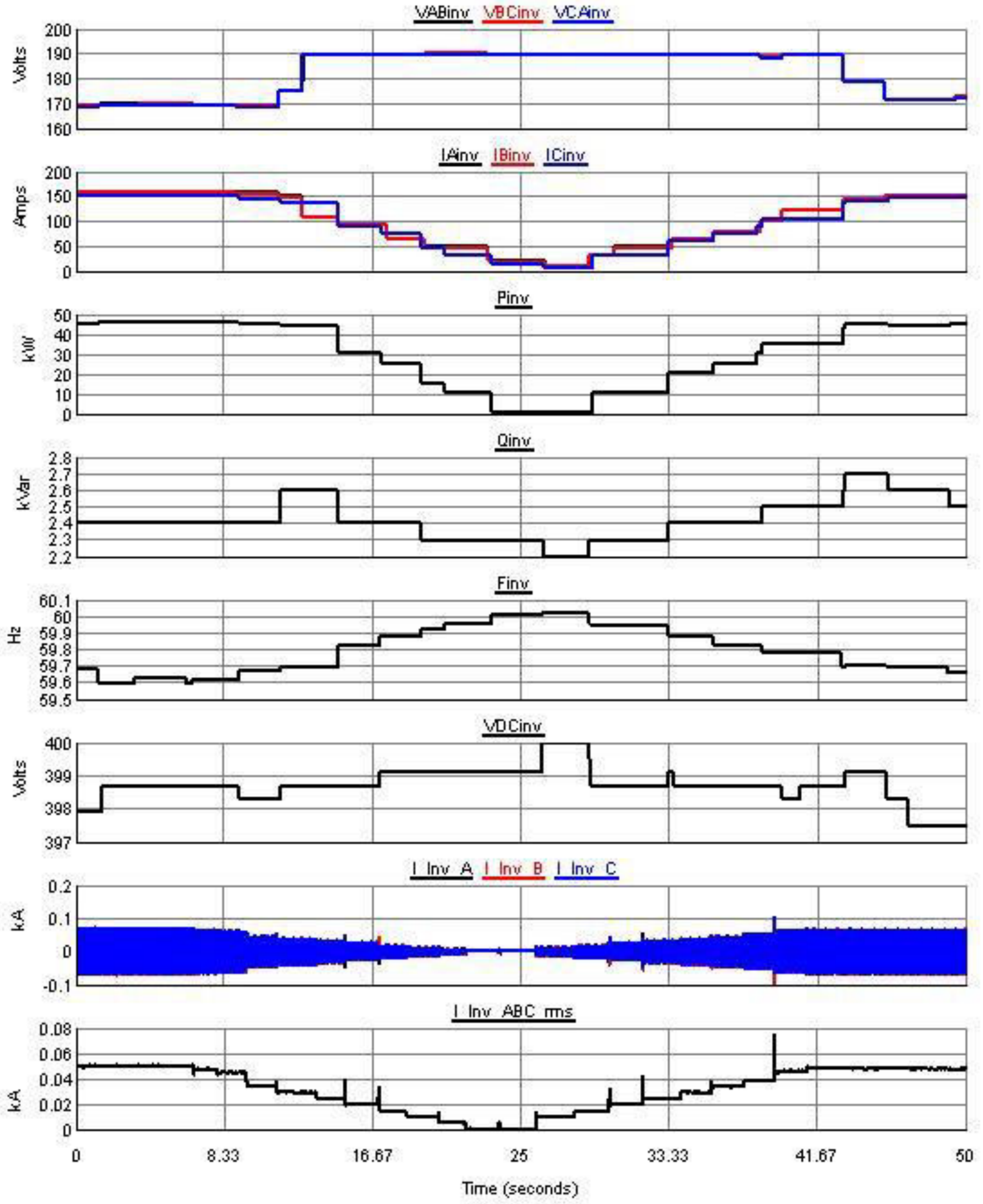

Figure 3.63:Adding a Ramp Load to the Inverter in VSI VF Mode

TEST 8.3B: ISLAND LOAD STEP VSI VF

On changing the load as a step, the system frequency changed as a response to the active power load. The voltage responded to the changes in the reactive power output of the inverter. The voltage and frequency response of the inverter was much more dynamic in the VF mode compared to the ISO Mode.

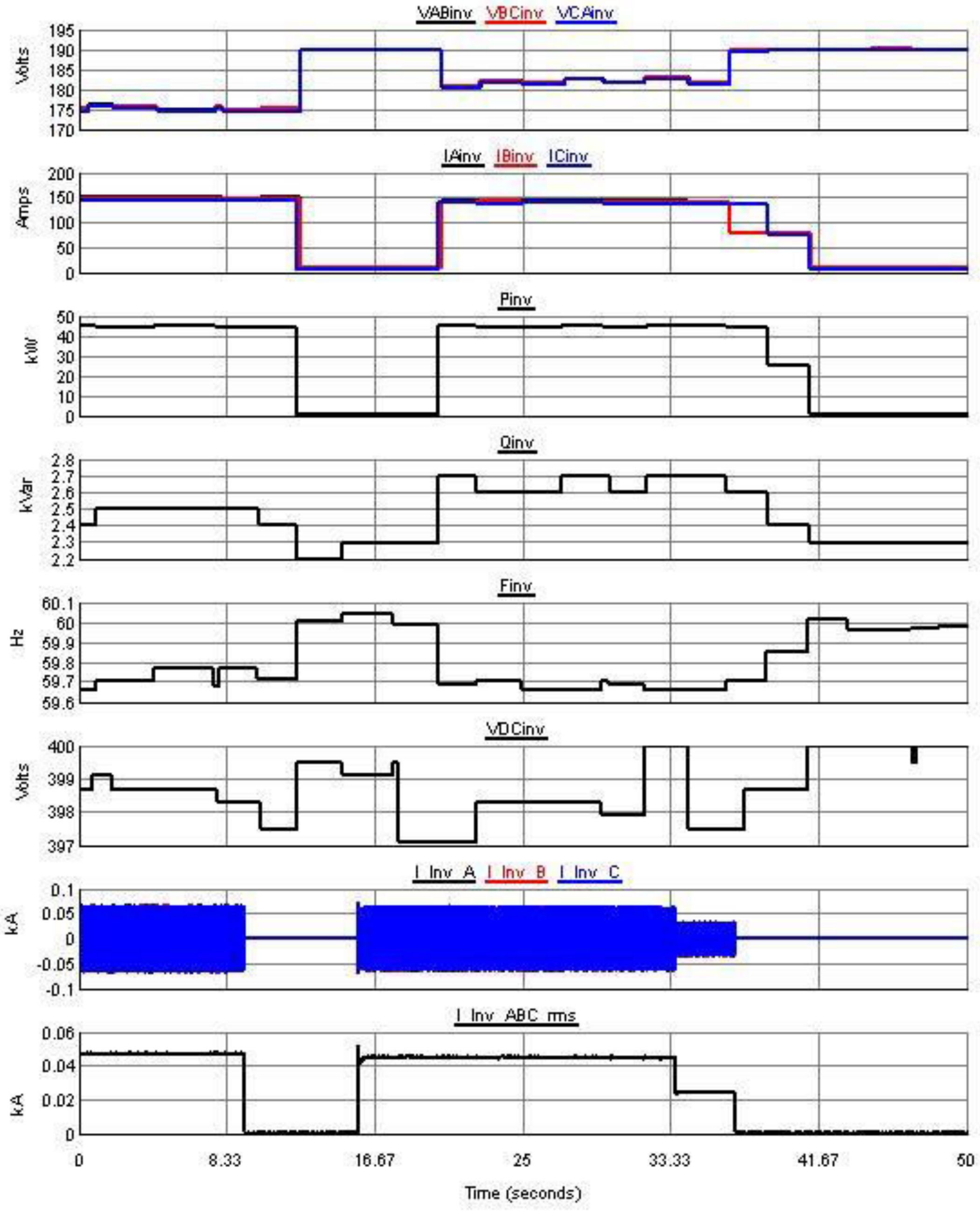

Figure 3.64:Adding a Ramp Load to the Inverter in VSI VF Mode

BLACK START UNINTENTIONAL TRIP

The inverter tripped unintentionally during the sudden drop of the load.

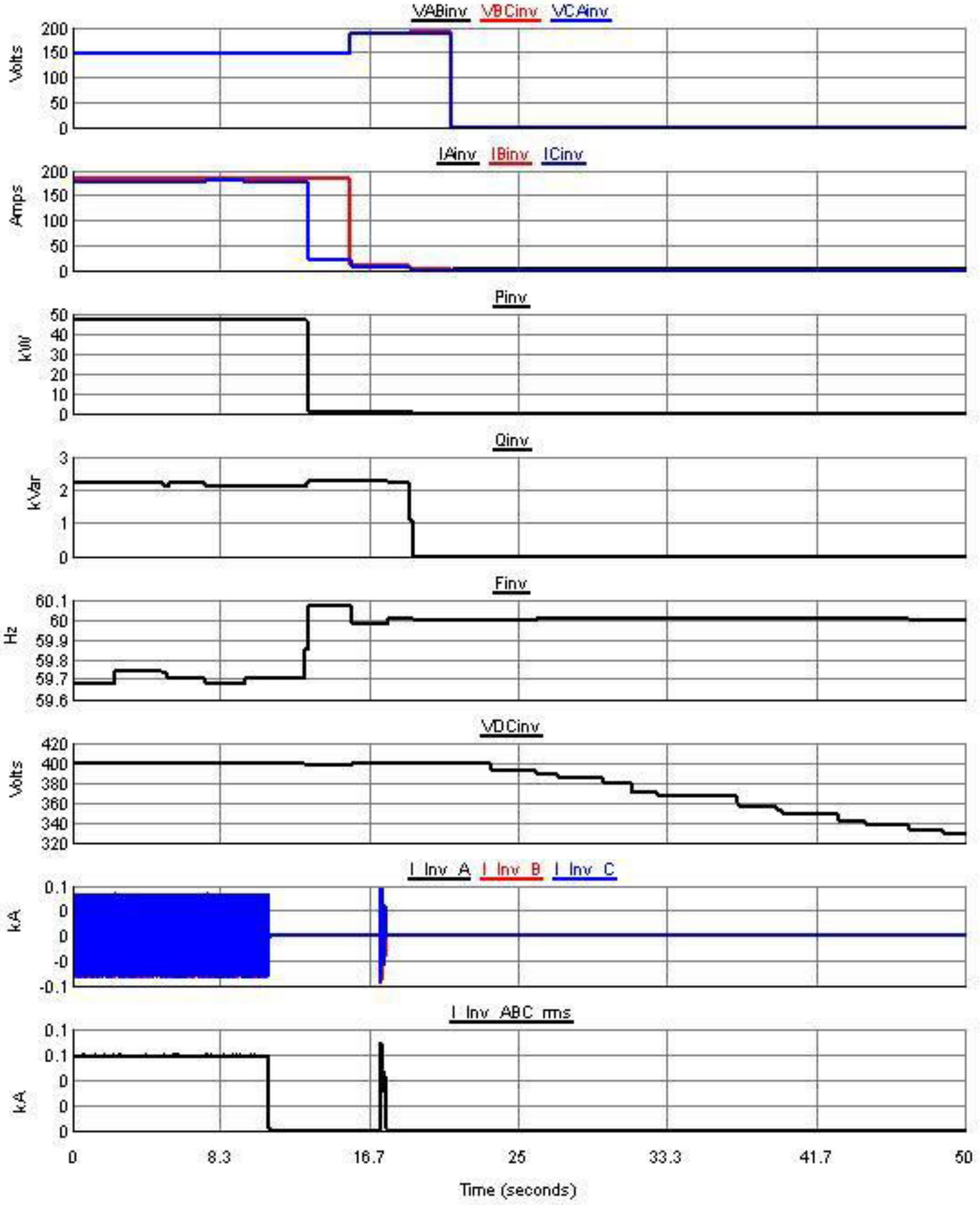

Figure 3.65: Unintentional Tripping of the Inverter

Test 9 – Load Leveling

The load-leveling function is like peak shaving in regard to the cycle of charging and discharging during different loading conditions. During the periods of high load demand, the DER can supply energy into the grid and it can charge while the load is light. This helps in reducing the load on less economical peak generating plants.

The objective of this test was to assess the economic benefits of using the DER to supply clean and emission-free energy, while reducing the use of less economical generation plants during high load demands

The procedure for testing was as follows:

- Set the DER output to constant power in the base mode operation.
- Starting with the base load, vary the local load in cyclic fashion of repeating crest and trough so that the load active power changes from 1200 kW to 800 kW. Make sure that the DER supplies constant power of 800 kW throughout these load changes.
- Activate the load-leveling mode on the DER with a set point of 1000 kW at the PCC that will maintain the power flow of 1000 kW (import) across the PCC and the rest of the power will be delivered by the DER.
- Record the DER power output during this event and analyze the behavior in following the variation in the load.
- Figure 3.66 shows a typical load profile to be used for this test.

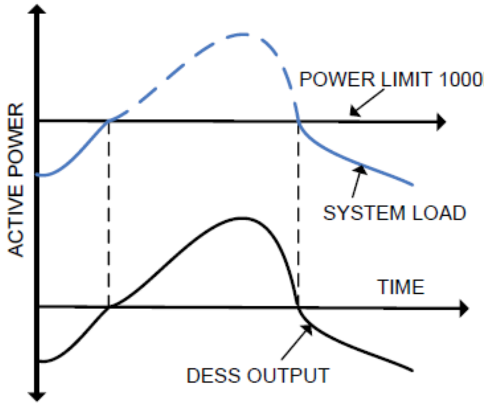

Figure 3.66: Load and DER Output Profile for Test #9

SCENARIO 1: DER CLOSE TO A SUBSTATION

TEST 9.1.1: WITHOUT LOAD LEVELING

On varying the system load by activating the DER in the schedule active power mode, the power output of the DER was maintained constant at 500 kW, while the fluctuations in the load were managed by the grid, which was reflected in the active power imported from the grid across the PCC and the increase in the active power generation of the source. The reactive power output did not change across the PCC, DER, or source.

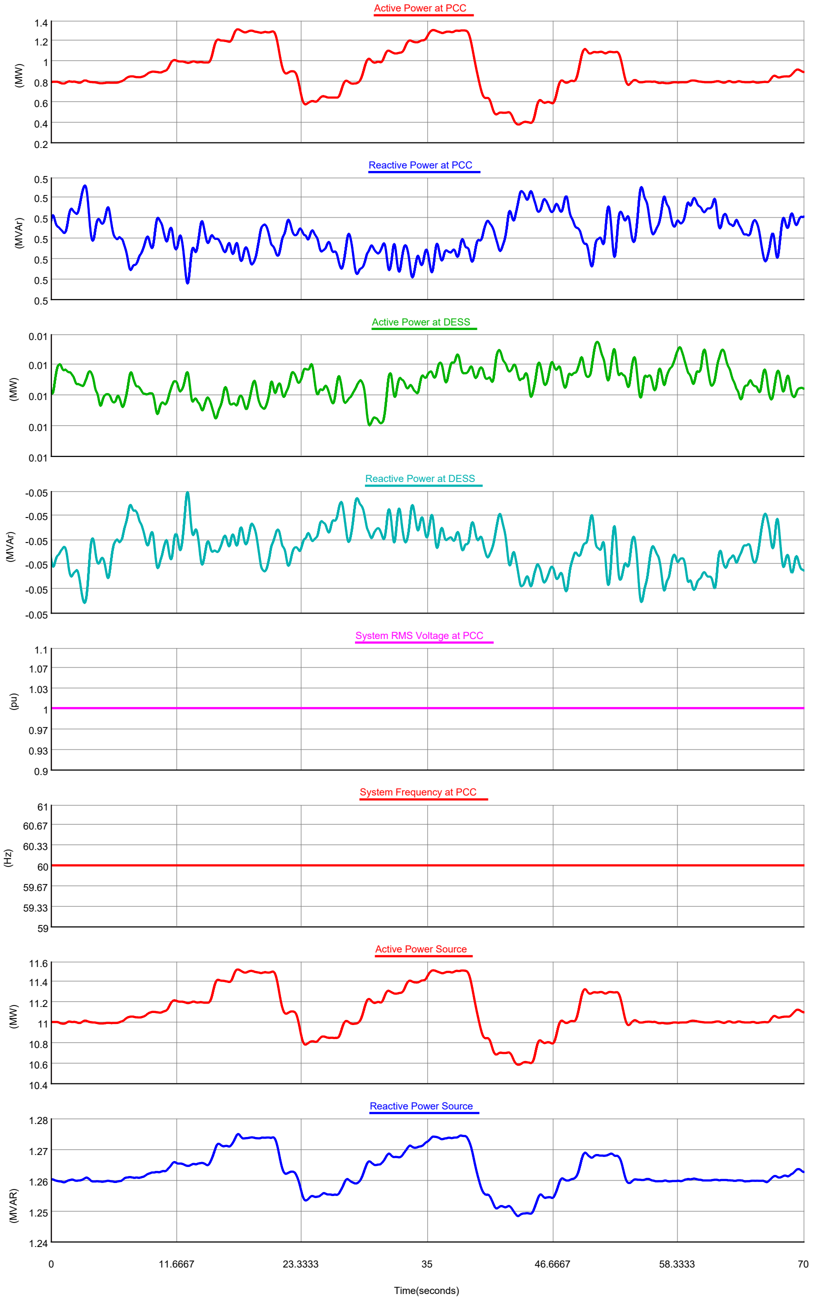

Figure 3.67: System Response for Test 9.1.1

TEST 9.1.2: LOAD LEVELING

Activating the load-leveling mode on the DER with a set point of 1000 kW at the PCC would maintain the power flow of 1000 kW (import) across the PCC. Fluctuations in the load were managed by the DER, which provided the required power during periods of heavy load and drew the excess power generated during periods of light loads. This ensured that the active power generated by the source remained constant and did not cause reverse power flow into the utilities during light load condition.

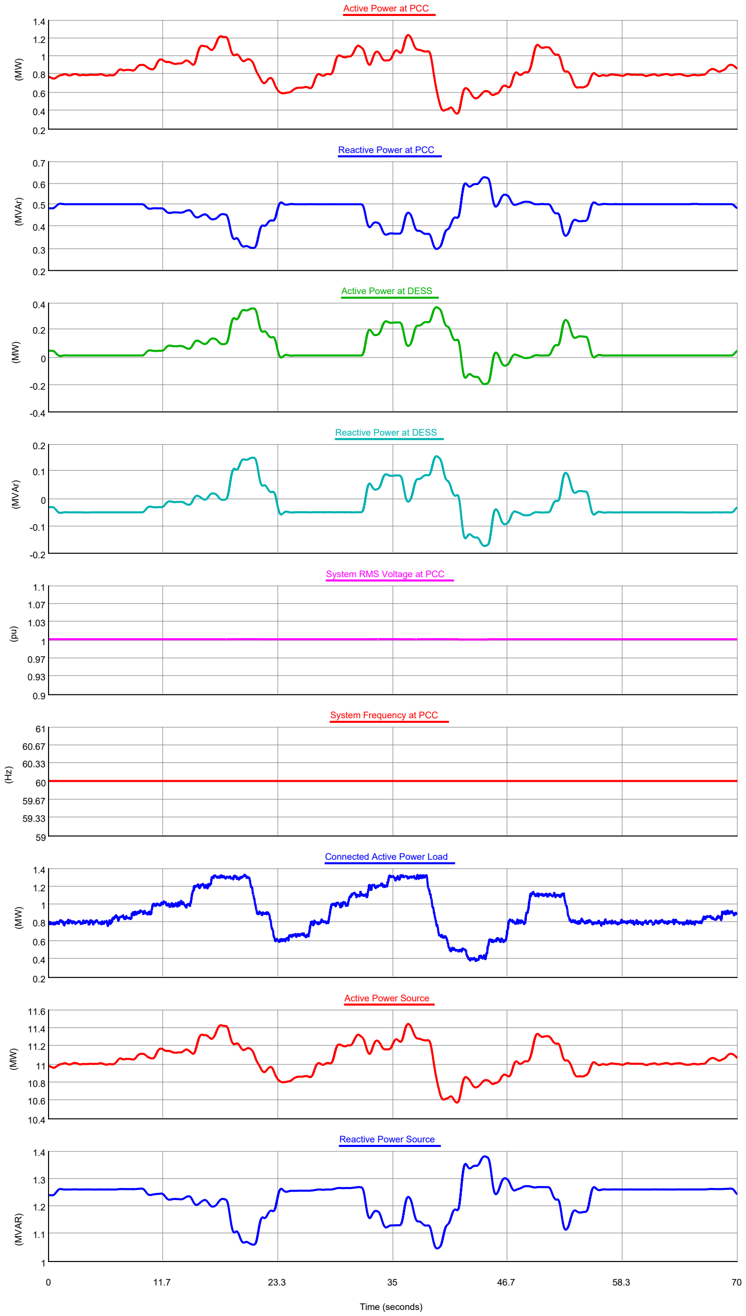

Figure 3.68: System Response for Test 9.1.2

Scenario 3: DER at the End of a Long Feeder

Test 9.3.1: Without Load Leveling

On varying the system load by activating the DER in the schedule active power mode, the power output of the DER was maintained constant at 500 kW, while the fluctuations in the load were managed by the grid, which was reflected in the active power imported from the grid across the PCC and the increase in the active power generation of the source. The reactive power output did not change across the PCC, DER, or source.

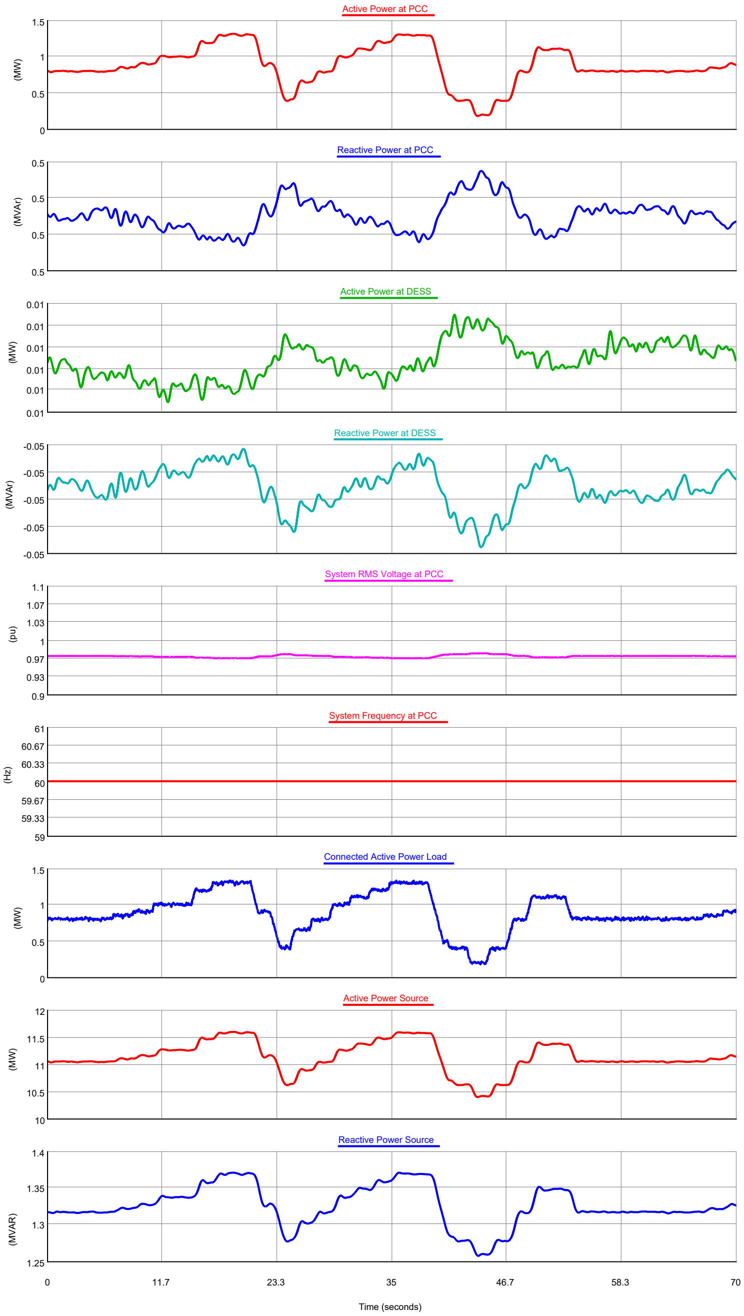

Figure 3.69: System Response for Test 9.3.1

TEST 9.3.2: LOAD LEVELING

Activating the load-leveling mode on the DER with a set point of 1000 kW at the PCC would maintain the power flow of 1000 kW (import) across the PCC. Fluctuations in the load were managed by the DER, which provided the required power during periods of heavy load and drew the excess power generated during periods of light loads. This ensured that the active power generated by the source remains constant and did not cause reverse power flow into the utilities during light load condition.

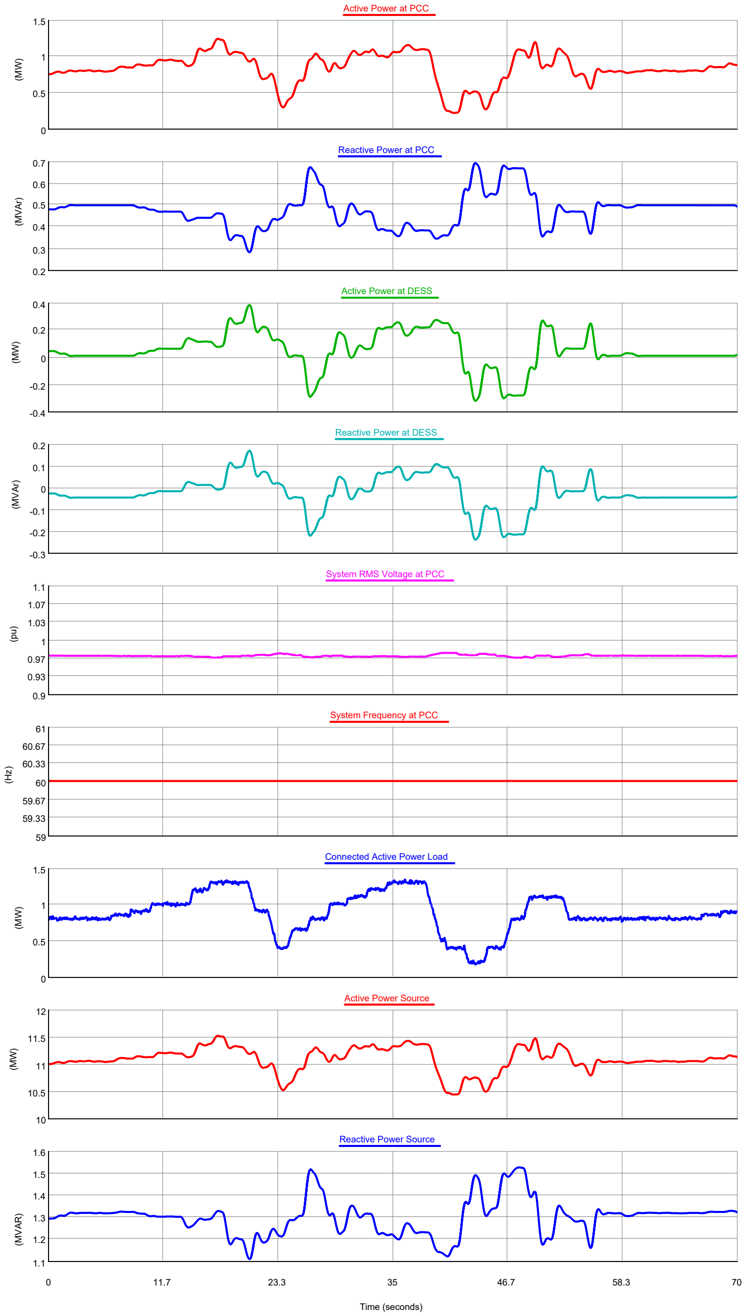

Figure 3.70: System Response for Test 9.3.2

SECTION 4 PROJECT RESULTS AND FINDINGS

This section discusses the test results obtained from the testing, presents findings and makes recommendations regarding commercial adoption of DER grid support functions. It also discusses the technical issues in terms of implementation and provide the value proposition.

DETAILED TECHNICAL RESULTS AND FINDINGS

This section discusses the summary of test results, functions of the DER inverter that are in line with the CPUC Rule 21 guidelines, the differences and areas that needs development. The smart inverter and the battery storage system are collectively referred to as the distributed energy storage system (ESS) and the inverter is referred to as a device under test (DUT). In this effort, an ESS was used as a DER to conduct the demonstrations.

Limiting Maximum Active Power Output

Per the Rule 21, the utility operator should be able to set the maximum limit on the DER output remotely. The maximum limit on the output could only be changed via local HMI on DUT. The change in the maximum active power limit was instantaneous and not ramped with a settable ramp rate.

For the demonstrations, the active power limit on the DER was changed manually from the HMI and the plot was recorded in the RTDS. Because of the limitation on the remote control of this function, the time delay could not be determined. Overall, the DER could limit its active power output successfully as specified by the user irrespective of the circuit power flow changes. If the DER receives an active power set point of more than the maximum limit set point, the output of the DER is held at the maximum limit set point. On the other hand, if the maximum limit set point is changed so that it is lower than the present active power output of the DER, the active power is reduced to the new maximum limit. The operation of this function is unaffected by the location of the DER in the circuit and yields similar results in all the scenarios. Figure 4.1 shows the change in active power when the maximum limit is reduced to 50%.

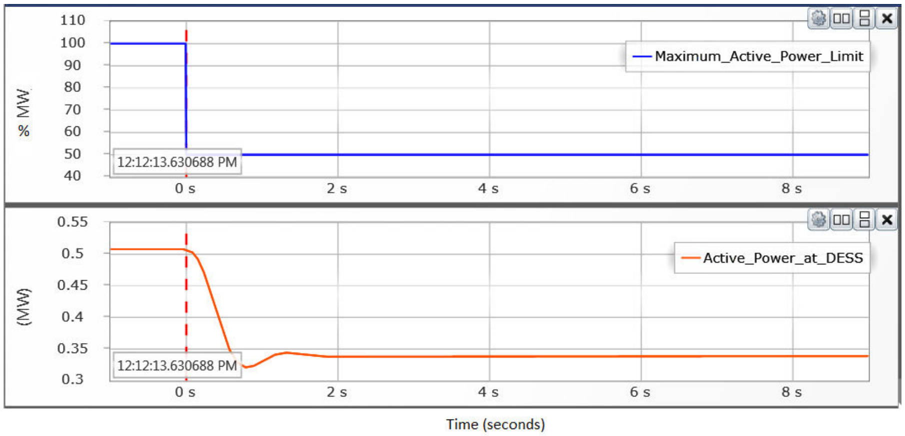

Figure 4.1: Limit Maximum Active Power Function

The main objective of this function is to provide a safety limit on the DER. The DER can still be used to perform other functions such as frequency-watt, but the active power regulates between the set positive and negative limits. The active power output of the DER can be limited to a value that keeps the current from exceeding current rating of the cables or overhead lines connecting to the utility system while allowing the DER to take part in the active power regulation.

Schedule Active Power Output

This function lets the operator schedule the active power output on the DER. The DUT has to be set in the active and reactive power schedule mode to execute the active power set point. Along with the active power set point, a positive and a negative ramp rate has to be provided to set the time response of the step change. For this testing, a ramp rate of +/- 100 kW per second was used. The rule 21 has marked the guidelines of this function as optional one in the regards that the maximum active power limit function can be used to set the active power for the energy storage systems such that the limit value indicates the active power set point as well. The DUT had a weekly scheduling function, wherein the active power dispatch can be scheduled during particular hours on a particular day of the week.

Varieties of tests were performed to validate this function on the test distribution circuit. The location of the DER in the circuit did not affect the performance of the DER in this mode, and it was effective under all the scenarios. The variations in load and voltage do not alter steady-state active power output. Overall, DER could provide the scheduled active power output as specified by the user within its rated capacity. Figure 4.2 shows that the change in loading on the circuit did not alter the output of the DER.

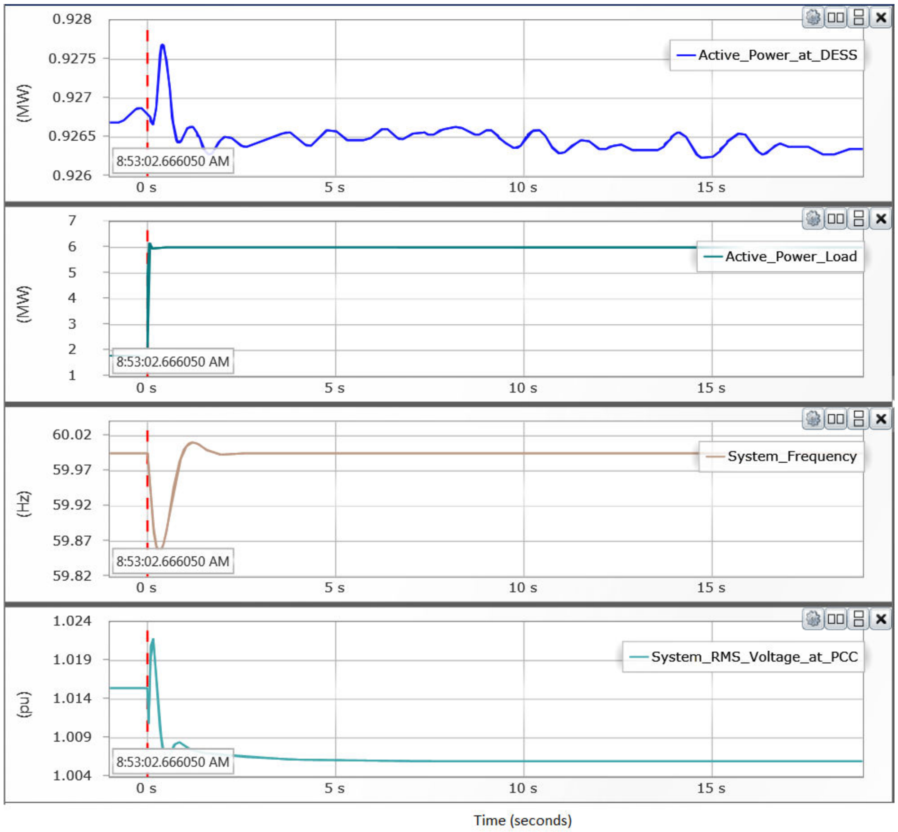

Figure 4.2: Schedule Active Power Output Function

The active power scheduling function helps establishing the base generation level on the distribution feeder, which helps the utility in load-demand-response management. Fixed active power output of the DER does not provide any significant value based on its location, however when operated in the fixed power factor mode, the reactive power contribution at the end of the circuit would help to improve overall voltage profile. The ability of changing the output ramp rates provides an advantage when operating with the traditional inertia based generation to offer smooth transition of power flow.

Volt-Watt

Volt-watt function enables the DER to manage its active power dispatch in response to the voltage of the system. The objective is to counter any changes in the voltage by varying the output active power to maintain the nominal voltage. When the DER is set in volt-watt control mode, it attempts to maintain the voltage of the system at reference value by curtailing the active power output. The DUT has settings for the voltage reference, dead band and the under and overvoltage droop to program the characteristics of the volt-watt function. For these testing a voltage droop setting of 6% was used. This function only regulates the active power of the DER therefore other high-level controls that operate on reactive power can be used simultaneously. Figure 4.3 shows the plot of active power in response to the rising voltage at the PCC, the increase in the system voltage is because of disconnection of the load on the feeder.

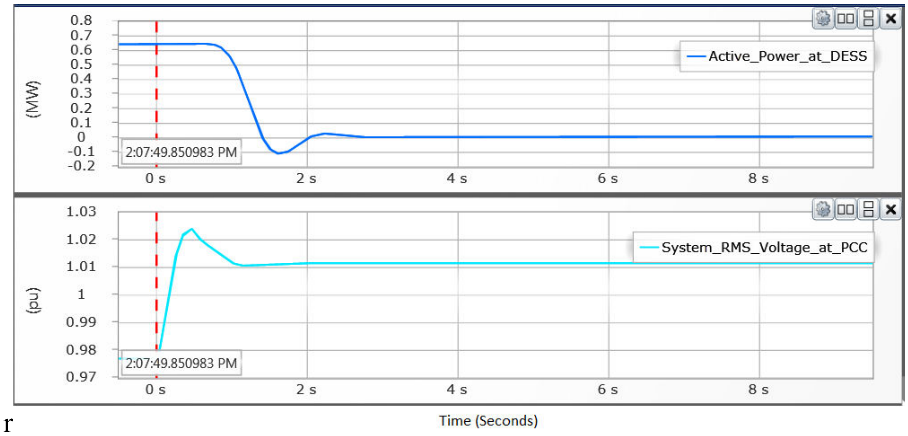

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Figure 4.3: Volt-Watt Function

The results of this test show that the DER active power output is at the highest (approximately 600 kW) in Scenario 3: DER at the End of a Long Feeder and its lowest in Scenario 1: DER Close to a Substation. This shows that this mode is much more effective in Scenario 3 because it maintains the voltage at reference value at the end of the feeder. The fluctuations in the frequency do not affect the DER operation in this mode in steady state.

This function is useful in the circuit where multiple DER devices are connected in the proximity. Because of the high penetration of the DER, the overall voltage on the feeder tends to rise beyond a value that would prevent other DER to turn online until the local voltage is within the safe operation limits. The volt-watt function curtails the active power output of the online DER so that other DER can be turned on. This function is not recommended to be used otherwise in the steady state where, to correct the low voltage, the feeder needs the reactive power fed in to the circuit instead of the active power. This is more useful in the overvoltage scenario that prevents energization of the DER. The voltage droop and the dead band settings of different DER depend on many factors in a particular distribution circuit; such as the ratings of the DER; number of DER in closed proximity and the location. In this particular circuit, the voltage at the far end of the feeder was about 0.97 pu with full load on the circuit, in this case the DER would not curtail the active power since the voltage is already below nominal value and overvoltage condition does not exist. By analyzing Figure 4.3, it can be noted that the droop settings can be set less than the present setting of 6% so that more output is curtailed for the same amount of change in the voltage and the voltage is settled back in to the dead band.

Volt-VAR

This function provides an ability to the DER to regulate the reactive power in the system to maintain the bus voltage to the reference value. The DUT had settings for the voltage reference, dead band and the under and overvoltage droop to program the characteristics of the volt-VAR function. The Rule 21 proposes having pre-programmed volt-VAR curves in the device memory so that operator can select it based on the system condition during particular time of the day. The DUT allows changing the droop settings (kVAR per percentage volt) of the controller to vary the reactive power contribution of the DER for 1% change in system voltage from the reference value. This creates a challenge for the operator to come up with a droop setting in different scenarios as compared to selecting from a set of per-programmed curves. CPUC also recommends the hysteresis function may be used on the volt-VAR curve for more flexibility; the controller on the DUT lacked the hysteresis function. For these tests, a voltage droop setting of 6% and a dead band of 1% was used.

The DER responded to fluctuations in voltage by increasing its reactive power dispatch at low voltage condition and decreasing its reactive power dispatch during high-voltage conditions. The results of this test show that this mode is very effective in Scenario 3: DER at the End of a Long Feeder) because the voltage is the lowest at the end of the feeder, and hence the reactive power dispatch is the highest. The location of the DER near the feeder transformer (Scenario 1: DER Close to a Substation) is not as effective because the DER reduces its reactive power output to maintain the voltage at 1 pu because the voltage is close to or above nominal near the substation. DER responded to the voltage, load, and generation changes to by regulating the reactive power in the system. Figure 4.4 shows the plot of reactive power output of the DER in response to the system voltage during the disturbance. Note that the spike in the voltage at about 12 seconds' mark is because of the capacitor bank switching after a set time delay. At this instance, the reactive power is supplied by the capacitor bank and the DER backs up on its output since the overall voltage is in the dead band.

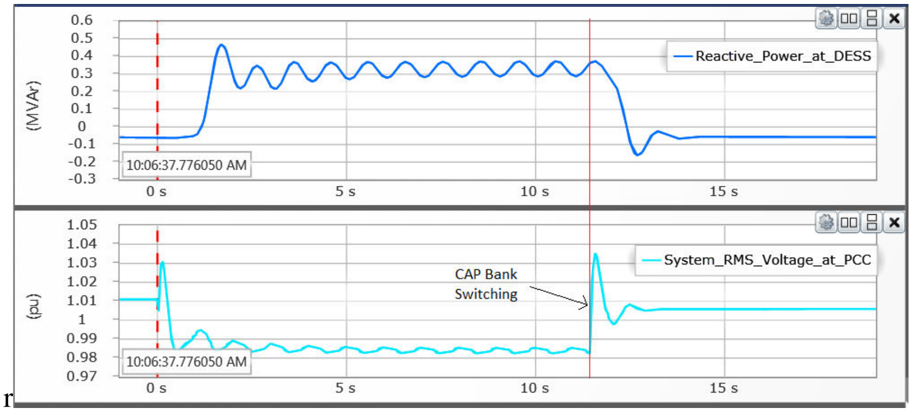

Figure 4.4: Volt-VAR Function

This highlights an interesting point about the need of coordination between the reactive power regulating devices when they are located close by to interact each other's performance. The DER is the faster device to react to the voltage disturbance in comparison to other devices such as capacitor banks (time delayed) and voltage regulators etc. The volt-VAR operation of the DER should be coordinated with the capacitor bank such that in the steady state when DER reaches its rating, the capacitor bank should switch on and take off the reactive power load from the DER. In this manner, the DER is only used for transient changes while the slower devices provide support during the steady state; this improves the overall system reliability without overburdening the DER. At the farthest end of the feeder, the DER was found to be producing more reactive power even in the steady state because of the poor voltage profile. This provides a good measure to system planners for installing a fixed capacitor bank for continued use instead of a DER.

In the distribution circuit where multiple DER are present near, it will be necessary coordinate their droop settings such that the devices with the higher ratings contribute more reactive power during the disturbance. This will prevent overloading and distribute the load efficiently among all the DER devices. A weighted droop setting based on the DER rating should be a good approach to the coordination.

One of the flexibility of this function is that, irrespective of the location of the DER, it can regulate the voltage at different points of interconnections (PCC) along the distribution circuit. This can be done by supplying measured voltage of that particular connection node to the DER. However, this posed a limitation with the DUT, in a way that this connection was hardwired to the power quality meter on the inverter control panel from AC side of the device. This provided no flexibility and the ease of use to test the volt -VAR regulation at variable PCC's. In a circuit where it necessitates that different PCC's be used for voltage regulation, the measured voltage signal can be transmitted via communication channel to the inverter controller (Modbus, DNP3 etc.)

Frequency-Watt

This function provides an ability to the DER to regulate the active power output in the system to maintain the system frequency to the reference value.

The DUT had settings for the frequency reference, dead band and the under and over frequency droop to program the characteristics of the Frequency-Watt function. The DUT allows changing the droop (kW per percentage frequency) of the controller to vary the active power contribution of the DER for 1% change in system frequency from the reference value. Per CPUC Rule 21 guidelines, the hysteresis function may to be used on the Frequency-Watt curve for more flexibility, the controller on the DUT lacked the hysteresis function. For these tests, a frequency droop setting of 6% nominal frequency and a dead band of 0.1 Hz had been used.

The test was conducted for all the scenarios and the various system conditions including load variations and the frequency, voltage fluctuations. The results of this test show that the location of the test DER does not affect the performance of the DER in frequency-watt mode. The DER responded to fluctuations in frequency by increasing its active power dispatch at low frequency condition and decreasing its active power dispatch during high-frequency conditions. The voltage variations did not have any significant impact on the active power dispatch of the DER. The Figure 4.5 below shows the plot of active power output of the DER during a frequency disturbance in the system. The dip in the frequency is caused by the energization of the load in the system and the DER increase its output to supply additional active power in the system until the traditional generation responds to the change.

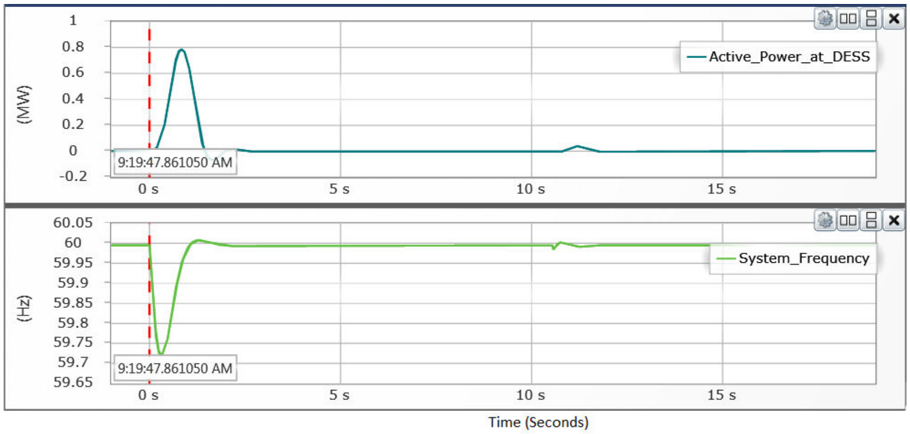

Figure 4.5: Frequency-Watt Function

In the distribution circuit where multiple DER are present in the proximity, it will be necessary to coordinate their droop settings such that the devices with the higher ratings contribute more active power during the disturbance. This will prevent overloading and distribute the load efficiently among all the DER devices. The DER, when operated in this mode can provide the frequency support when other DER such as photovoltaic systems start to ramp down towards the end of the day while the conventional generation is still trying to ramp up. When the system frequency is in the stable band DER can be used to run in other control mode such as peak shaving, SOC management etc. Since frequency-watt affects only the active power output of the DER, the control modes that operate on reactive power can be used simultaneously.

DER Response to Emergencies

This test examined the capability of the inverter to communicate the information with the utility management system. Following are some of the emergency commands and requests that are exchanged between the utility and the DER managements system.

ISSUE DISCONNECT OR RECONNECT COMMANDS TO THE DER SYSTEM FROM THE UTILITY

A start and stop command can be sent remotely over Modbus to the DER controller for connecting and disconnecting the DER from the system. The startup process takes up to 4 seconds after the start command is issued to the controller. Figure 4.6 shows the startup transient during the inverter AC breaker closing. Once the DER is online, different mode commands can be sent with the required active and reactive power set points.

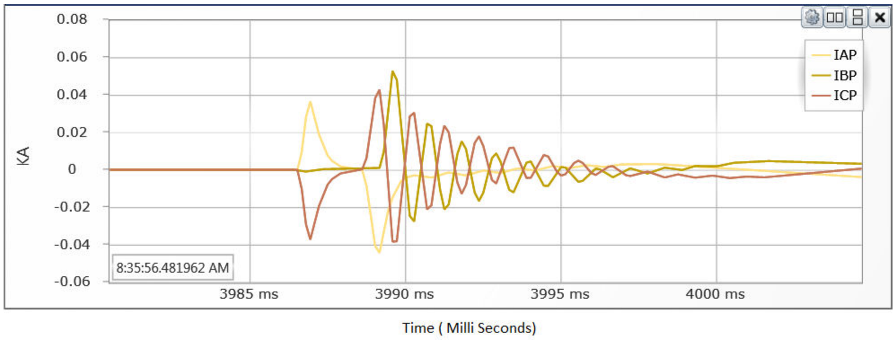

Figure 4.6: Inverter Startup Transients

UPDATE VOLTAGE RIDE-THROUGH CURVES TO CHANGE ANTI-ISLANDING SETTINGS

The voltage ride-through settings on the tested DER can only be set via the HMI, since this setting in not available in the Modbus register. Therefore, it could not be tested in this effort.

UPDATE FREQUENCY RIDE-THROUGH CURVES TO CHANGE ANTI-ISLANDING SETTINGS

The frequency ride-through settings on the tested DER can only be set via the HMI, since this setting is not available in the Modbus register. Therefore, it could not be tested in this effort.

REQUEST NOTIFICATION FROM THE DER SYSTEM ABOUT THE STATUS OF MICROGRID CONNECTION

The tested DER continuously broadcasts its status to the remote managements system via Modbus, indicating if the DER is online or offline. Along with this status information, the DER also sends the power output information. Based on this information utility operator can take operations decisions during different periods of the day.

REQUEST NOTIFICATION FROM THE DER SYSTEM ABOUT THE SPINNING RESERVE

The tested DER sends the present state of charge to the remote management system via Modbus, which aids the utility operator with load and generation forecast.

Spinning Reserve

The purpose of this test was to assess the benefits of using the DER an alternative to spinning reserve to provide the active power support during different system conditions as compared to conventional diesel generators in terms of response time, standby losses, durability of support, and availability. The DER is connected near the end of the feeder (Scenario 3) in this test. The results of this test proved that the DER is quite effective in sustaining loads during periods of under-frequency, providing voltage and frequency support within a short period. In addition to being a fast spinning resource, it also proves to be more effective in terms of cost and efficiency and better in terms of environmental factors and ease of operation and maintenance. The DER reacted to the under-voltage and under-frequency in the system during generation outage by acting as a source of spinning reserve providing voltage and frequency support to feed the local loads in the affected region.

Black Start

The purpose of this test is to assess the benefits of using the DER to black start the system after a complete system outage. The result of this test shows the effectiveness of using the DER to black start the system just like the traditional generation to bring the system online in the increment of loads and generations on the circuit. Once the grid breaker opens, causing the system to enter a blackout, the DER enters VSI mode creating reference for voltage and frequency. With the DER in VSI mode, additional load and generation sources can be connected in the system in the subsequent steps. The DER, like the PV system, need a voltage reference from the DER to initiate the startup process to feed the load. The only difference of using the DER as a black start source as opposed to the traditional generators is that the DER offers no inertia to the system.

The DER responded successfully by operating in VSI mode providing voltage and frequency support during the black start.

Load Leveling

The load-leveling function is like load and generation following in the manner that it involves the cycle of charging and discharging during different loading conditions. During periods of high-load demand, the DER can supply energy into the grid and charge while the load is light. This helps reduce the load on less economical peak generating plants. The DUT has a setting for peak shaving and the base loading active power limits. These two settings create a band envelope such that if the load at the PCC changes above or below this limit, the DER produces or absorbs the active power. The controller needs to monitor the active power flow through the PCC for this mode to function. This supervised active power signal is transmitted to the controller over Modbus.

The purpose of this function is to ensure that the import of active power across the grid remains the same throughout the periods of load fluctuations. This reduces the load on less economical peak generation plants. The results of this test on different scenarios had similar and effective impact on the system throughout. While the DER responded to the load fluctuations, the power import across the PCC remained constant, which maintained the active power imported from the source at a constant value. Figure 4.7 below shows the active power output of the DER responding to the changing power flow at the PCC. For this test, the peak shaving limit was set to 1000 kW and the base loading limit was set to 600 kW. When the active power at the PCC was within the band of peak shaving and base loading the DER output was zero as indicated by the dead band in the plot below.

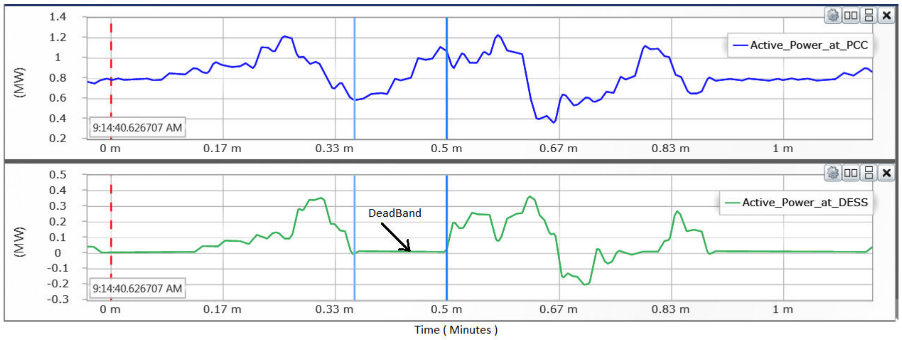

Figure 4.7: Load Leveling Function

The objective of this test was to assess the economic benefits of using the DER to supply clean and emission-free energy, while reducing the use of less economical generation plants during high-load demands. The peak shaving and base loading settings should be set based on the loading conditions on the feeder throughout the day; maximum deviation of the base load over a period of time and the rating of the DER that is going to feed the deficit power and absorb the surplus power. Overall, The DER mitigated the impact of the load fluctuation by keeping the power import at the PCC constant under different scenarios.

RECOMMENDATIONS

The following recommendations are made based on the results of the pre-commercial demonstrations in the laboratory. For more details on the application situations where the recommended commercial adoption would provide the greatest value, see the discussions in previous sections.

Volt-VAR Function

In the demonstrations, DER performed voltage regulation successfully in different test scenarios to maintain the system voltage. The DER was a faster device in terms of response time during the disturbance compared to traditional voltage regulating devices such as capacitor banks. This function contributed to the system stability autonomously and helped the grid sustain the disturbance. It prevents frequent operation of the capacitor banks and the voltage regulators by providing the dynamic voltage regulation. In a distribution system, which has multiple DER, this function can efficiently provide voltage stability to the grid. It is recommended to pursue this function commercially in the DER inverters.

Frequency-Watt Function

The frequency-watt function of the DER provided the smooth active power regulation for the frequency disturbances during the demonstrations. The DER provided the active power to the system to maintain the frequency. This function is recommended to be used in the distribution circuit which has a large amount of intermittent generation. The frequency-watt function mitigates the frequency fluctuations caused by these sources. The location of the DER does not impact the operation of the frequency-watt function. This function complements the volt-VAR function, in regards that both functions can operate independently at the same time and provide voltage and frequency regulation. It is highly recommended to pursue these grid support functions in the commercial DER inverter.

Load Leveling Function

Load leveling function maintained the power import form the PCC within the specified dead-band during the demonstrations. During heavy and light loading periods, the DER supplied and absorbed the deficit and surplus power. The DER supported the load fluctuation by keeping the power import at the PCC constant under different scenarios. This function smooths out the load fluctuations on the feeder and makes the load forecasting simpler for distribution system operators. Load leveling concept is common in other types of DER such as diesel generators, which is called peak shaving. When used with ESS, it provides both peak shaving and base loading, since ESS can supply as well as absorb active power. It will be beneficial and is recommended to implement this function in the commercial DER inverter.

Black Start

The results of this demonstration show the effectiveness of using the ESS to black start the system just like the conventional generation source to bring the system online in the increment of loads and generations on the circuit. Once the grid breaker opens, causing the system to enter a blackout, the ESS enters VSI mode creating reference for voltage and frequency. With the ESS in VSI mode, additional load and generation sources can be connected in the system in the subsequent steps. The DER, like the PV system, need a voltage reference from the ESS to initiate the startup process to feed the load. It is highly recommended to pursue black start functionality commercially to be used in the microgrids in the distributions system.

Spinning Reserve

The results of this demonstrations proved that the ESS is quite effective in sustaining loads during periods of under-frequency, providing voltage and frequency support within a short period. In addition to being a fast spinning resource, it also proves to be more effective in terms of cost and efficiency and better in terms of environmental factors and ease of operation and maintenance. The ESS reacted to the under-voltage and under-frequency in the system during generation outage by acting as a source of spinning reserve providing voltage and frequency support to feed the local loads in the affected region. It is recommended to have this function implemented in the commercial ESS inverter. The ESS can run in the idle mode with minimal loss of charge to provide spinning reserve.

DER Monitoring and Control

DER monitoring allows system operator visibility into DER operation that enables efficient use of DER. All the important status points should be relayed to the remote management system. For the ESS, the information like state of charge, online/offline status, power output etc. is necessary to make control decisions. The availability of this information aids the control actions such as connecting/disconnecting the DER, updating voltage and frequency ride-though settings. The ability of DER to communicate with the remote system and to allow DER monitoring and control is highly desirable with increasing penetration of DER in the system to make informed decision about the operation of the system. It is recommended that this function be implemented in the DER.

Volt-Watt Function

The volt-watt function curtails the active power output of the DER during the overvoltage in the system. This function has a very narrow applicability in terms of grid support. The voltage regulation is best carried out by the volt-VAR function, which provides reactive power support instead of active power. Because of the high penetration of the DER, the overall voltage on the feeder tends to rise beyond a value that would prevent other DER to turn online until the local voltage is within the safe operation limits. The volt-watt function curtails the active power output of the online DER so that other DER can be turned on. This function is not recommended to be used otherwise in the steady state where, to correct the low voltage, the feeder needs the reactive power fed in to the circuit instead of the active power. This is more useful in the overvoltage scenario that prevents energization of the DER.

TECHNOLOGY TRANSFER PLAN

A primary benefit of the EPIC program is the technology and knowledge sharing that occurs both internally within SDG&E and across the industry. To facilitate this knowledge sharing, SDG&E will share the results of this project by widely announcing the availability of this report to industry stakeholders on its EPIC website, by submitting papers to technical journals and conferences, and by presentations in EPIC and other industry workshops and forums. Additionally, presentations will be given to internal stakeholders at SDG&E.

SECTION 5 METRICS AND VALUE PROPOSITION

METRICS

The following metrics (shown in Table 8) were identified for this project as potential project benefits at larger scale deployment. Given the pre-commercial nature of this EPIC project, these metrics would apply in future scenarios after widespread commercial adoption. The following metrics are potential benefits that are concluded from different tests cases performed in this effort:

Table 8. EPIC metrics for grid support functions of DER

D.13-11-025, Attachment 4. List of Proposed Metrics and Potential Areas of Measurement (as applicable to a specific project or investment area in applied research, technology demonstration, and market facilitation)
1. Potential energy and cost savings
b. Total electricity deliveries from grid-connected distributed generation facilities
e. Peak load reduction (MW) from summer and winter programs
f. Avoided customer energy use (kWh saved)
g. Percentage of demand response enabled by automated demand response technology
3. Economic benefits
c. Reduction in electrical losses in the transmission and distribution system
e. Non-energy economic benefits
f. Improvements in system operation efficiencies stemming from increased utility dispatchability of customer demand side management
5. Safety, power quality, and reliability (equipment, electricity system)
a. Outage number, frequency, and duration reduction
f. Reduced flicker and other power quality differences
7. Identification of barriers or issues resolved that prevented widespread deployment of technology or strategy
b. Increased use of cost-effective digital information and control technology to improve reliability, security, and efficiency of the electric grid (PU Code § 8360)

VALUE PROPOSITION

The purpose of EPIC funding is to support investments in R&D projects that benefit the electricity customers of California IOUs. The primary principles of EPIC are to invest in technologies and approaches that promote greater reliability, lower costs, and increased safety. This section discusses each of the functions in detail in terms of the value it provides to the overall system operation. Primary and secondary benefits are presented wherever applicable to demonstrate the value of the function for commercial adoptability.

Limit Maximum Active Power Output

In this mode, the active power output of the DER is restrained by a maximum specified limiting value. This function can be used to prevent the localized overvoltage conditions by curtailing DER output. This test is conducted under different scenarios and under different system conditions including load. Because of the changing load conditions and varying operating set points the DER operates as controlled by the system operator within the specified maximum limit. If the DER receives an active power set point of more than the maximum limit set point, the output of the DER is held at the maximum limit set point. On the other hand, if the maximum limit set point is changed so that it is lower than the present active power output of the DER, the active power is reduced to the new maximum limit. The operation of this function is unaffected by the location of the DER in the circuit and yields similar results in all the scenarios.

Primary Principles: The limit on the active power act as an additional safety measure, to protect the equipment from unintended operation, when an undesirable set point is issued by the grid operator. This limit can be set once considering the rating of the equipment and can only be changed if needed. This improves the reliability of the system when operating in the grid support mode with active power regulation. Although this function is integral part of most inverters, having an ability to control this limit remotely by the grid operator, gives more operational flexibility.

Schedule Active Power Output

In this mode, the DER is set at a constant active power dispatch and the DER tries to limit its active power output at that value. This test was conducted for all the four scenarios. The location of the DER in the circuit did not affect the performance of the DER in this mode, and it was effective under all the scenarios. The variations in load and voltage do not alter steady-state active power output. The frequency fluctuations do not affect the DER in any condition.

Primary Principles: In this mode, the inverter operates in the base mode, where it supplies or consumes the active power depending on the operational needs. A schedule can be implemented during the day for the output of the inverter based on the cost of electricity and other environmental factors. This enables the operator to dispatch clean energy at lower costs. This also takes the load off peak generating stations during high load demand periods. The overall redistribution of power improves the reliability of the grid.

Secondary Principles: The ability to control and schedule power on these renewable assets provides more transparency to the grid operator for load generation forecasting by making efficient use of the resources.

Volt-Watt Function

Volt-watt mode enables the DER to manage its active power dispatch in response to the voltage of the system. The objective is to counter any changes in the voltage by varying the output active power to maintain the nominal voltage. When the DER is set in volt-watt control mode, it attempts to maintain the voltage of the system at reference value by curtailing the active power output. The results of this test show that the DER active power output is at the highest in Scenario 3: DER at the End of a Long Feeder and its lowest in Scenario 1: DER Close to a Substation. This shows that this mode is much more effective in Scenario 3 because it maintains the voltage at reference value at the end of the feeder, which improves the overall circuit voltage profile. The fluctuations in the active power load and frequency do not affect the DER operation in this mode in steady-state conditions.

Primary Principles: This function is particularly important, when multiple DER are connected on the same feeder, which tends to rise the voltage on the feeder beyond a nominal value that energizing further DER cannot be achieved because of the high voltage. In this scenario, when the online DER if set in the volt-watt mode, would curtail the output so that voltage falls within the acceptable limit. This enables reliable operation of the microgrid with operational flexibility since it can control the output of the DER to maintain the voltage on the feeder. It increases equipment and personnel safety by maintaining the voltage at a nominal value.

Secondary Principles: This function allows for multiple DER operate in parallel by maintaining the voltage within nominal limit to offer more affordable renewable energy services to the customers. More penetration of the renewable energy reduces negative environmental impact.

Volt-VAR Function

Volt-VAR mode enables the DER to manage its reactive power dispatch in response to the voltage fluctuations. The test was conducted for all the four scenarios and the various system conditions including load variations and the frequency, voltage fluctuations. The DER responded to fluctuations in voltage by increasing its reactive power dispatch at low voltage condition and decreasing its reactive power dispatch during high-voltage conditions. The results of this test show that this mode is very effective in Scenario 3: DER at the End of a Long Feeder because the voltage is the lowest at the end of the feeder, and hence the reactive power dispatch is the highest. The location of the DER near the feeder transformer in Scenario 1: DER Close to a Substation is not as effective because the DER reduces its reactive power output to maintain the voltage at 1 pu because the voltage is close to or above nominal near the substation. The change in frequency did not affect the DER in this mode during steady-state conditions. The change in reactive load caused minimal change in voltage.

Primary Principles: The volt-VAR function provides seamless voltage regulation on the feeder which provides benefit over the stepped capacitor banks. The inverter in this mode provides voltage support during transient and steady state. With proper coordination, multiple devices can be operated in parallel to have the efficient voltage regulation. This provides greater reliability of operation by improving the voltage profile on the feeder compared to slow acting voltage regulating devices such as voltage regulators and capacitor banks. The volt-VAR function involves no switching or the tap change operations like traditional device, which reduces periodic maintenance and improves service life of equipment.

Frequency-Watt Function

Frequency-watt mode enables the DER to manage its active power dispatch in response to frequency fluctuations. The test is conducted for all the four scenarios and the various system conditions including load variations and the frequency, voltage fluctuations. The results of this test show that the location of the test DER does not affect the performance of the DER in frequency-watt mode. The DER responded to fluctuations in frequency by increasing its active power dispatch at low frequency condition and decreasing its active power dispatch during high-frequency conditions. The voltage or load variations did not have any significant impact on the active power dispatch of the DER.

Primary Principles: The frequency watt function provides seamless regulation during the event of under-frequency caused by events such as load switching. This function provides reliability when the other intermittent sources renewable sources of energy reduce output because of cloud cover or lack of wind, the DER provides additional output to counter the changes in the DER output. The regulation can also occur in a manner that DER can operate in the charging mode to absorb the excess output in the system, which may occur during the light load condition. Since DER acts as quick reacting source to mitigate these frequency fluctuations, it takes load off the conventional generations. This leads to efficient and low-cost operations of the grid.

DER Response to Emergencies

A start and stop command can be sent remotely over Modbus to the DER controller for connecting and disconnecting the DER from the system. The startup process takes up to 4 seconds after the start command is issued to the controller. Once the DER is online, different mode commands can be sent with the required active and reactive power set points. The voltage ride-through settings on the tested DER can only be set via the HMI since this setting in not available in the Modbus register. The frequency ride-through settings on the tested DER can only be set via the HMI since this setting is not available in the Modbus register. The tested DER continuously broadcasts its status to the remote managements system via Modbus, indicating if the DER is online or offline. Along with this status information, the DER also sends the power output information. Based on this information utility operator can take operations decisions during different periods of the day. The tested DER sends the present SOC to the remote management system via Modbus to assist the utility operator with load and generation forecast.

Primary Principles: The ability of the DER inverter to communicate to relay the status information and receive the control commands from the remote managements system, provides operational flexibility to the grid operator, which aids the operator to make sound decisions based on the overall system condition. A DER inverter can be started and stopped to connect and disconnect from the rest of the system. The output can be modified and the ramp rates can be changed depending on the need. In addition, the ramp rates and gains for the volt-VAR, frequency-watt and volt-watt functions can be changed to suit different scenarios. Overall, this flexibility provides reliable operation with increased safety.

Spinning Reserve

The purpose of this test is to assess the benefits of using the DER a source of spinning reserve to provide the active and reactive power support during different system conditions as compared to conventional diesel generators. The DER is connected near the end of the feeder (Scenario 3) in this test. The results of this test proved that the DER is quite effective in sustaining loads during periods of under-frequency, providing voltage and frequency support within a short period.

Primary Principles: The DER can remain in idle mode with minimal loss of charge unlike the conventional diesel generators, which consumes fuel even when it is not outputting the power. Because of this benefit, storage system is more cost effective as a source of spinning reserve. It is more efficient and reliable source to provide the grid support during the disturbance or the outage. It provides clean energy and enhances environmental sustainability and provides ease of operation and maintenance. The detailed cost benefit analysis is provided in Appendix A.

Black Start

The purpose of this test is to assess the benefits of using the DER to black start the system after a complete system outage. The result of this test shows the effectiveness of using the DER to black start the system just like the traditional generation to bring the system online in the increment of loads and generations on the circuit. Once the grid breaker opens, causing the system to enter a blackout, the DER enters VSI mode creating reference for voltage and frequency. With the DER in VSI mode, additional load and generation sources can be connected in the system in the subsequent steps. The DER, like the PV system, need a voltage reference from the DER to initiate the startup process to feed the load. The only difference of using the DER as a black start source as opposed to the traditional generators is that the DER offers no inertia to the system.

Primary Principles: With the black start functionality, the DER can be used to power up the microgrid during the system outage, to feed the local load. In addition, other types of renewables can be paralleled once the microgrid is formed. This provides reduced outage duration for the microgrid, once the grid is back online, microgrid can be synchronized without interrupting the load. The storage system operating in parallel with the PV system is an ideal example of renewable microgrid operating at a very low cost without any negative environmental impact.

Load Leveling

The purpose of this function is to ensure that the import of active power across the grid remains the same throughout the periods of load fluctuations. This reduces the load on less economical peak generation plants. The results of this test on different scenarios had similar and effective impact on the system throughout. While the DER responded to the load fluctuations, the power import across the PCC remained constant, which ensured that the active and reactive power imported from the source remained constant as well.

Primary Principles: With the load levelling, the DER system can be set to follow the load, which means, it responds to load changes during high as well as low loading conditions. The load demand for the utility at the PCC remains constant throughout, which helps offset stress from the economical peak generating plants. This leads to lower cost of operation with improved reliability.

SECTION 6 REFERENCES

[1] ASPEN Model of the SDG&E System.

[2] IEEE 1547a-2014, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.

[3] T. Fenimore, A. Gould, and L. Wright, “Implementing a Microgrid Using Standard Utility Control Equipment,” proceedings of the Power and Energy Automation Conference, Spokane, WA, March 2016.

[4] A. Yazdani and P. P. Dash, “A Control Methodology and Characterization of Dynamics for a Photovoltaic (PV) System Interfaced with a Distribution Network,” IEEE *Transactions on Power Delivery*, Vol. 24, No. 3, July 2009.

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APPENDIX A SOFTWARE SIMULATION TESTING

Software testing, with the test inverter simulated in the RTDS, was conducted prior to the PHIL testing with the hardware inverter. A software simulation of demonstration DER was used for this assessment. The objective of the software tests was same as the PHIL tests. This section presents the results of the software testing. Only core functions of the DER were demonstrated in the software testing.

DEVICE UNDER TEST

The device under test was modeled as a DER with a capacity of 1 MW and 1500 kWh. The DER had an average value model of control system that was like the photovoltaic (PV) control from Section 2—A controllable AC voltage source and a controllable DC source. The control was achieved by controlling the line currents and voltages and converting them into a direct-quadrature (DQ) frame using Park’s transformation. The various control parameters were real power output and reactive power output, which were controllable through sliders. Figure A.1 shows the DER model.

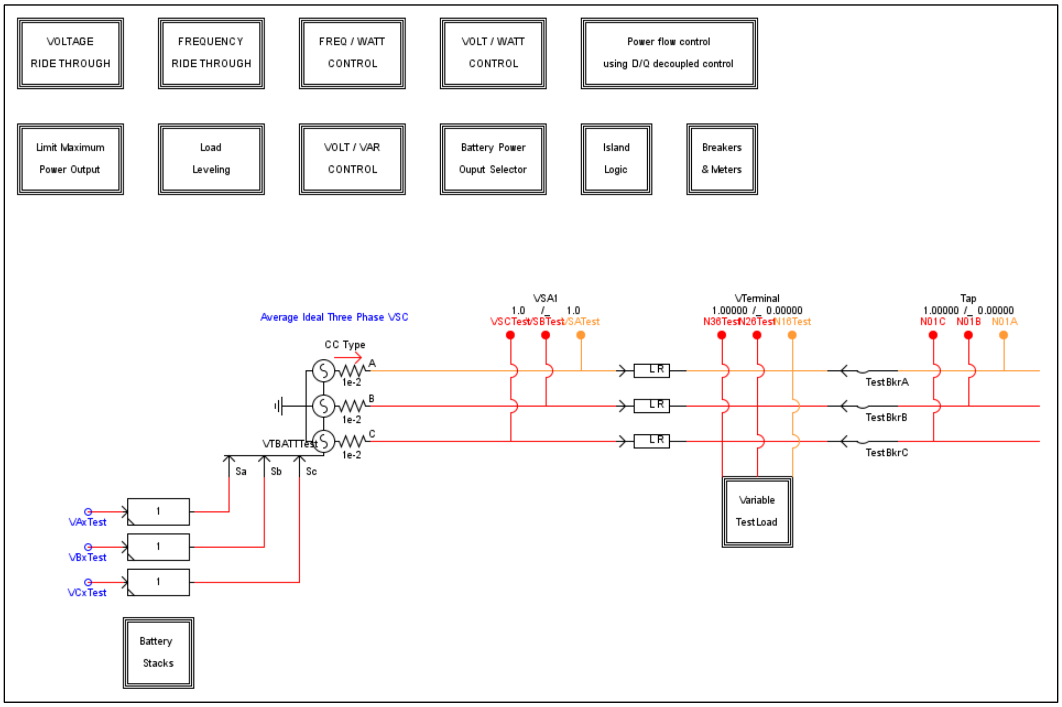

Figure A.1: DER Test Inverter Model

The DER is modeled generically such that it can be moved around in the circuit without affecting the functionality of the device to simulate multiple testing locations for penetration points. The DER provides the grid support functions and the ride-through protection functions.

TEST 3 – VOLT-WATT

This function was identified for use as compensation for the voltage variability that results from intermittent renewable sources or other loads. volt-watt is intended to provide a flexible mechanism through which inverters may be configured to dynamically provide voltage stabilization. This function involves the dynamic production of active power (watts) to resist variations in the voltage at the PCC.

The objective is to counter any changes in the voltage by varying the output power. When the DER is set in volt-watt control mode, it tries to maintain the voltage of the system to 1 pu by curtailing the active power output.

The procedure for testing was as follows:

Step 1. Vary the system voltage beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER.
Step 2. Change the voltage by changing the load in steps or by changing the grid voltage (the DER should respond in such a way that the system voltage is maintained within the nominal values).
Step 3. Increase the output of the DER to its maximum capacity, which should lead to the voltage increase at the PCC bus (when the DER is put into volt-watt mode at this stage, the system voltage should revert into the nominal band because of the power curtailment by the function).
Step 4. Compare the results with the baseline case and develop conclusions based on these findings.

Table A.1 lists the tests that were conducted.

Table A.1: DER Volt-Watt Test Cases

Test	Test Description	Expected Response
Test 3. x.1	Mode activation with active power set point of 500 kW	DER dispatches 500 kW at steady state
Test 3. x.2	Increase the system load by 500 kW	DER dispatches 500 kW at steady state
Test 3. x.3	Decrease the system load by 500 kW	DER dispatches 500 kW at steady state
Test 3. x.4	Increase the system voltage by 5%	DER decreases active power output to offset voltage increase
Test 3. x.5	Decrease the system voltage by 5%	DER increases active power output to offset voltage decrease
Test 3. x.6	Increase the system frequency by 0.5 Hz for 1 s	DER dispatches 500 kW at steady state
Test 3. x.7	Decrease the system frequency by 0.5 Hz for 1 s	DER dispatches 500 kW at steady state

Note: “x” denotes the scenario under test.

Scenario 1: DER Close to a Substation

TEST 3.1.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The system was initially operating in the schedule active power mode where the active and reactive power set points were at 500 kW and 200 kVAR, respectively. The system local load was at 900 kW and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profile remained unaffected by the transition.

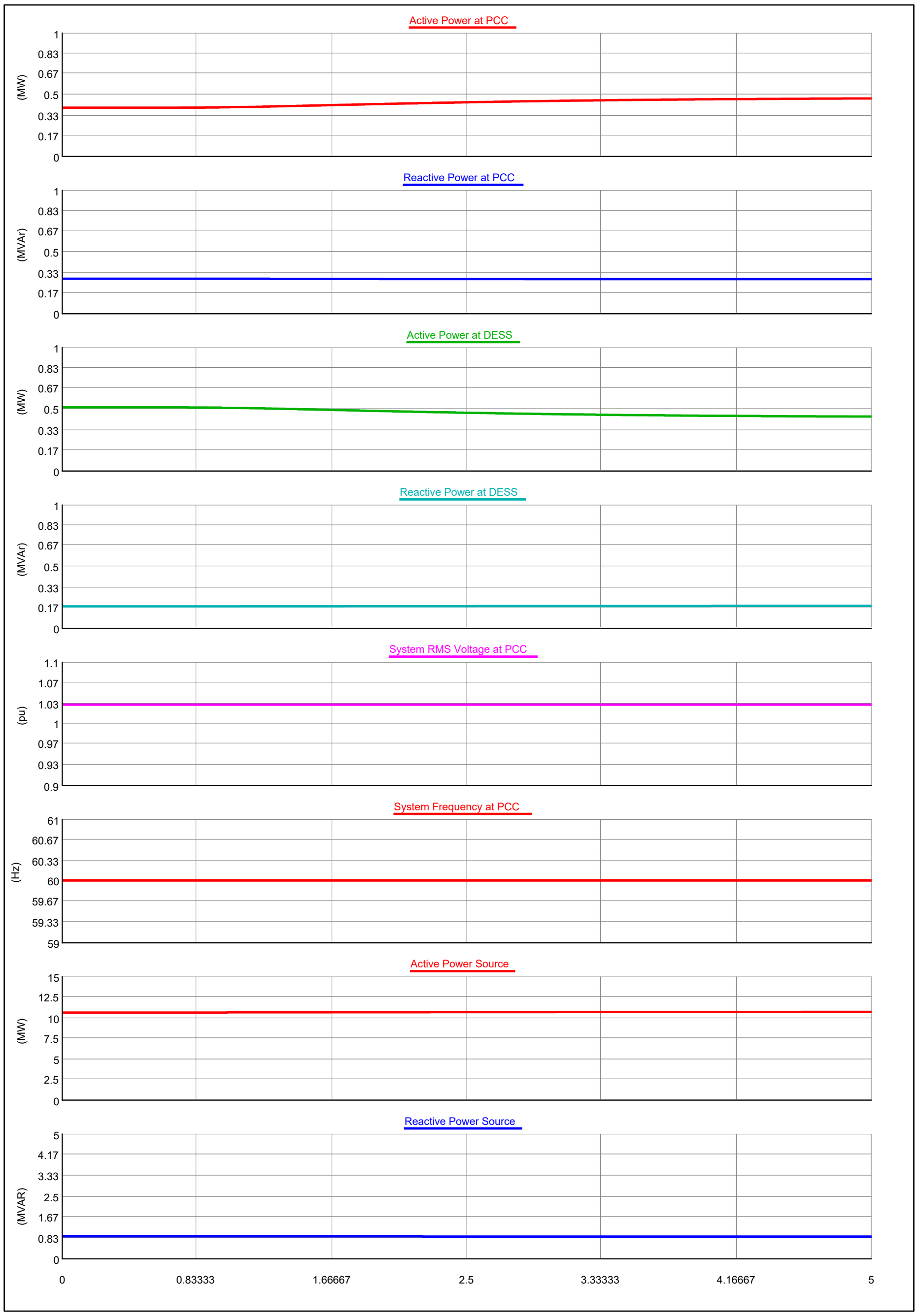

Figure A.2: System Response for Test 3.1.1

TEST 3.1.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and system voltage and frequency were not affected.

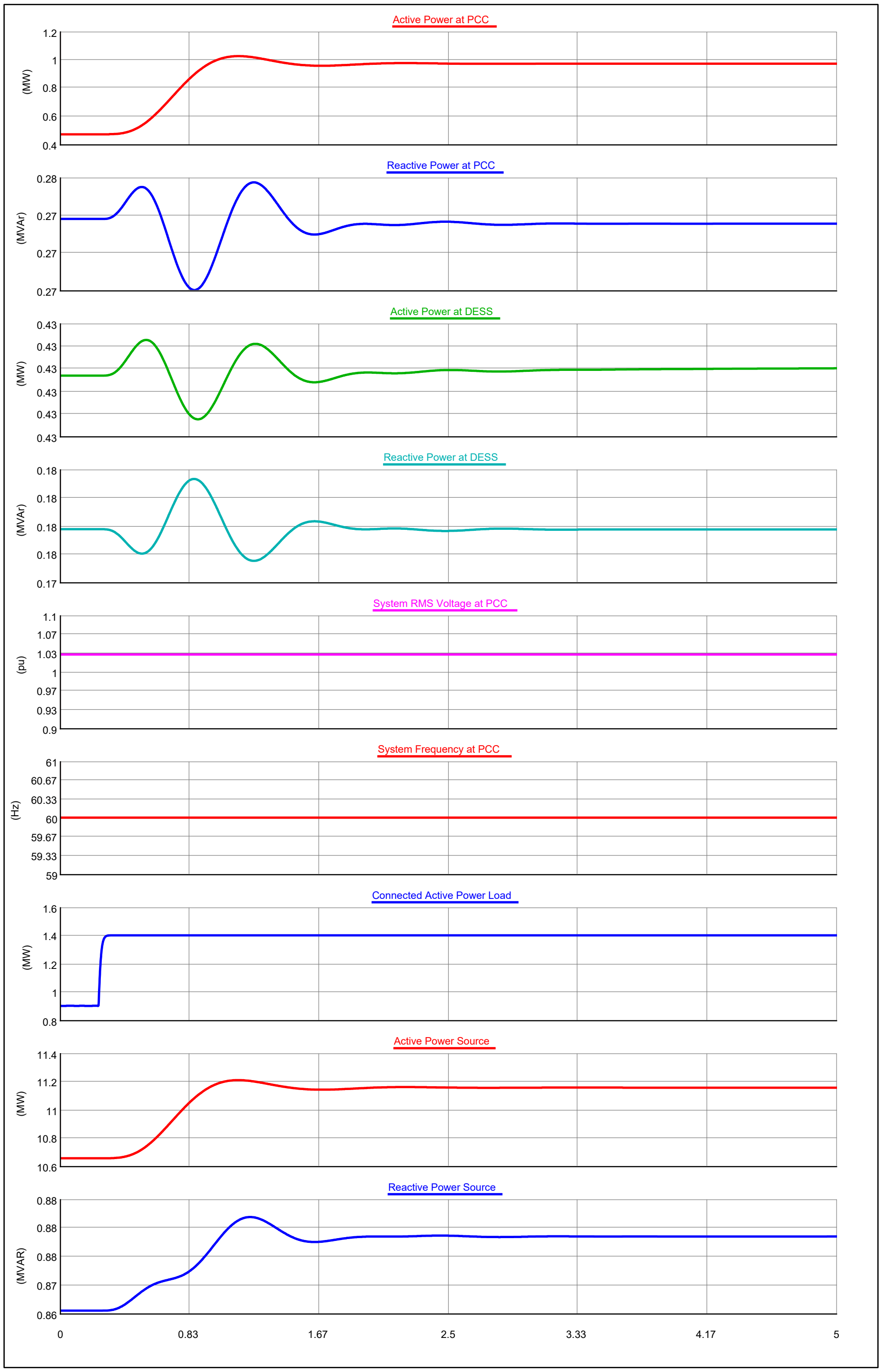

Figure A.3: System Response for Test 3.1.2

TEST 3.1.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power at the DER settled to its steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and system voltage and frequency were not affected.

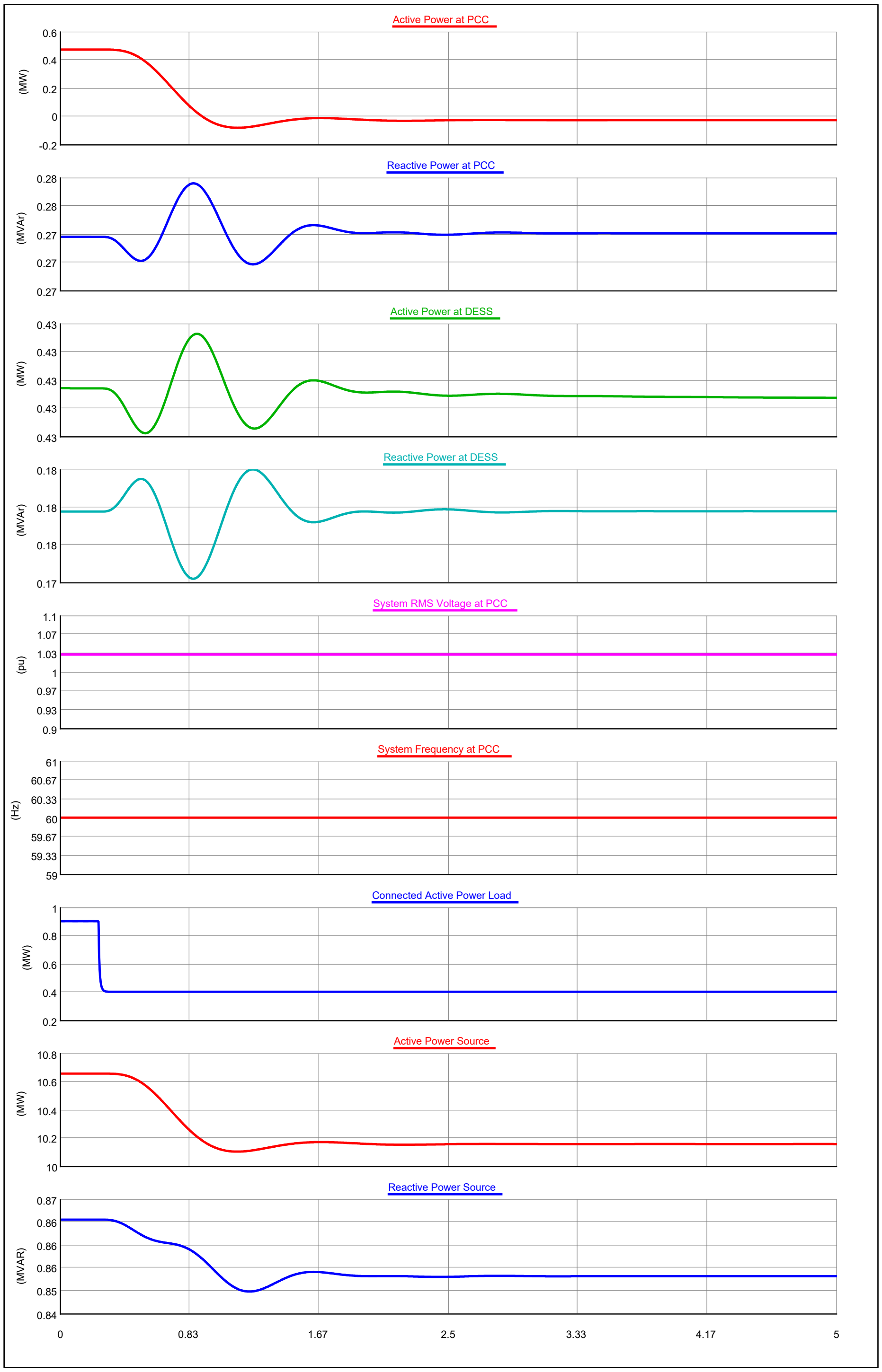

Figure A.4: System Response for Test 3.1.3

TEST 3.1.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system pu voltage by 5 percent from 1.025 pu to 1.075 pu, the active power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

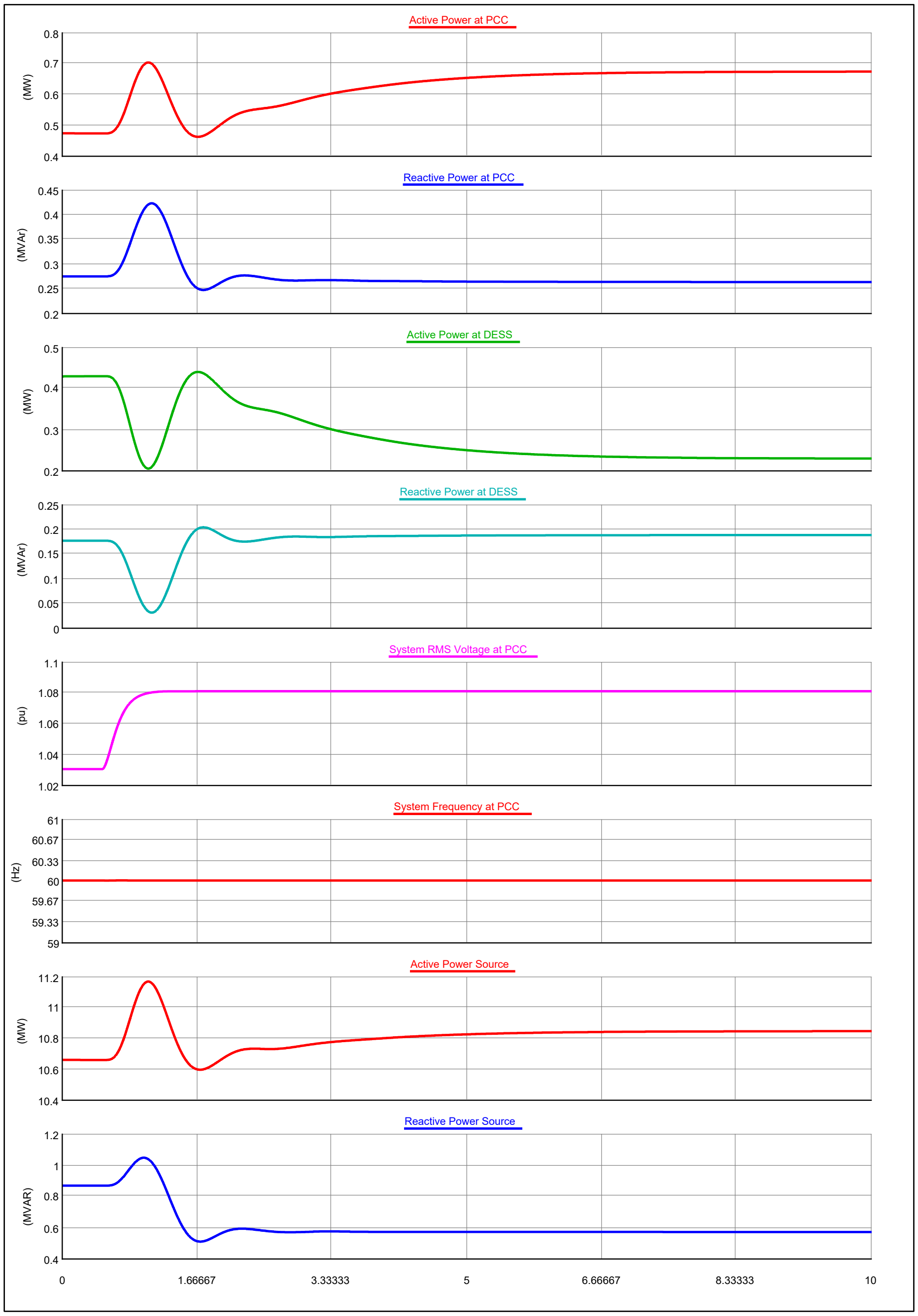

Figure A.5: System Response for Test 3.1.4

TEST 3.1.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system pu voltage by 5 percent from 1.025 pu to 0.975 pu, the real power at the DER increased so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid additional power import from the grid due to the voltage drop across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

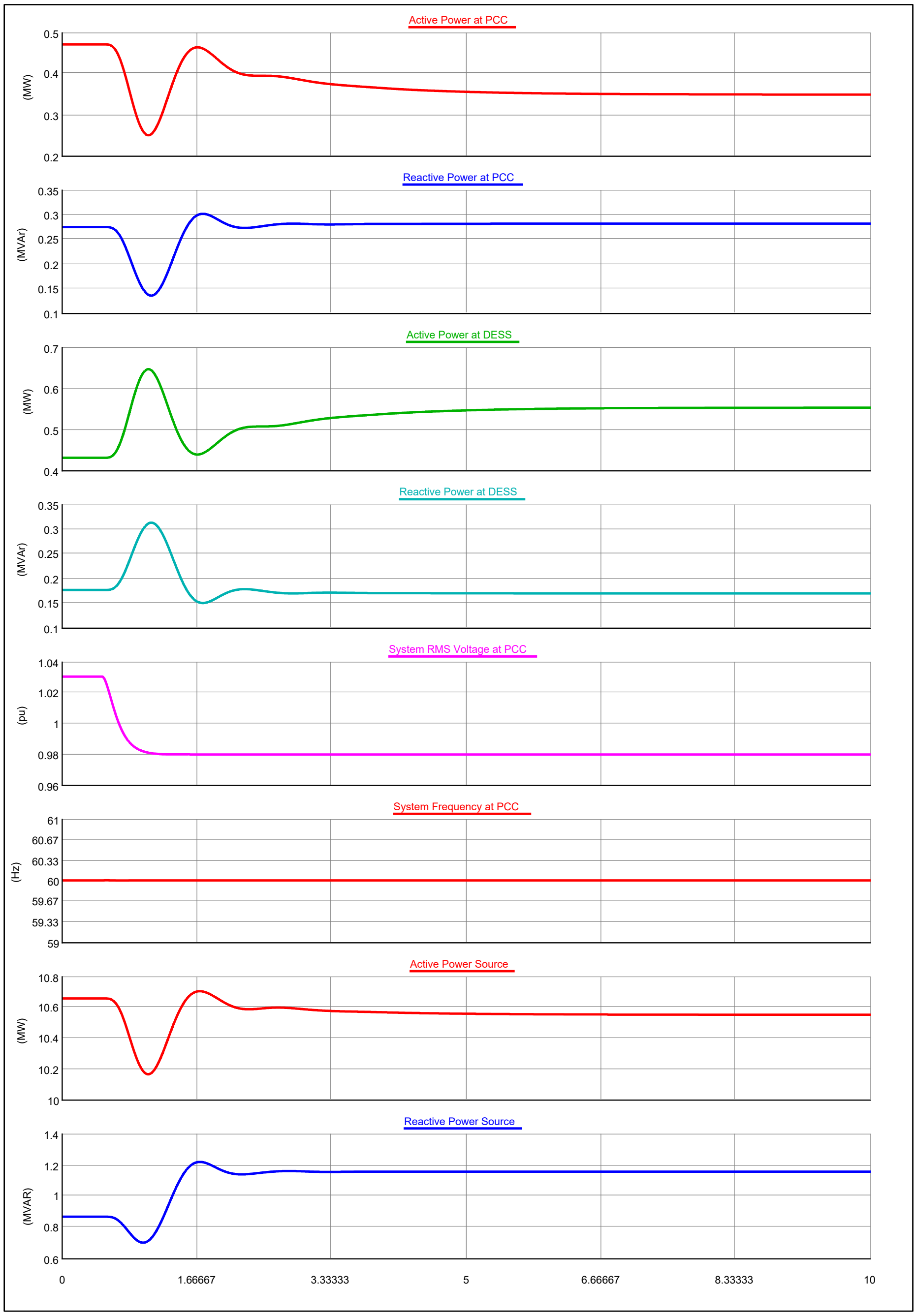

Figure A.6: System Response for Test 3.1.5

Test 3.1.6: Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.025 pu in steady state.

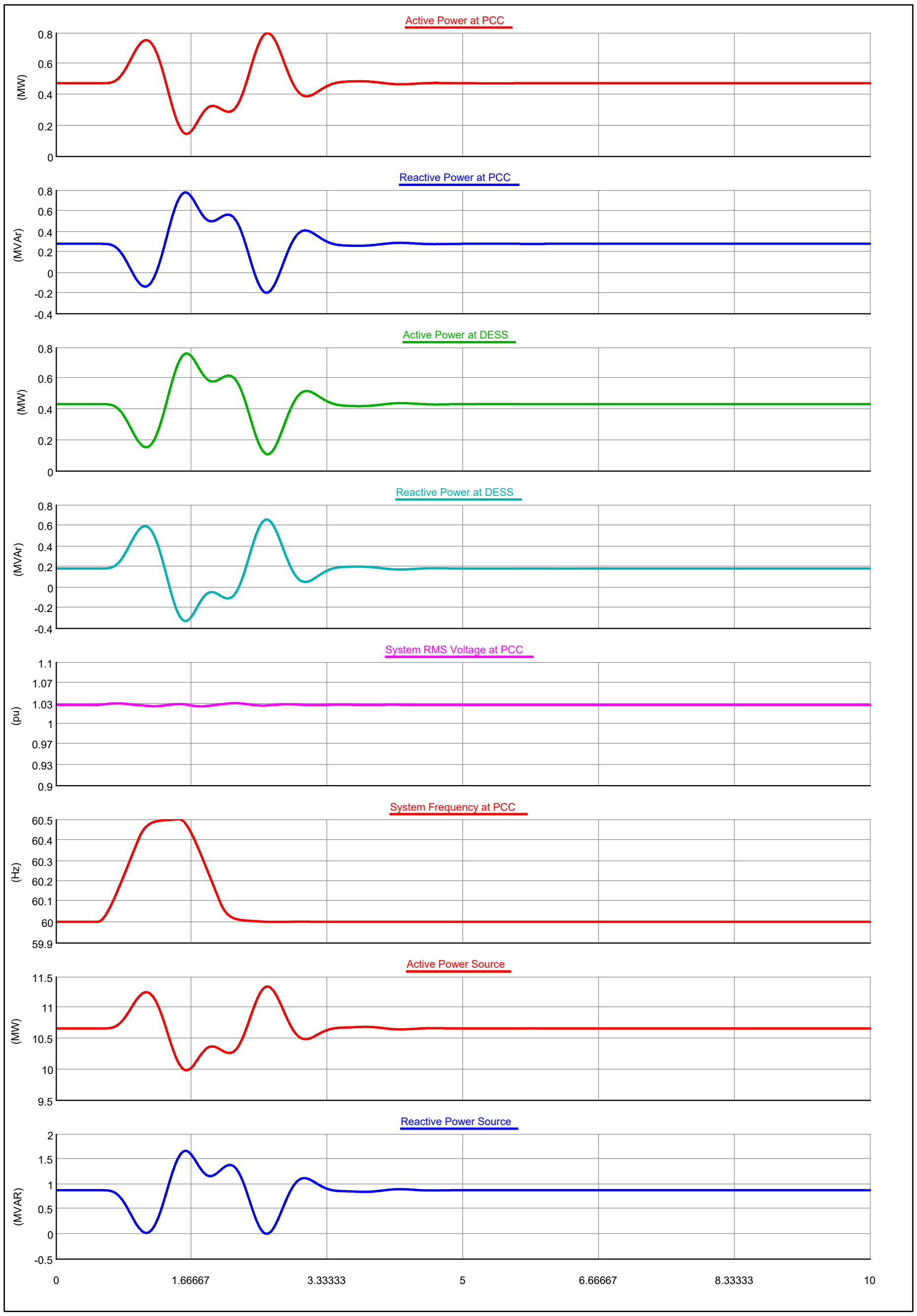

Figure A.7: System Response for Test 3.1.6

TEST 3.1.7: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.025 pu in steady state.

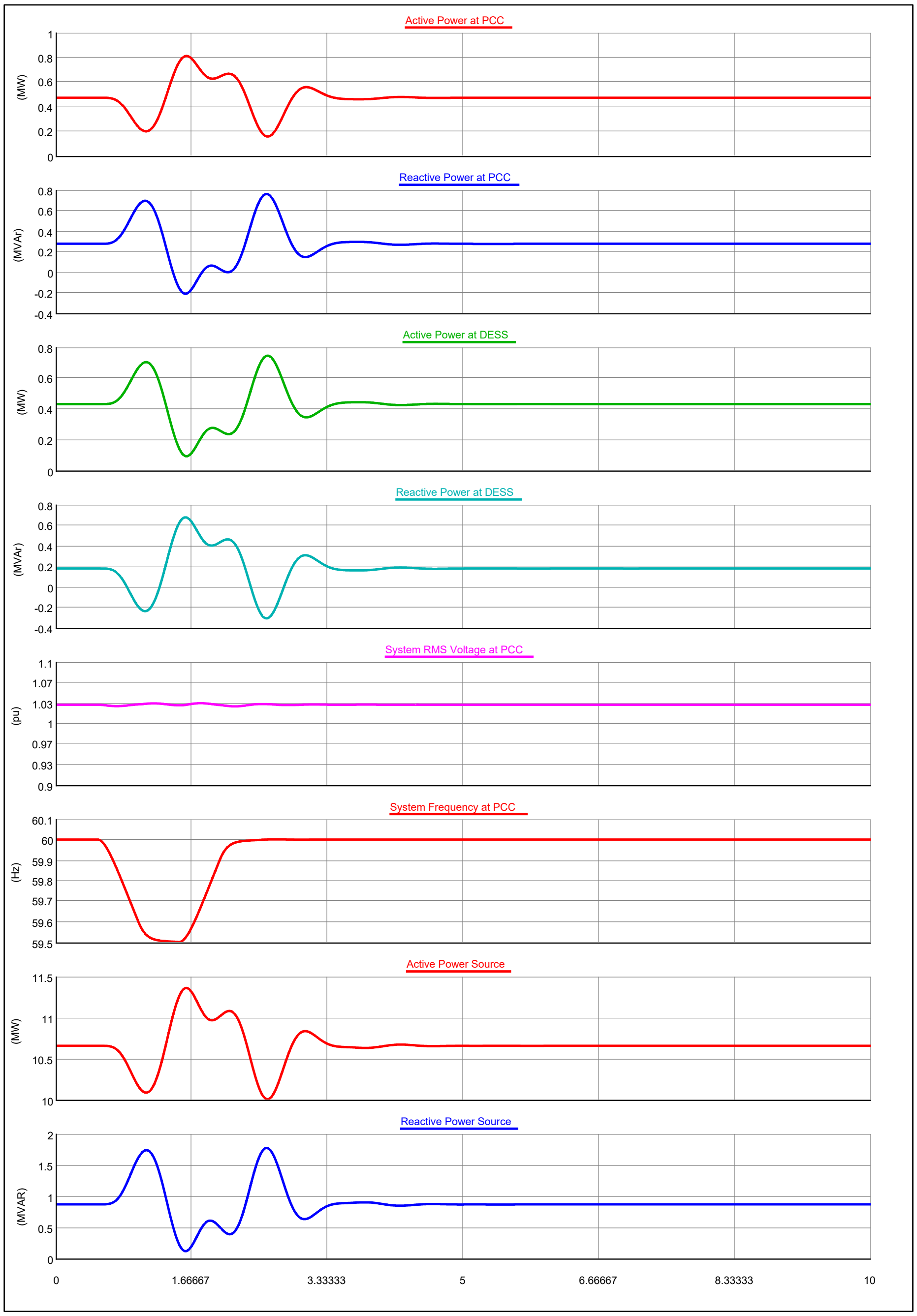

Figure A.8: System Response for Test 3.1.7

Scenario 3: DER at the End of a Long Feeder

TEST 3.3.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The system was initially operating in the schedule active power mode where the active and reactive power set points were at 500 kW and 200 kVAR, respectively. The system local load was at 900 kW and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profiles remained unaffected by the transition.

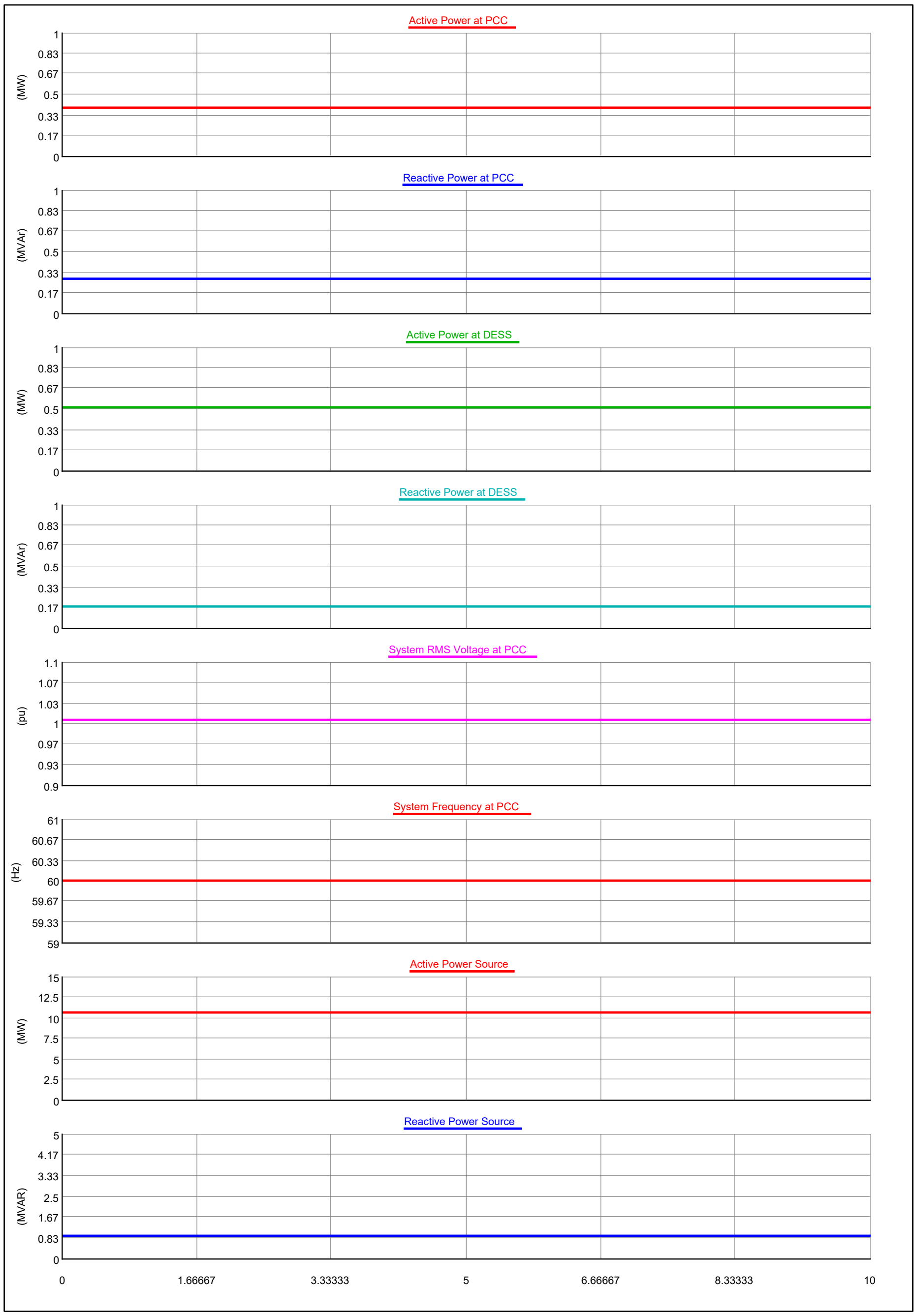

Figure A.9: System Response for Test 3.3.1

TEST 3.3.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

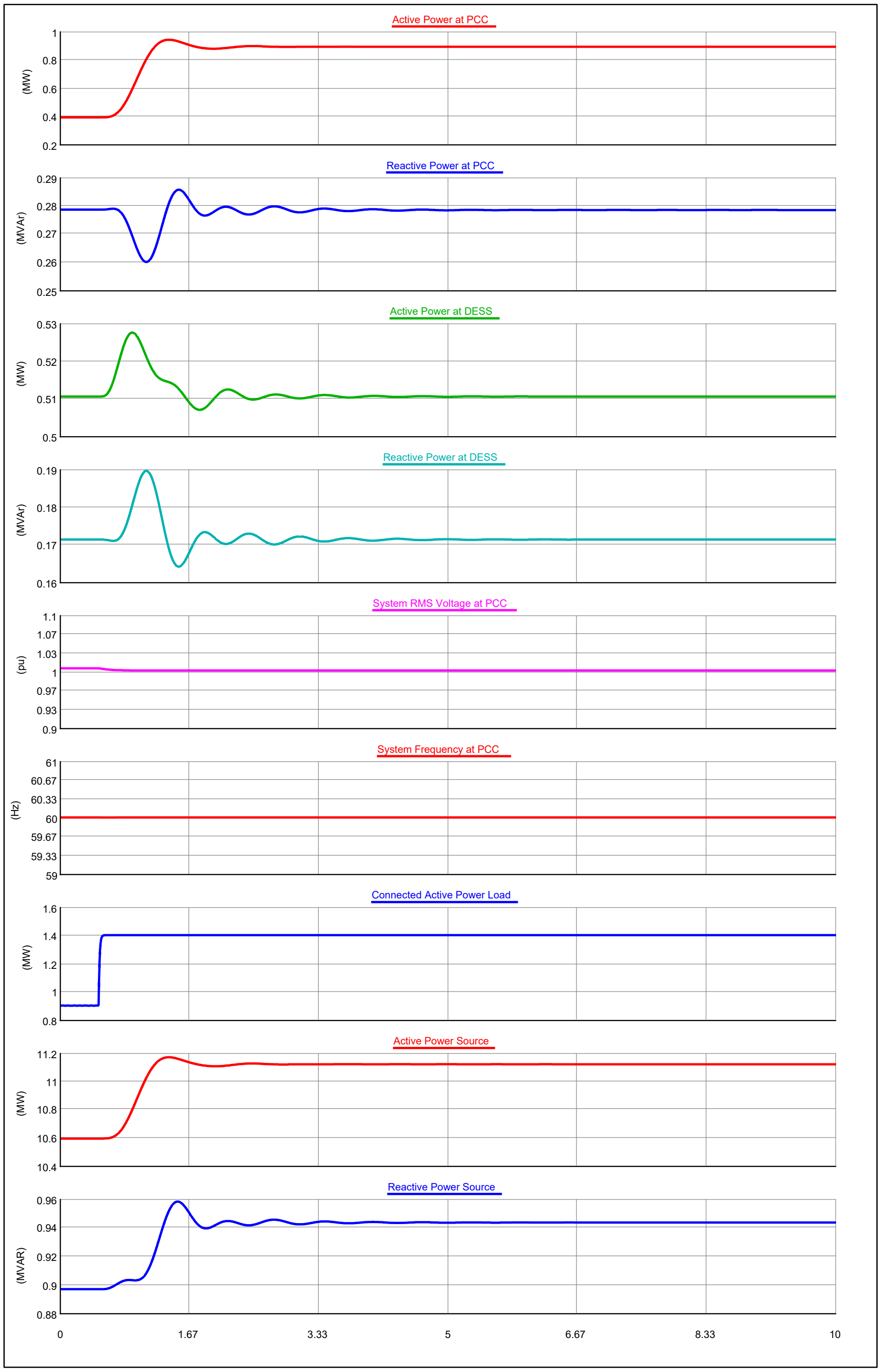

Figure A.10: System Response for Test 3.3.2

Test 3.3.3: Decrease the System Load by 500 kW

On decreasing the active power load by 500 kW, the real power at the DER settled to its steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

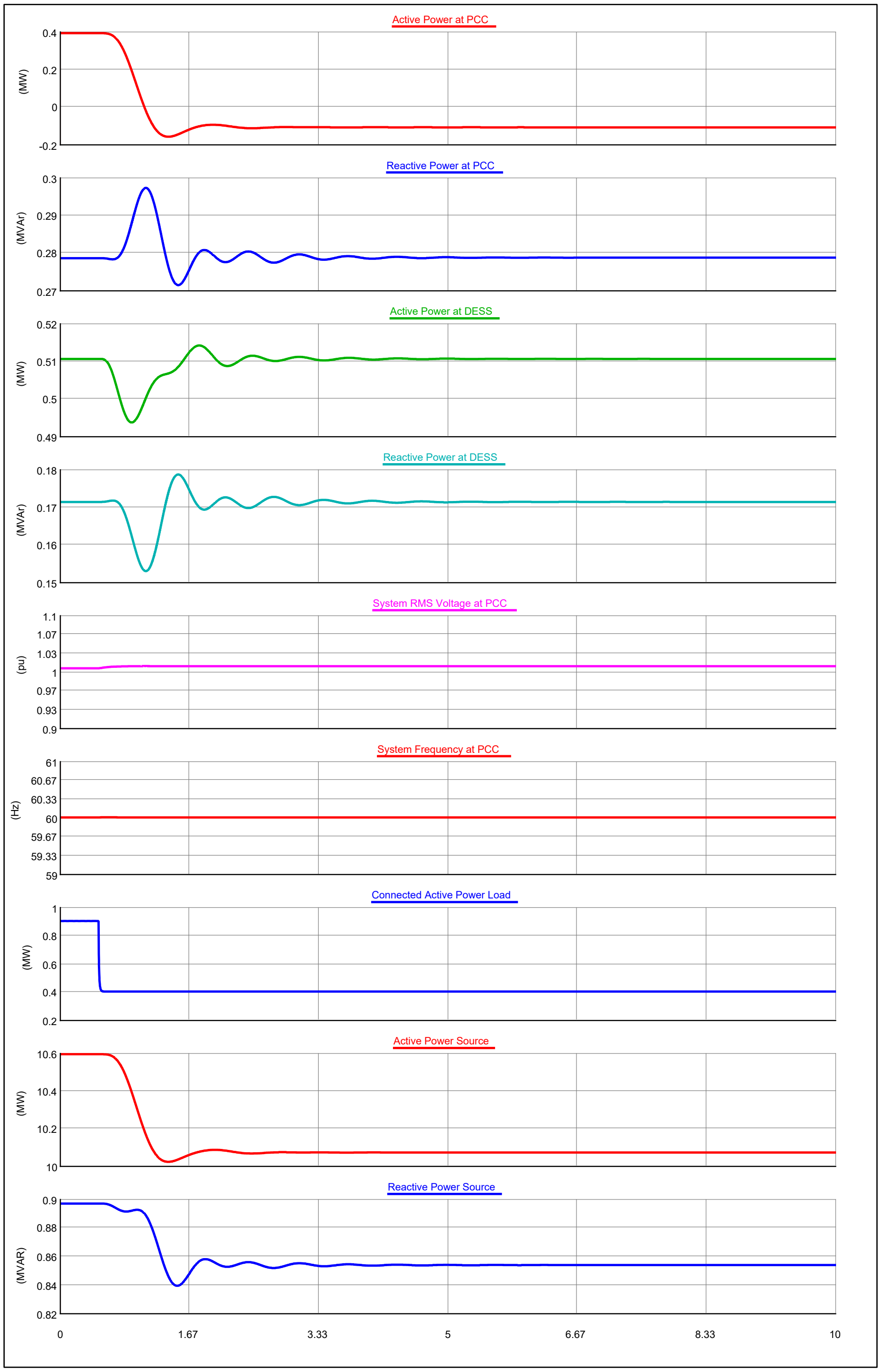

Figure A.11: System Response for Test 3.3.3

Test 3.3.4: Increase the System Voltage by 5 Percent

On increasing the system pu voltage by 5 percent from 1.002 pu to 1.052 pu, the real power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

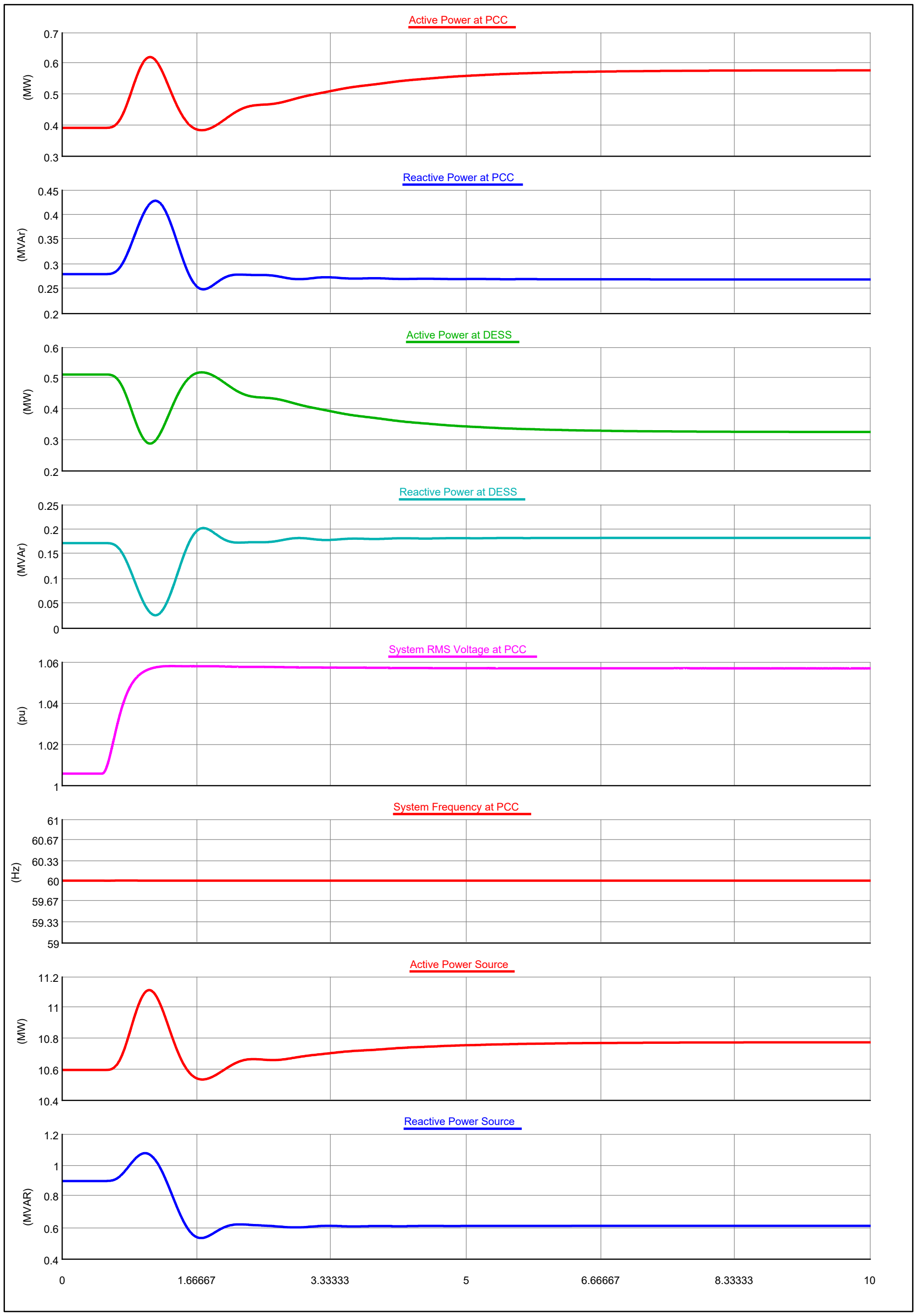

Figure A.12: System Response for Test 3.3.4

Test 3.3.5: Decrease the System Voltage by 5 Percent

On decreasing the system pu voltage by 5 percent from 1.002 pu to 0.952 pu, the real power at the DER increased so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid additional power import from the grid due to the voltage drop across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

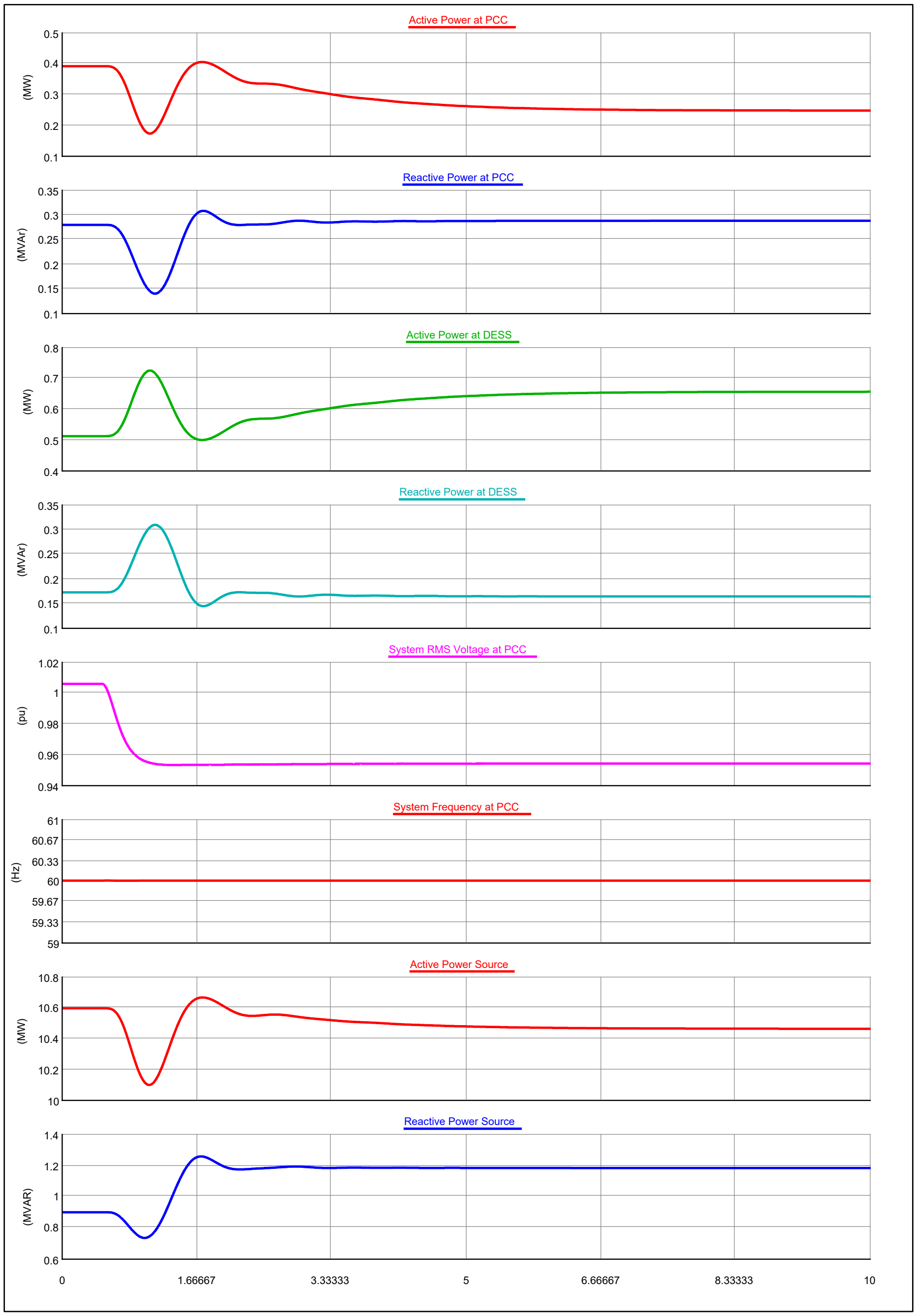

Figure A.13: System Response for Test 3.3.5

TEST 3.3.6: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

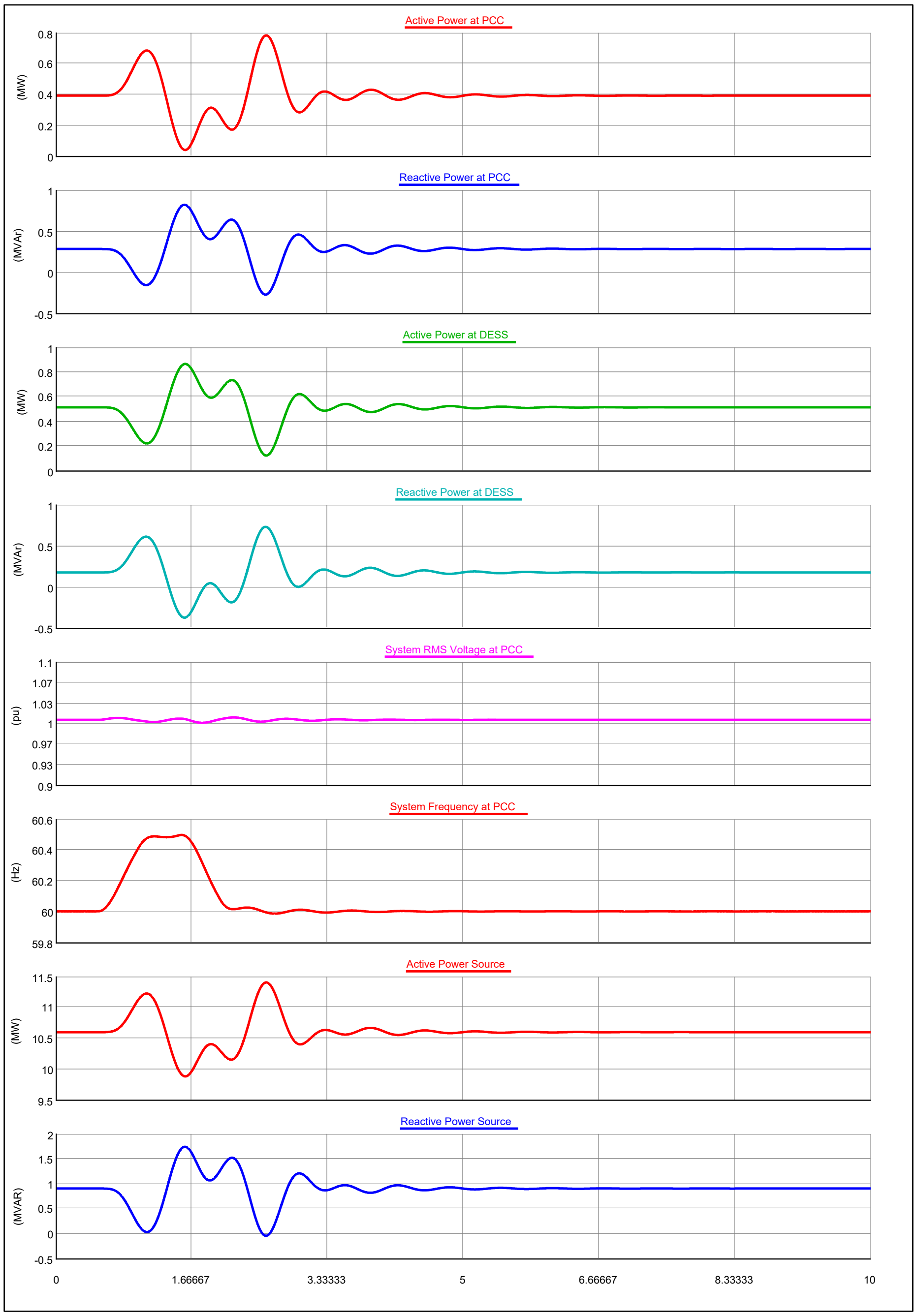

Figure A.14: System Response for Test 3.3.6

TEST 3.3.7: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

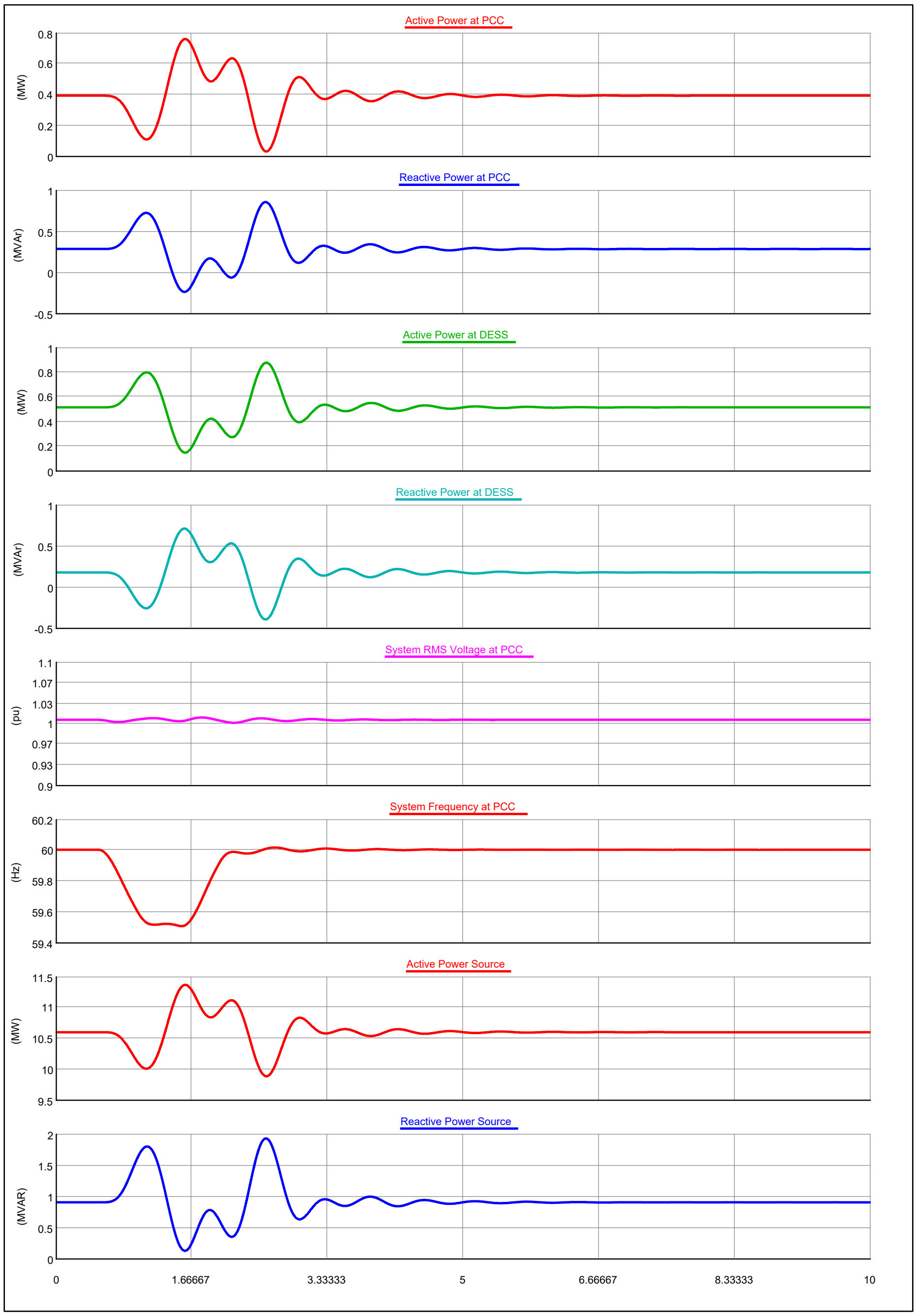

Figure A.15: System Response for test 3.3.7

Scenario 4: Multiple Diverse Types of DER on the Same Circuit

TEST 3.4.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The system was initially operating in the schedule active power mode where the active and reactive power set points were at 500 kW and 200 kVAR, respectively. The system local load was at 900 kW and 450 kVAR. On activating the volt-watt mode, the real and the reactive power at the DER and PCC settled at steady state. No visible disturbance was observed following mode activation. The voltage and frequency profiles remained unaffected by the transition.

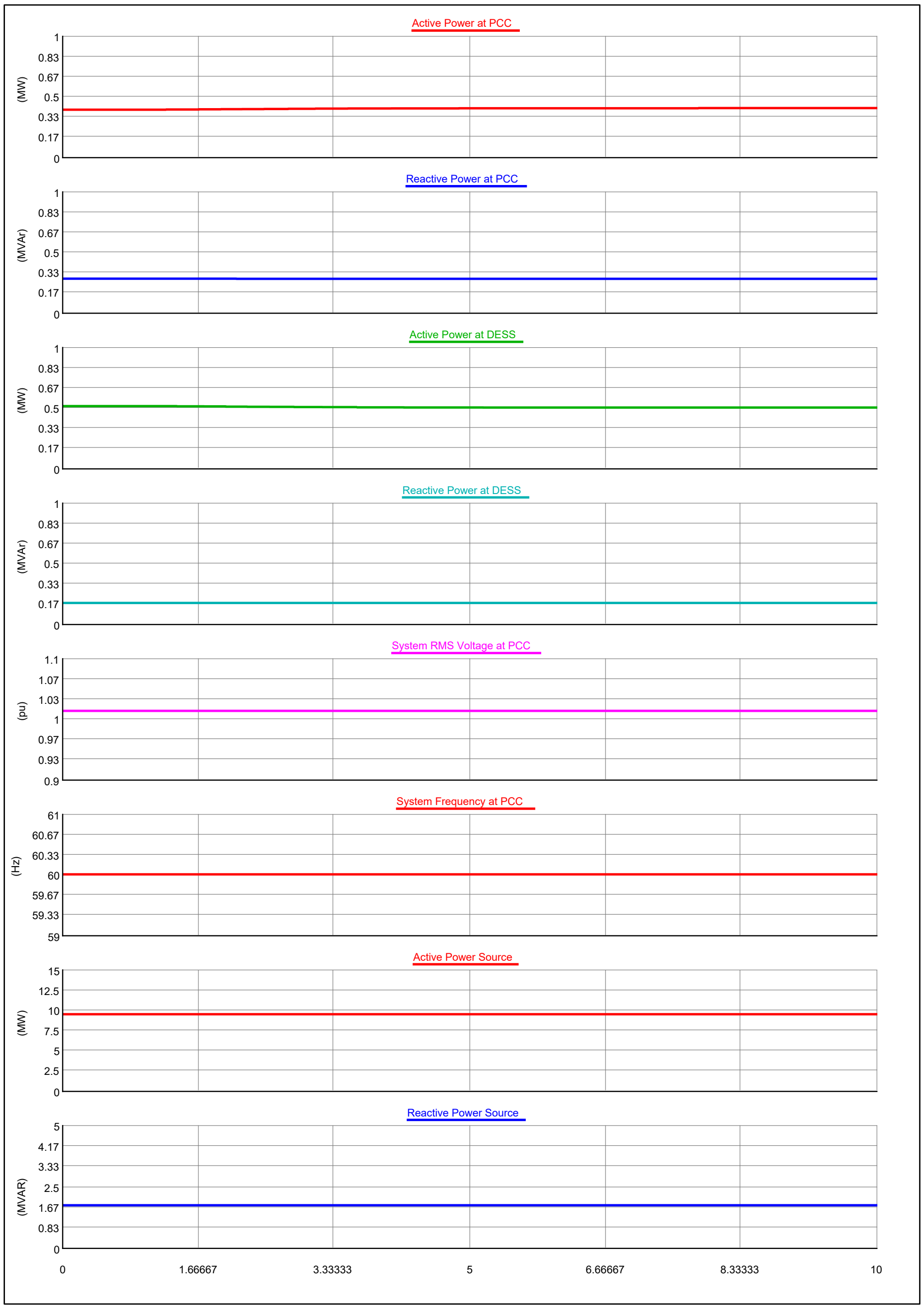

Figure A.16: System Response for Test 3.4.1

TEST 3.4.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

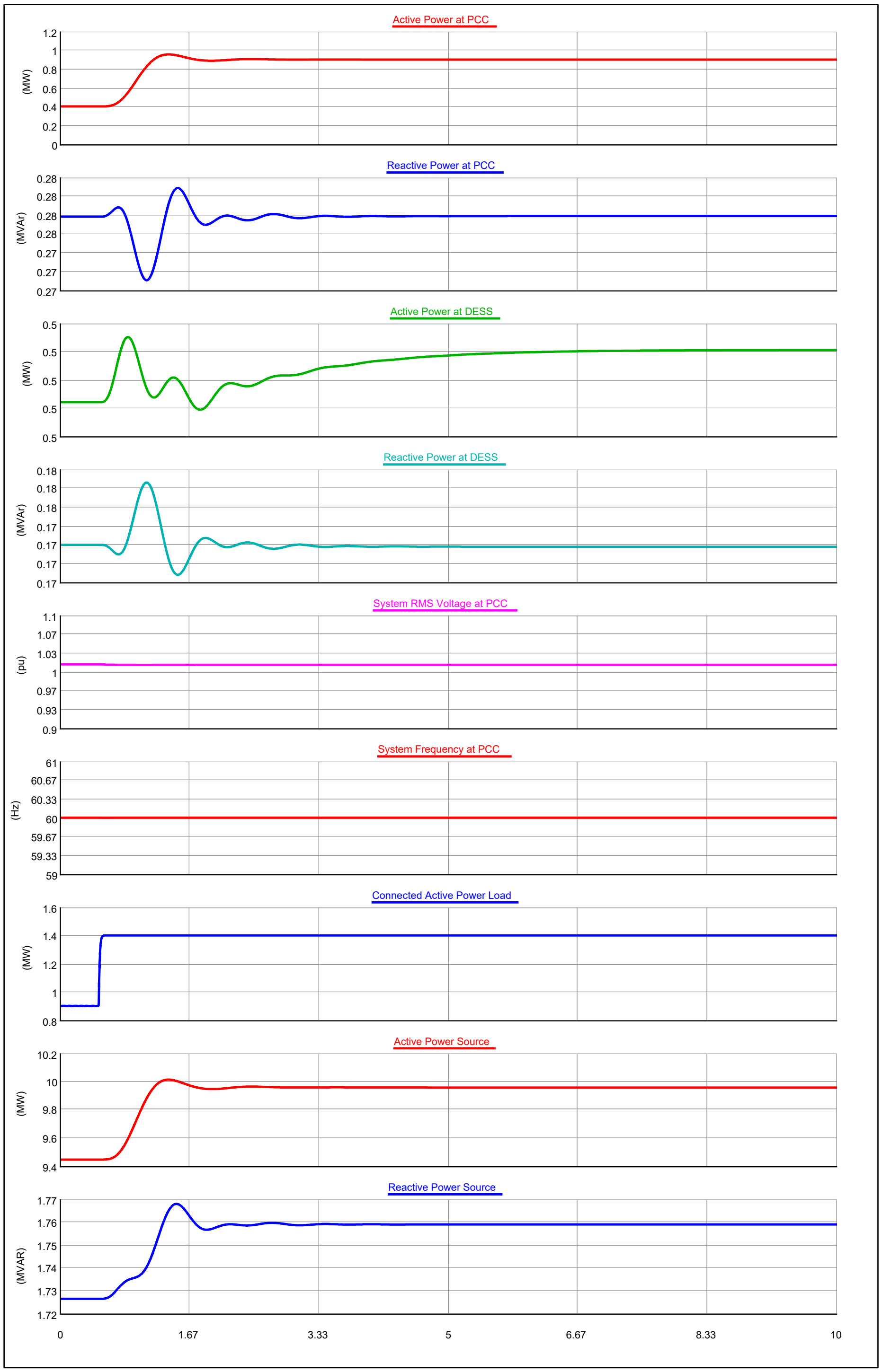

Figure A.17: System Response for Test 3.4.2

Test 3.4.3: Decrease the System Load by 500 kW

On decreasing the active power load by 500 kW, the real power at the DER settled to steady state, while the additional load was supported by the grid through the PCC. The reactive power flow and the system voltage and frequency were not affected.

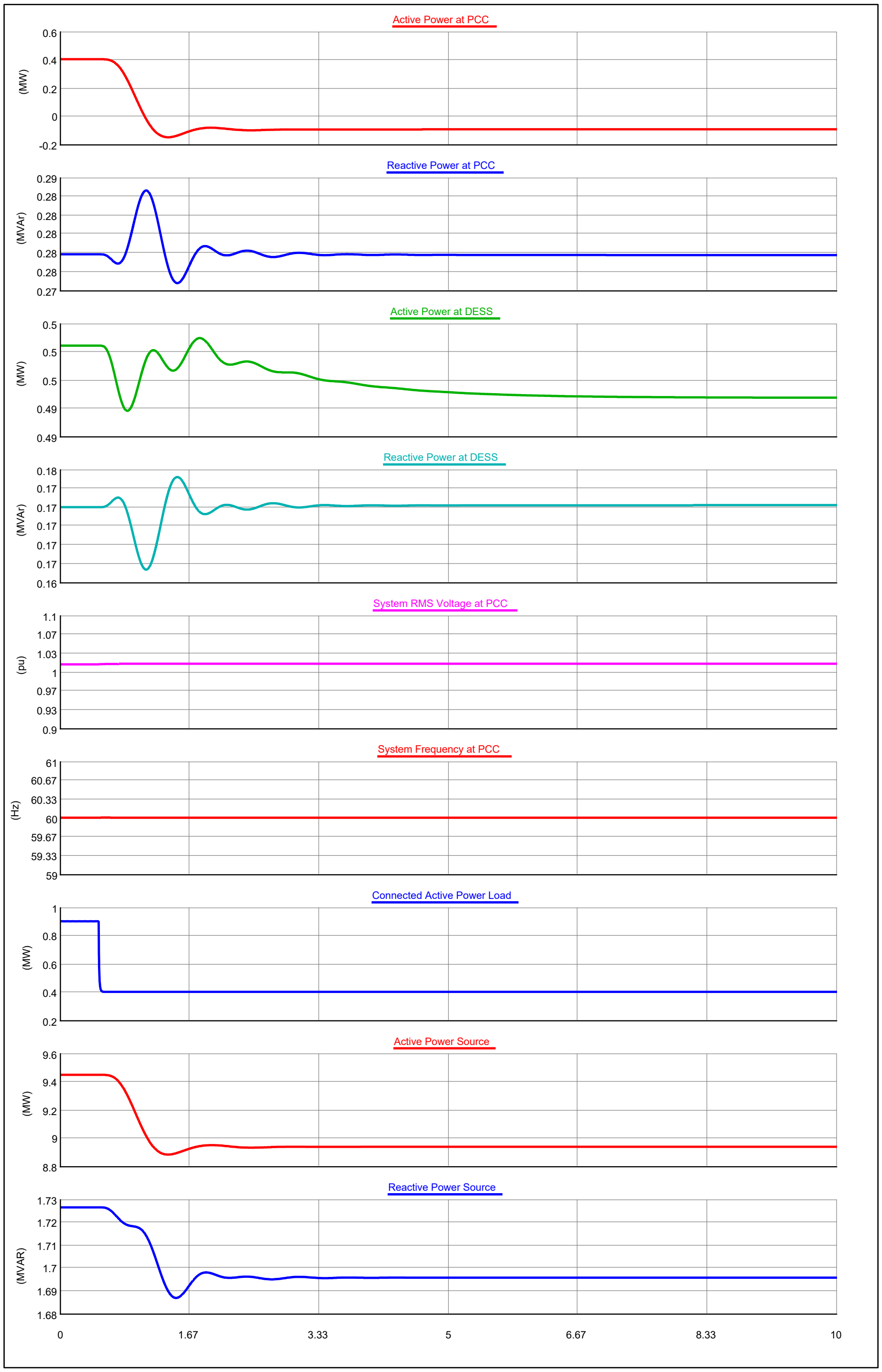

Figure A.18: System Response for Test 3.4.3

TEST 3.4.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system pu voltage by 5 percent from 1.018 pu to 1.068 pu, the real power at the DER fell so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid reverse flow into the grid due to the increased voltage across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

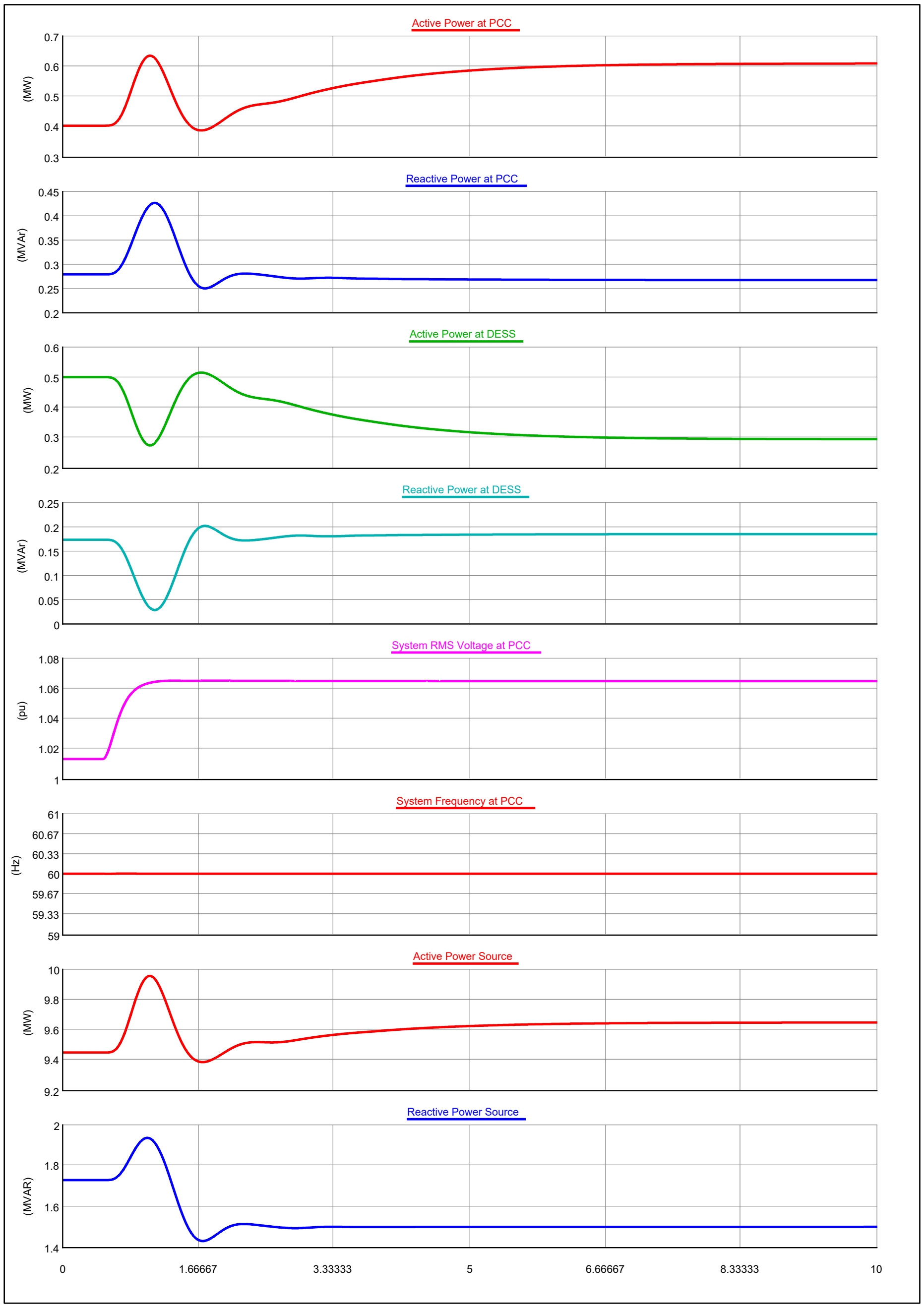

Figure A.19: System Response for Test 3.4.4

Test 3.4.5: Decrease the System Voltage by 5 Percent

On decreasing the system pu voltage by 5 percent from 1.018 pu to 0.968 pu, the real power at the DER increased so that more power was imported from the grid to keep the power import in the same direction. This balanced the power flow across the PCC to avoid additional power import from the grid due to the voltage drop across the terminals. The reactive power returned to its prior set point during steady state, and the system frequency remained undisturbed during the transition.

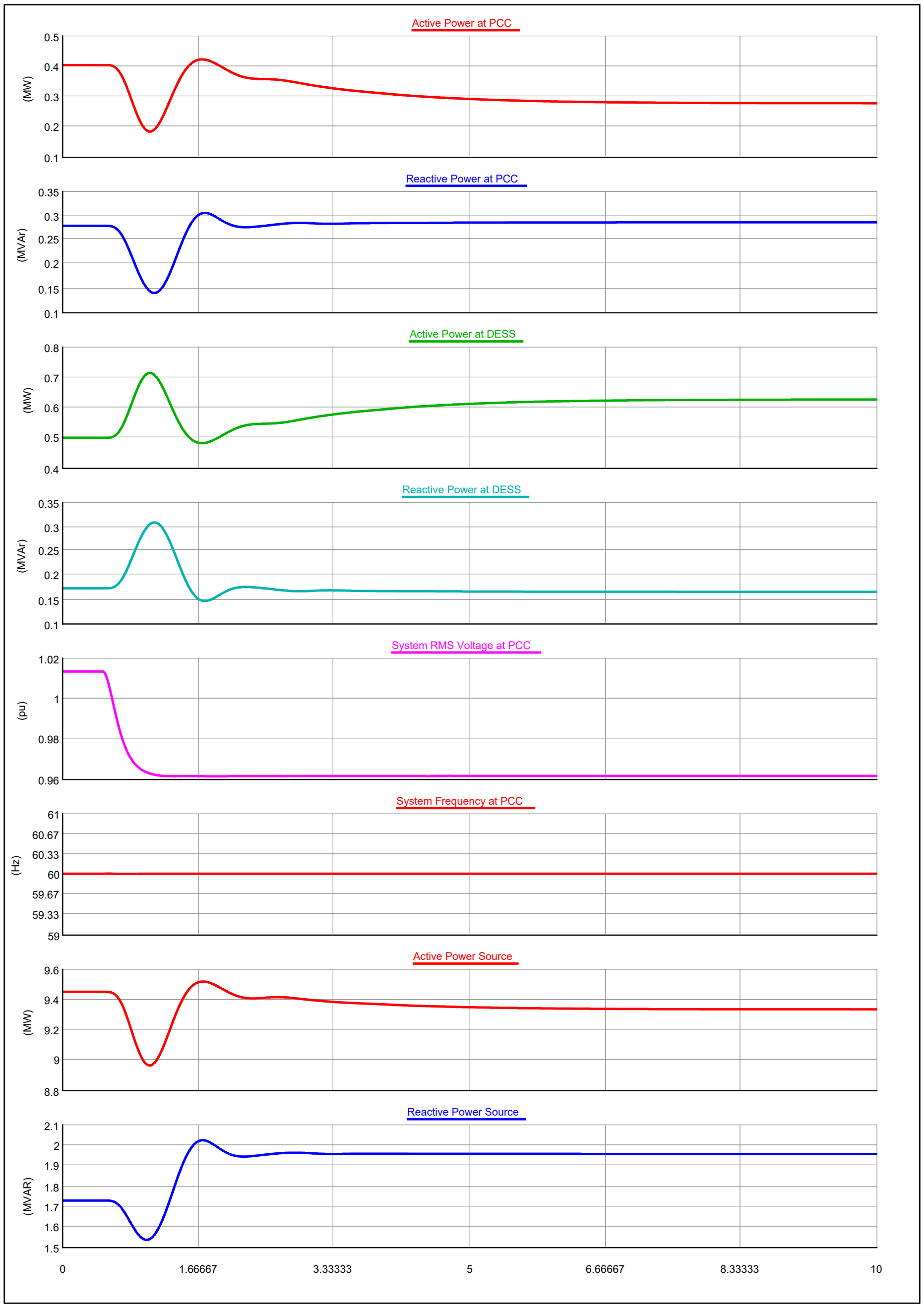

Figure A.20: System Response for Test 3.4.5

TEST 3.4.6: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.018 pu in steady state.

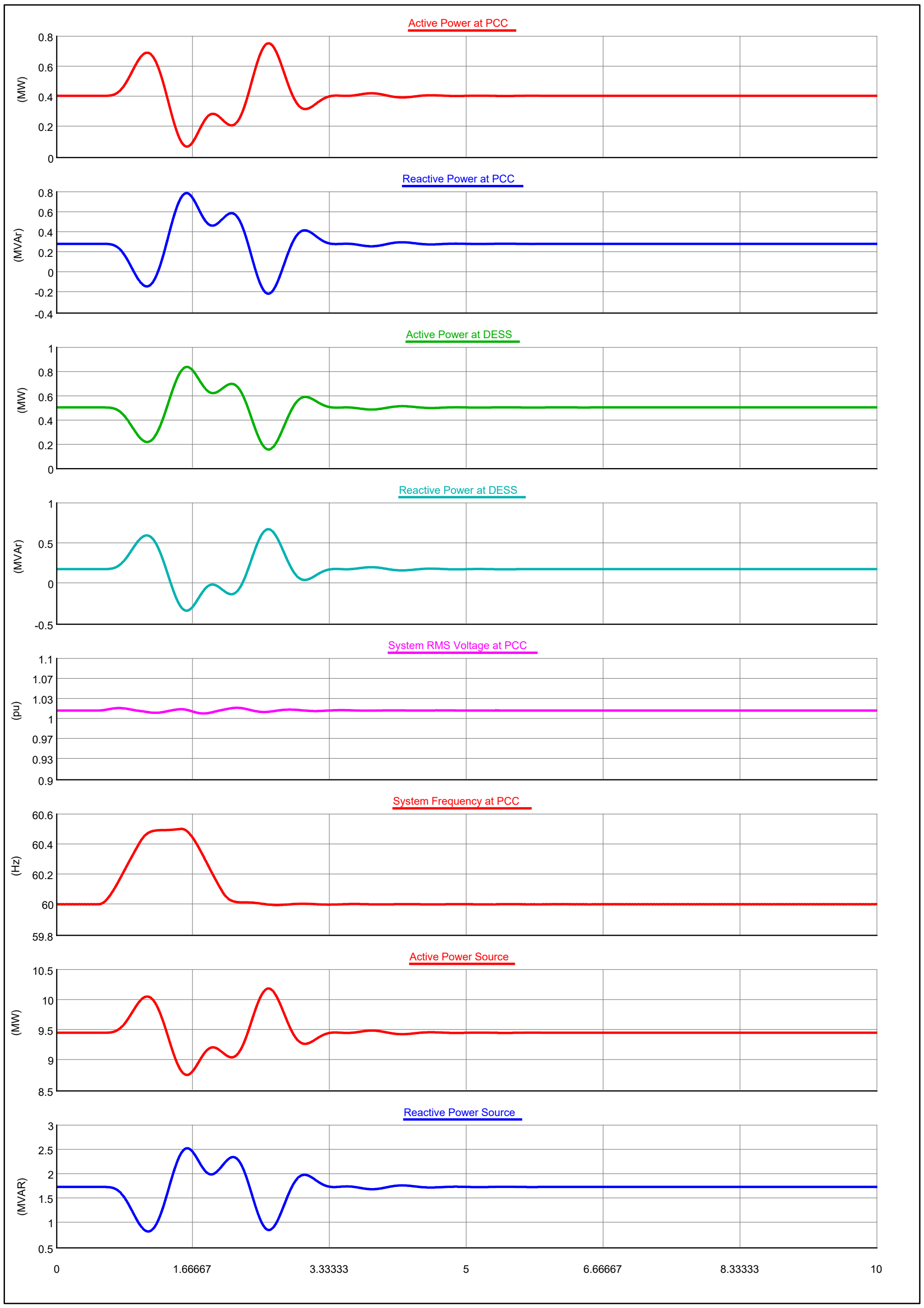

Figure A.21: System Response for Test 3.4.6

Test 3.4.7: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.018 pu in steady state.

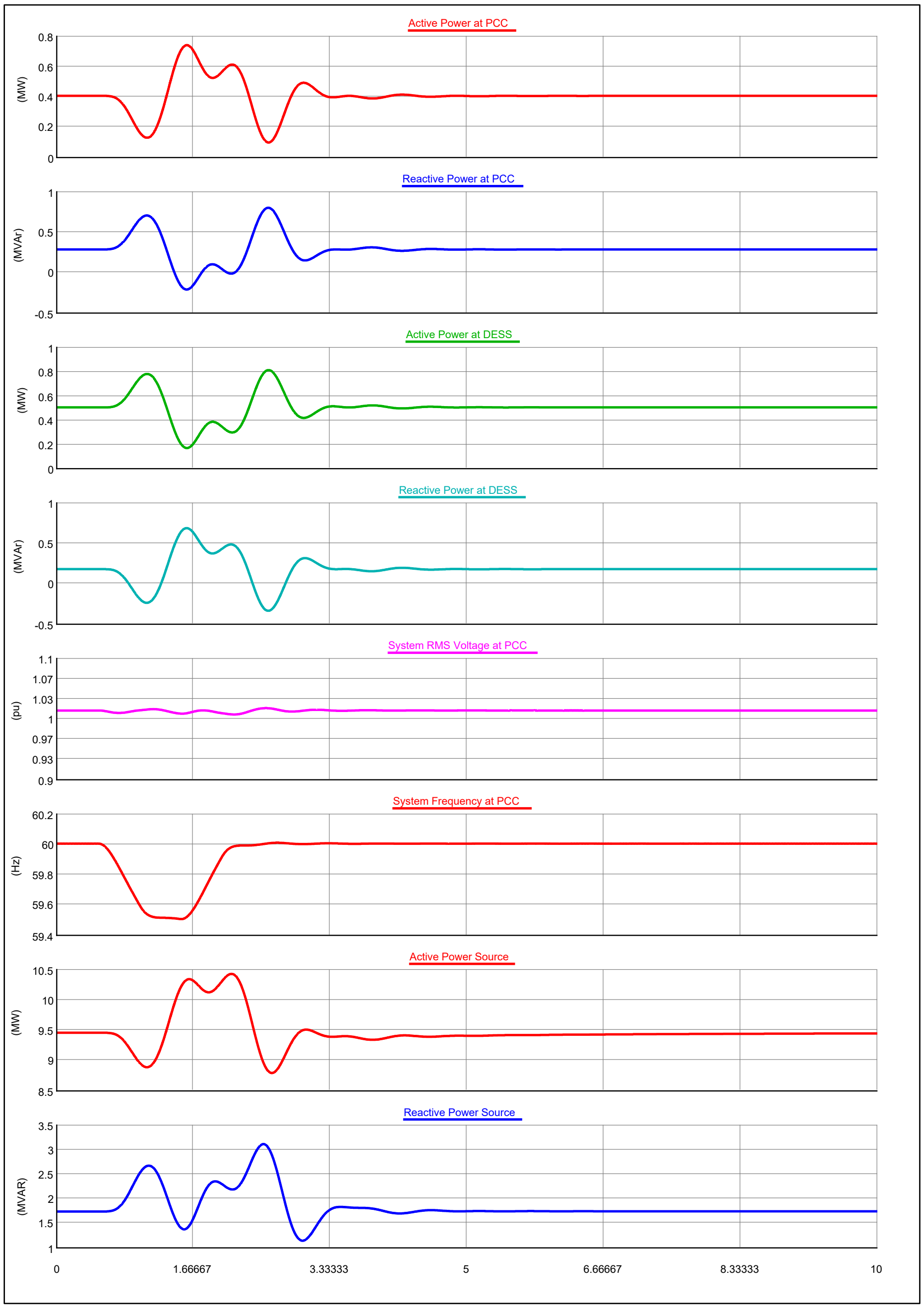

Figure A.22: System Response for Test 3.4.7

TEST 4 – VOLT-VAR

This function is intended to provide a mechanism through which a DER may be configured to manage its own VAR output in response to a fluctuation in the local service voltage. This function involves the dynamic production of reactive power (VARs) to resist variations in the voltage at the PCC.

Using the different circuit scenarios, the DER is put into volt-VAR mode. The objective is to counter any changes in the voltage by varying the output reactive power. When the DER is set in volt-VAR mode, it tries to maintain the voltage of the system to 1 pu by regulating the reactive power output.

The procedure for testing was as follows:

Step 1. Vary the system voltage beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER (the DER should respond in such a way that the system voltage is maintained within the nominal values).
Step 2. Change the voltage by changing the load in steps or by changing the grid voltage (when the DER is put into volt-VAR mode, the system voltage should revert into the nominal band because of the DER reactive power regulation).
Step 3. Compare the results with the baseline case and develop conclusions based on these findings.

Table A.2 lists the tests that will be conducted.

Table A.2: DER Volt-VAR Test Cases

Test	Test Description	Expected Response
Test 4. x.1	Mode activation with active power set point of 200 kVAR	DER dispatches 200 kVAR at steady state
Test 4. x.2	Increase the system load by 500 kVAR	DER dispatches 200 kVAR at steady state
Test 4. x.3	Decrease the system load by 500 kVAR	DER dispatches 200 kVAR at steady state
Test 4. x.4	Increase the system voltage by 5%	DER decreases reactive power output to offset voltage increase
Test 4. x.5	Decrease the system voltage by 5%	DER increases reactive power output to offset voltage decrease
Test 4. x.6	a) Ramp up the system voltage to 109%, at the rate of 30% per minute, and hold it for 5 s b) Ramp down the system voltage to 90%, at the rate of 30% per minute, and hold it for 5 s c) Ramp up the system voltage, back to nominal voltage (refer to Figure 3.28)	DER decreases its reactive power output to offset voltage increases and following that DER increases its reactive power output to offset voltage decrease. DER settles back at 200 kVAR at steady state.
Test 4. x.7	Increase the system frequency by 0.5 Hz for 1 s	DER dispatches 200 kVAR at steady state
Test 4. x.8	Decrease the system frequency by 0.5 Hz for 1 s	DER dispatches 200 kVAR at steady state

Note: “x” denotes the scenario under test.

Scenario 1: DER Close to a Substation

TEST 4.1.1: MODE ACTIVATION WITH REACTIVE POWER SET POINT OF 200 KVAR

The initial set points of the DER were at 500 kW and 200 kVAR. The active and reactive power load were at 900 kW and 550 kVAR respectively. When the mode was activated, the reactive power input of the DER dropped to 99 kVAR as the voltage at the PCC was greater than 1.025 pu; hence, the DER reduced its reactive power output to maintain the terminal voltage at the same value. The active power dispatch of the DER remained unaffected and therefore did not change across the PCC and the source. The system voltage and frequency did not change with the activation of the mode.

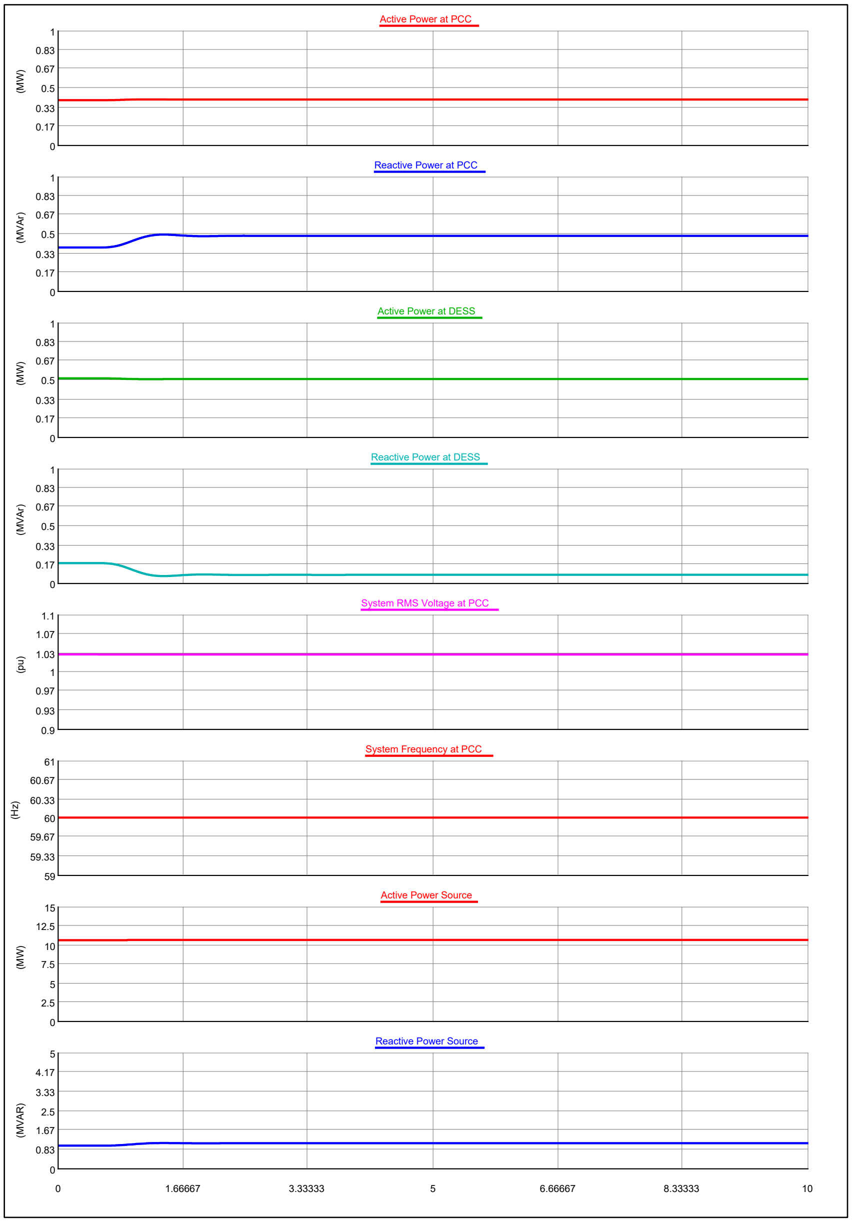

Figure A.23: System Response for Test 4.1.1

Test 4.1.2: Increase the System Load by 500 KVAR

On increasing the reactive power load by 500 kVAR to 1050 kVAR at the PCC, the reactive power at the DER remained unchanged at steady state because the reactive power set point at the DER was determined by the system voltage, which was not affected significantly during the load variation. The system voltage decreased minimally because of the inflow of the reactive power from the grid. The additional reactive power load was supported by the PCC to keep the node voltage constant. The frequency and the real power at the DER and PCC remained unaffected as well.

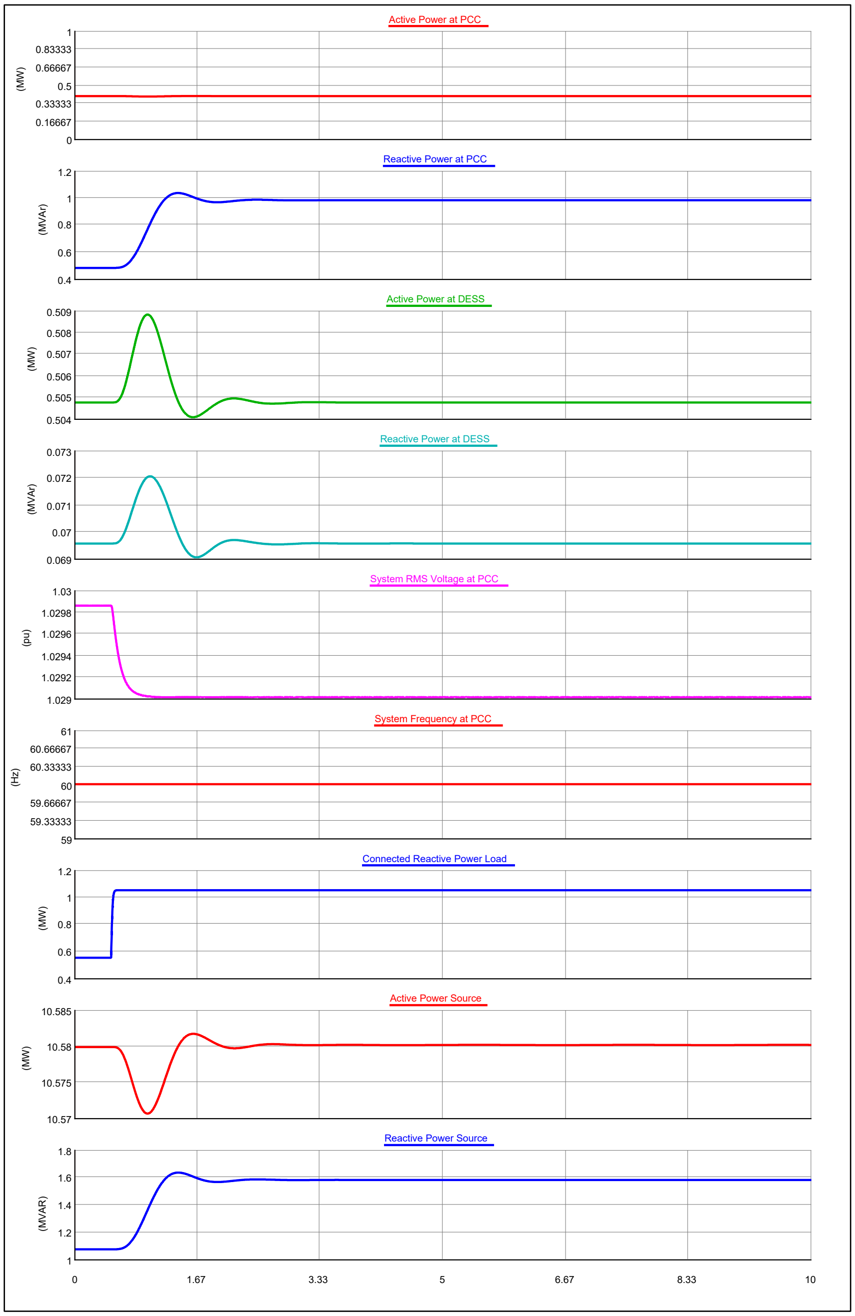

Figure A.24: System Response for Test 4.1.2

TEST 4.1.3: DECREASE THE SYSTEM LOAD BY 500 KVAR

On decreasing the reactive power, the load decreased from 550 kVAR to 50 kVAR. Like the observations for Test 4.1.2, the reactive power at the DER remained unaffected, while the grid drew power from the DER to maintain the load voltage at the PCC constant. The real power and frequency remained unaffected by the VAR changes, while the system voltage increased slightly because of the excess reactive power generated that was injected into the grid through the PCC.

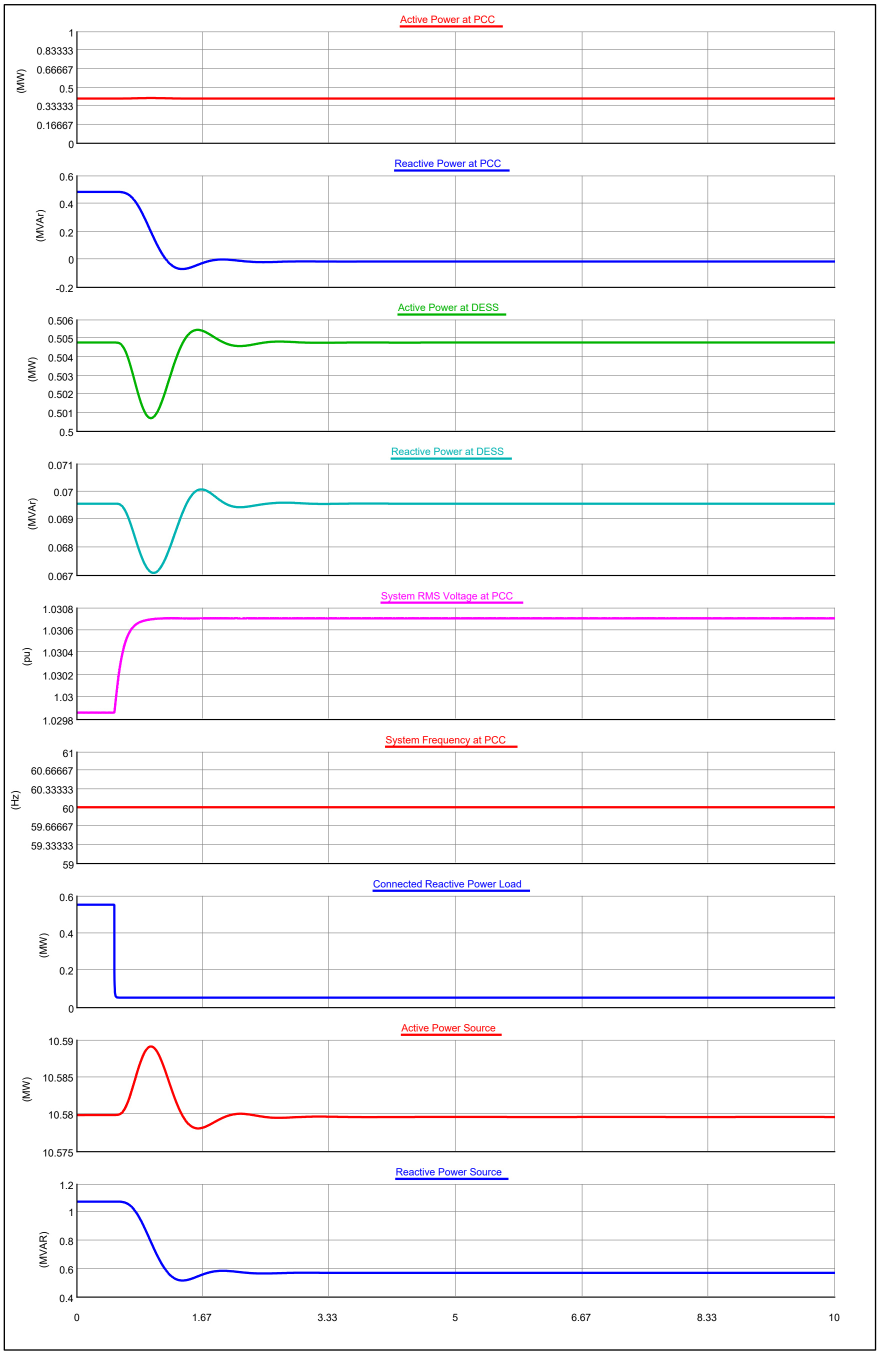

Figure A.25: System Response for Test 4.1.3

TEST 4.1.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 1.025 pu to 1.075 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected.

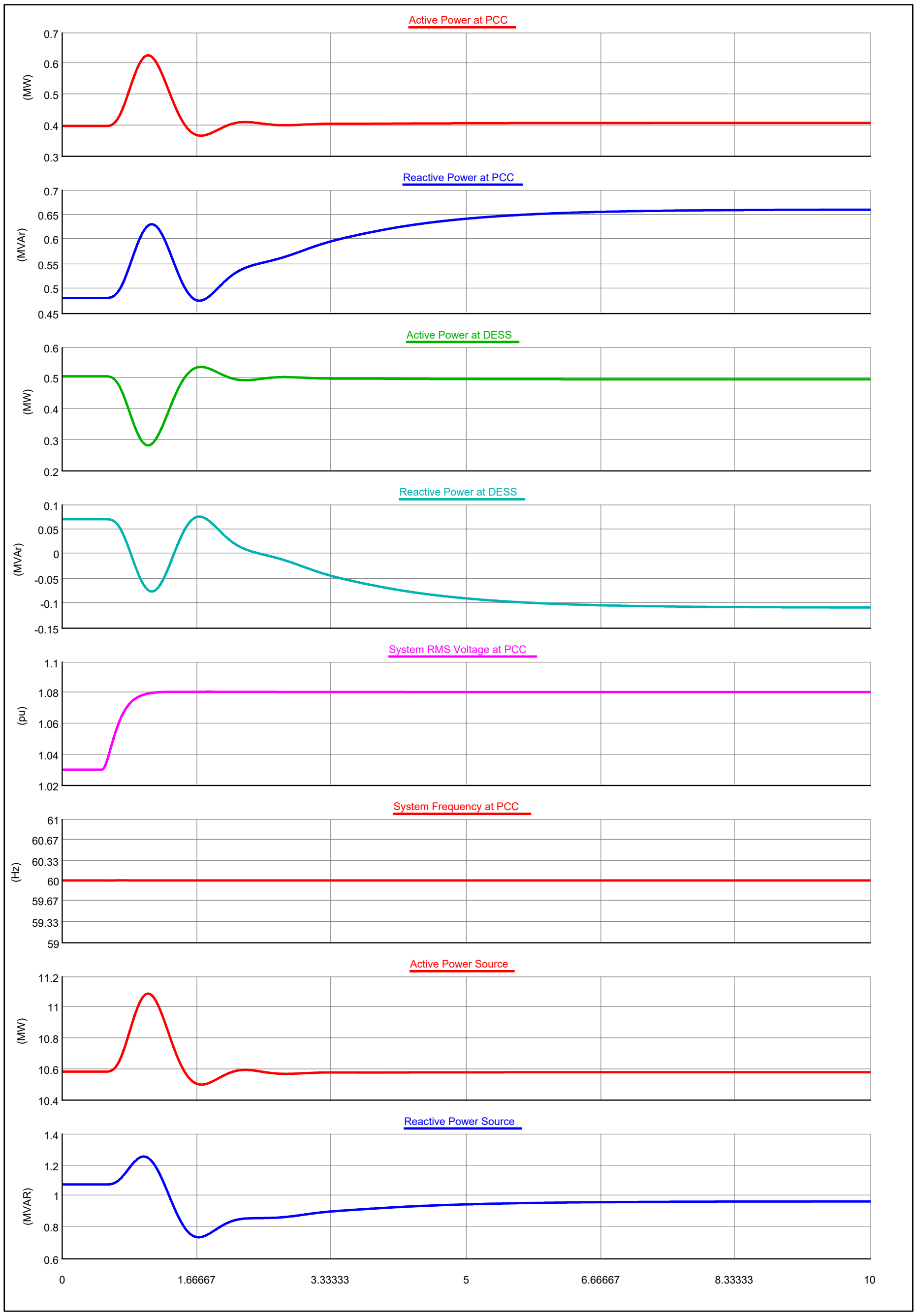

Figure A.26: System Response for Test 4.1.4

TEST 4.1.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 1.025 pu to 0.975 pu, the reactive power output of the DER increased and produced more reactive power maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected by the change at steady state.

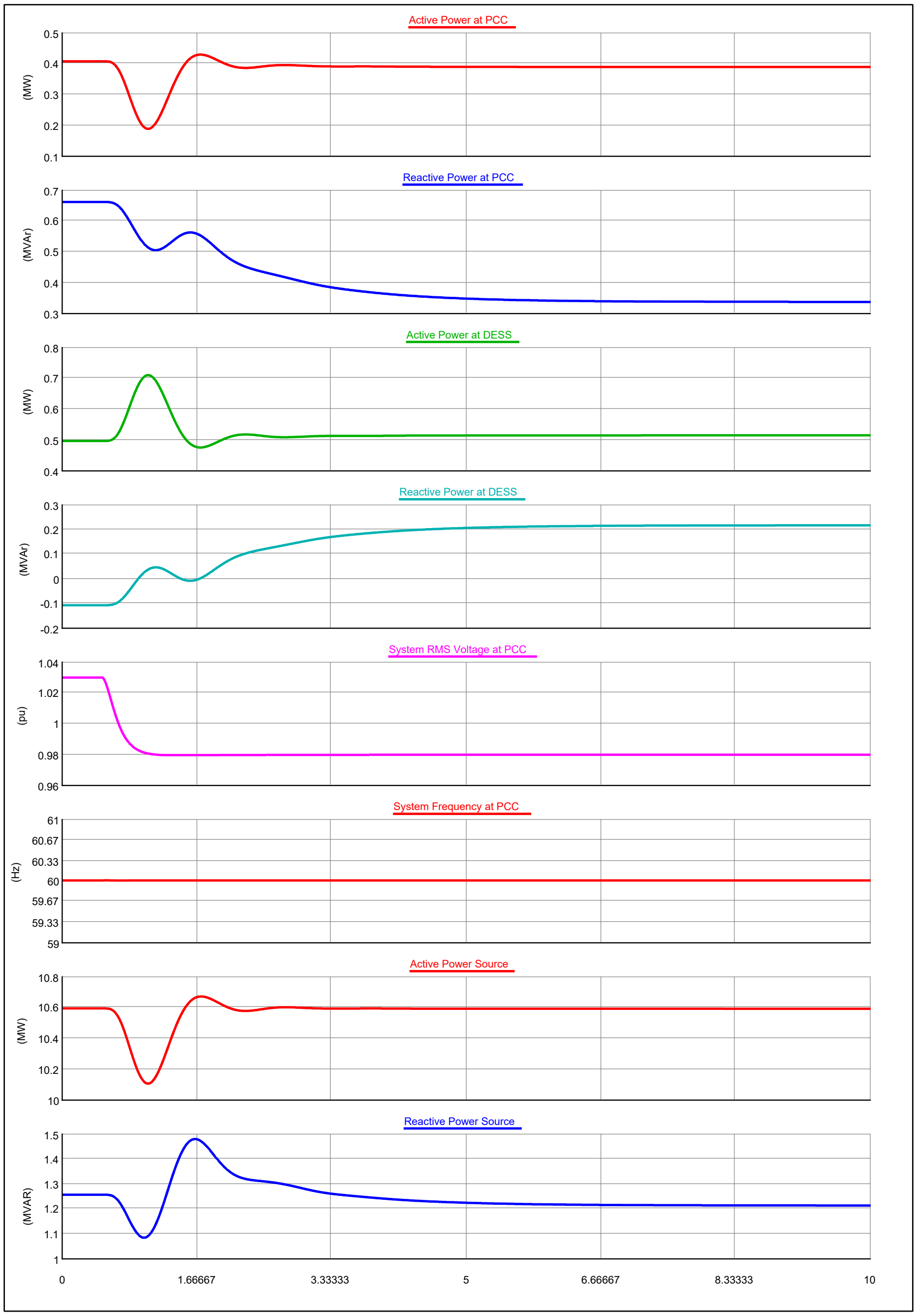

Figure A.27: System Response for Test 4.1.5

TEST 4.1.6 VARY THE SYSTEM VOLTAGE

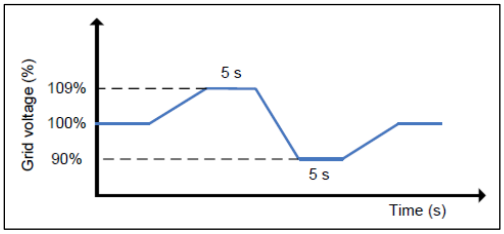

Figure A.28: System Voltage Profile for Test 4.1.6

The voltage profile at the PCC was varied, as shown in Figure A.28 . On increasing the voltage to 109 percent at a ramp rate of 0.02 volts per unit per second, the DER reactive power output decreased, while the reactive power import from the grid increased. The increase in voltage caused both system capacitors to turn off during the rising edge of the voltage. This decrease in the DER reactive power output, along with the turning off the capacitor, caused the source reactive power to increase. The active power at the DER and PCC changed minimally during this transition; however, it did not reach the steady-state value. Once the voltage reached 109 percent, it was held for 5 seconds. Then the voltage dropped from 109 percent to 90 percent, during which the reactive power output of the DER increased and the power import from the PCC reduced to maintain the node voltage constant. The reduction in voltage caused one of the capacitors near the end of the feeder to turn on, which supplemented the reactive power along with the DER results, resulting in the reduction of reactive power import from the source. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

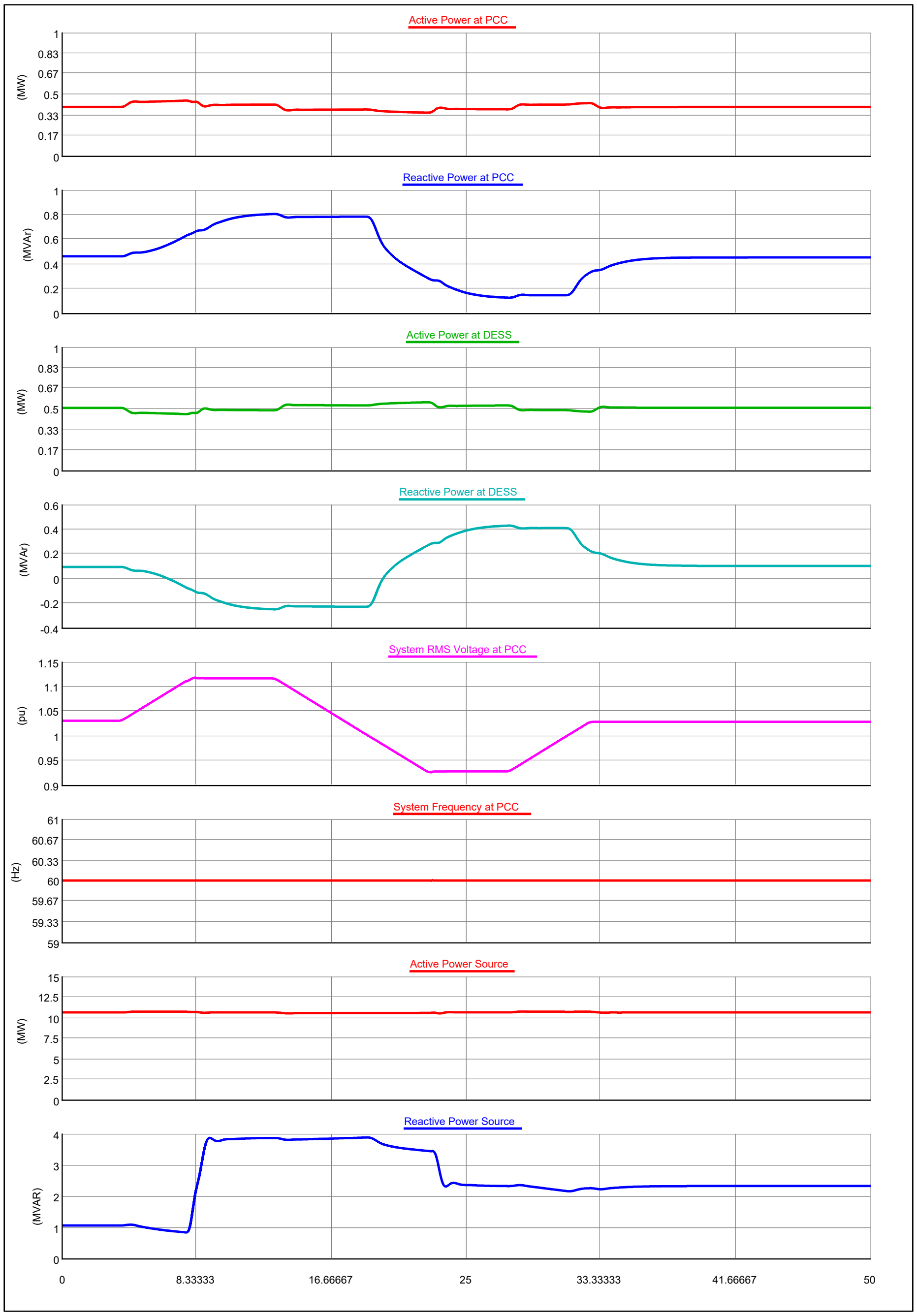

Figure A.29: System Response for Test 4.1.6

Test 4.1.7: Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.025 pu in steady state.

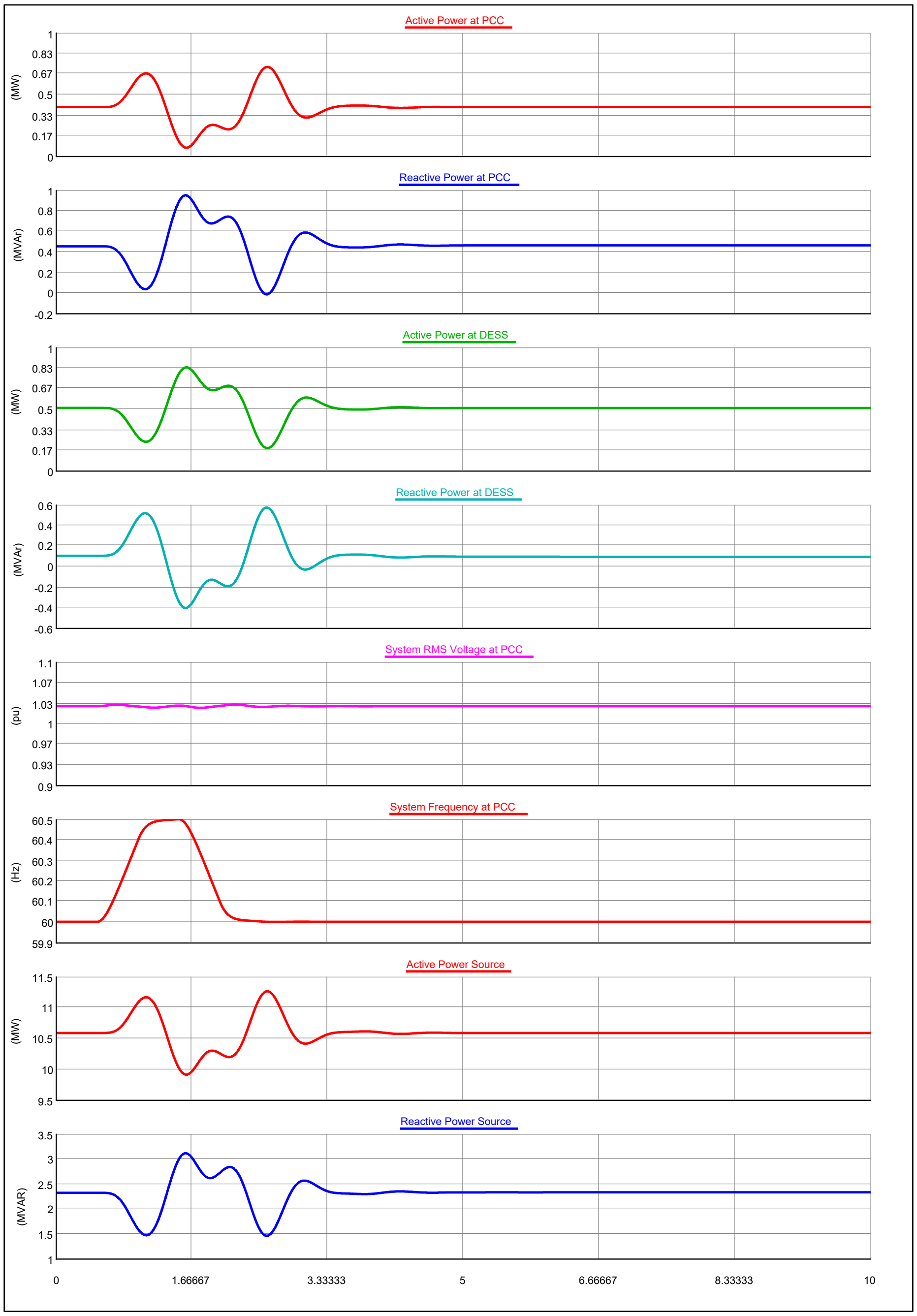

Figure A.30: System Response for Test 4.1.7

Test 4.1.8: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.025 pu in steady state.

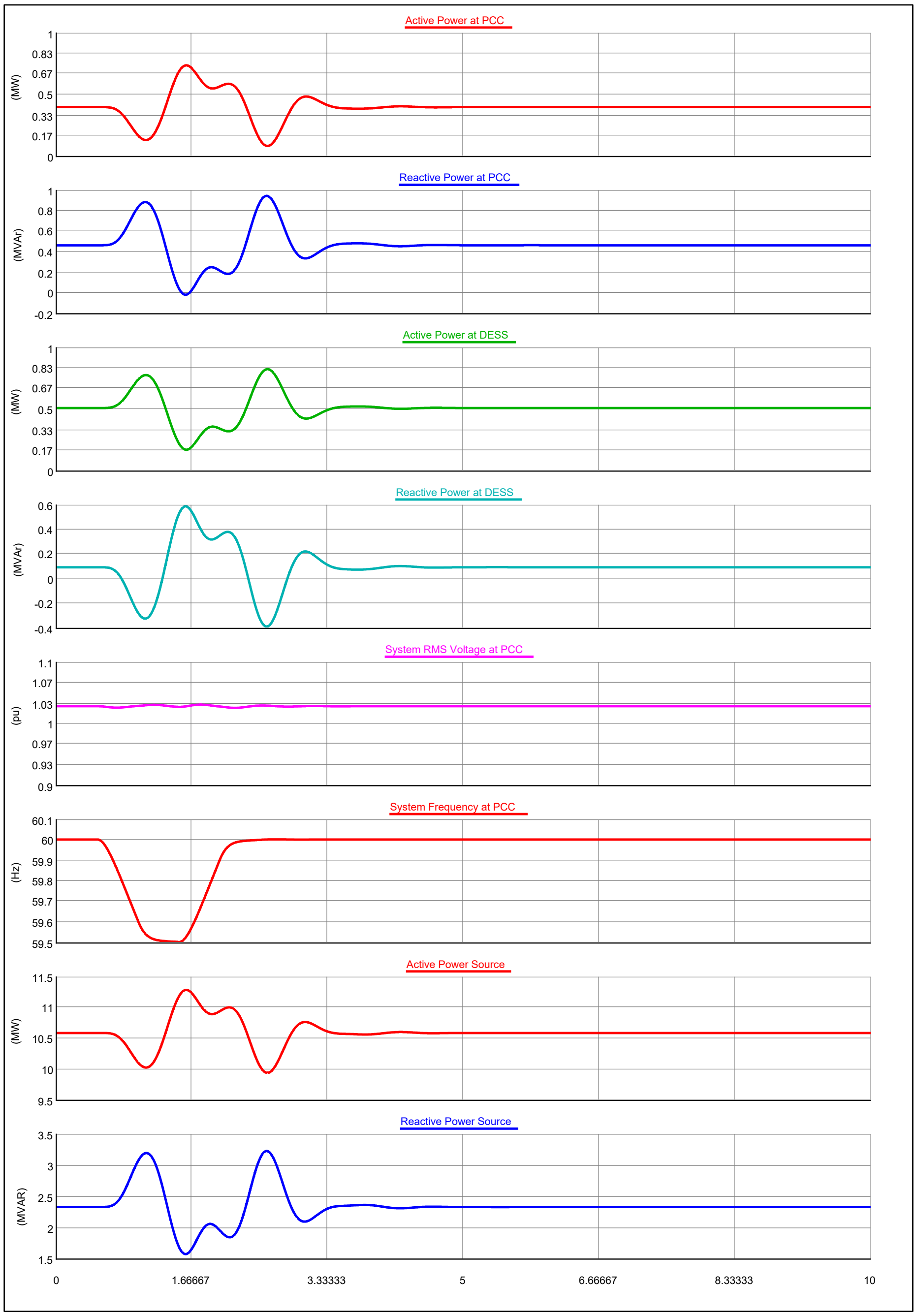

Figure A.31: System Response for Test 4.1.8

Scenario 2: DER on a Complex Circuit with a Multitude of Controllable Devices

TEST 4.2.1: MODE ACTIVATION WITH REACTIVE POWER SET POINT OF 200 KVAR

The initial set point of the DER was at 500 kW and 200 kVAR. The active and reactive power load were at 900 kW and 550 kVAR, respectively. When the mode was activated, the reactive power input of the DER dropped to 136 kVAR as the voltage at the PCC was greater than 1.018 pu; hence, the DER reduced its reactive power output to maintain the terminal voltage at the same value. The active power dispatch of the DER remained unaffected and therefore did not change across the PCC and the source. The system voltage and frequency did not change with the activation of the mode.

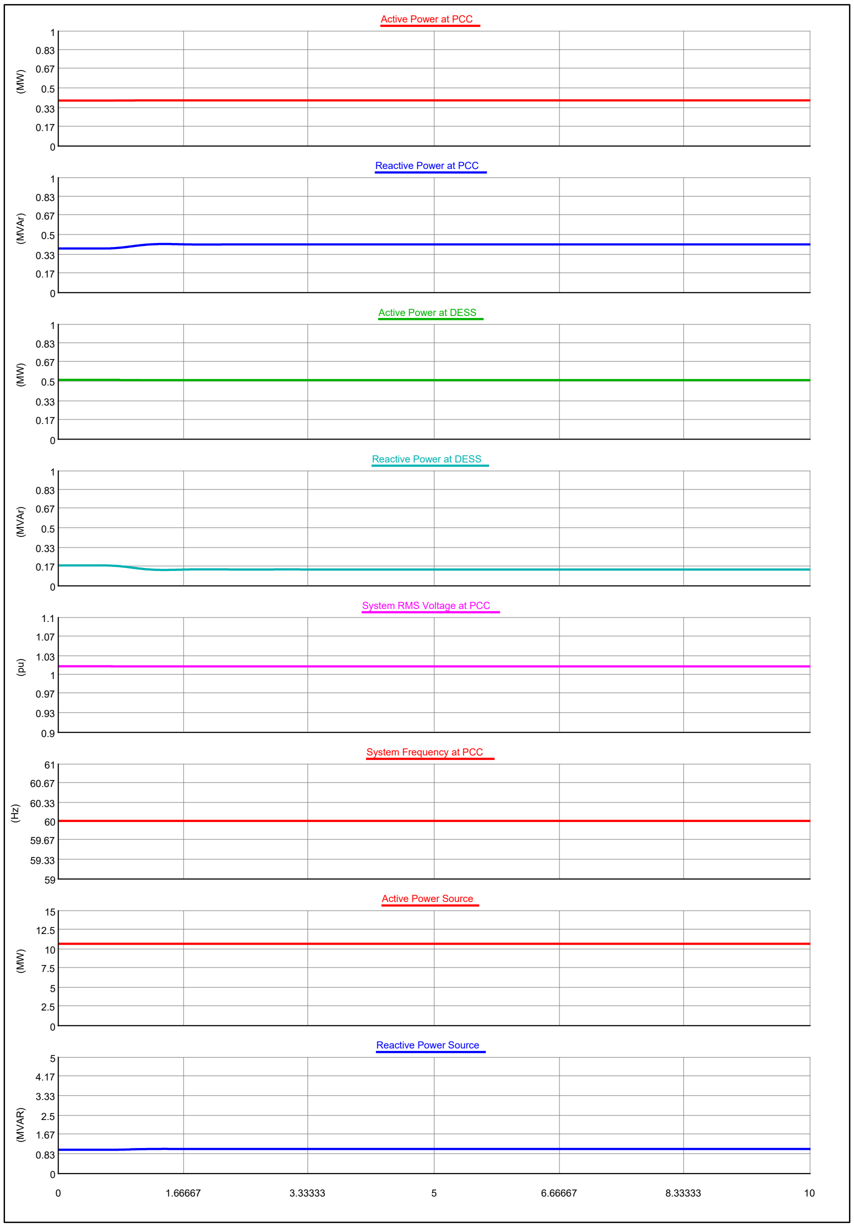

Figure A.32: System Response for Test 4.2.1

Test 4.2.2: Increase the System Load by 500 KVAR

On increasing the reactive power load by 500 kVAR to 1050 kVAR at the PCC, the reactive power at the DER remained unchanged at steady state because the reactive power set point at the DER was determined by the system voltage, which was not affected significantly during the load variation. The system voltage decreased minimally because of the inflow of the reactive power from the grid. The additional reactive power load was supported by the PCC to keep the node voltage constant. The frequency and the real power at the DER and PCC remained unaffected as well.

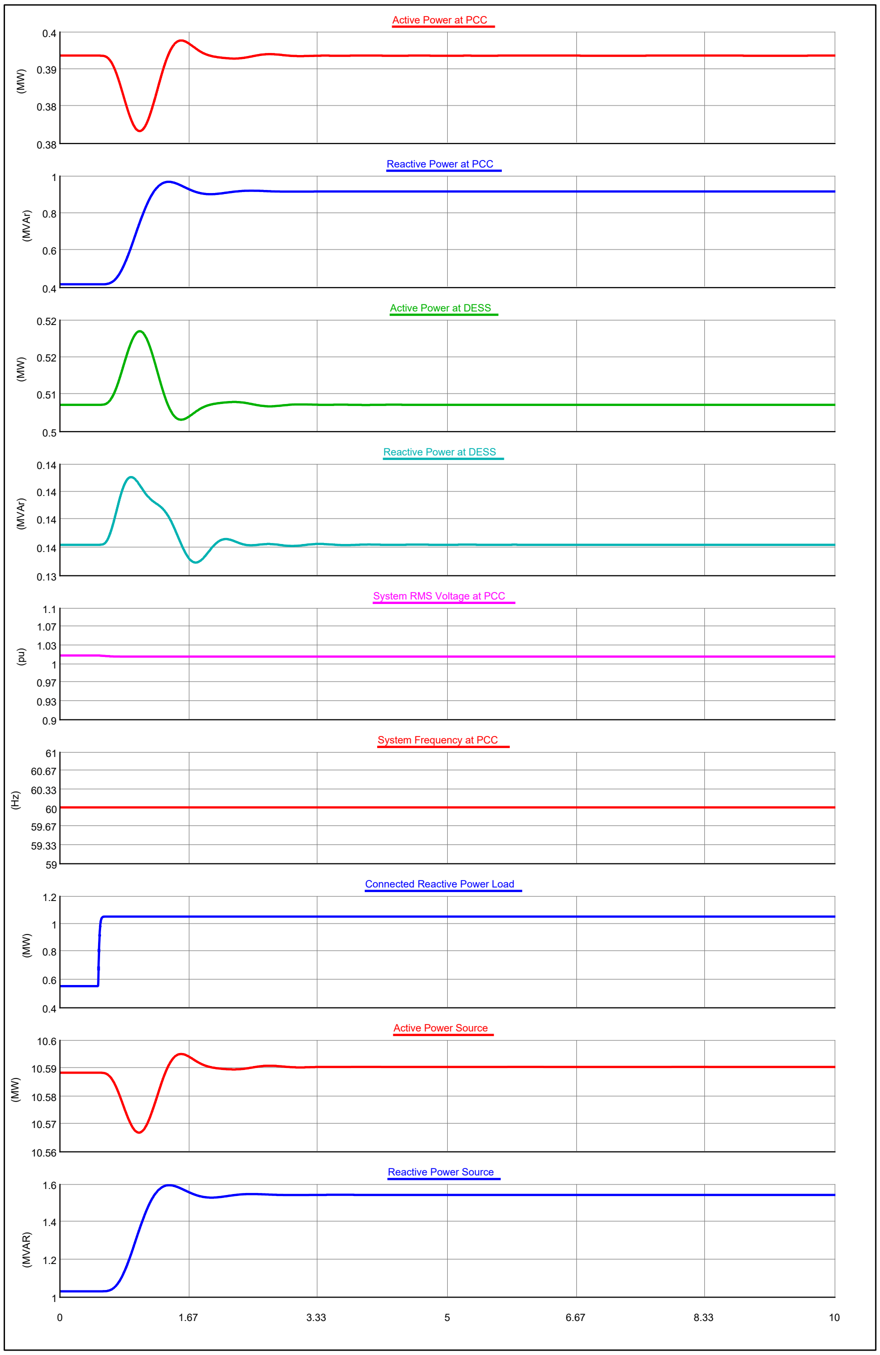

Figure A.33: System Response for Test 4.2.2

TEST 4.2.3: DECREASE THE SYSTEM LOAD BY 500 KVAR

On decreasing the reactive power, the load decreased from 550 kVAR to 50 kVAR. Like the observations from Test 4.2.2, the reactive power at the DER remained unaffected, while the grid drew power from the DER to maintain the load voltage at the PCC constant. The real power and frequency remained unaffected by the VAR changes, while the system voltage increased slightly because of the excess reactive power generated that was injected into the grid through the PCC.

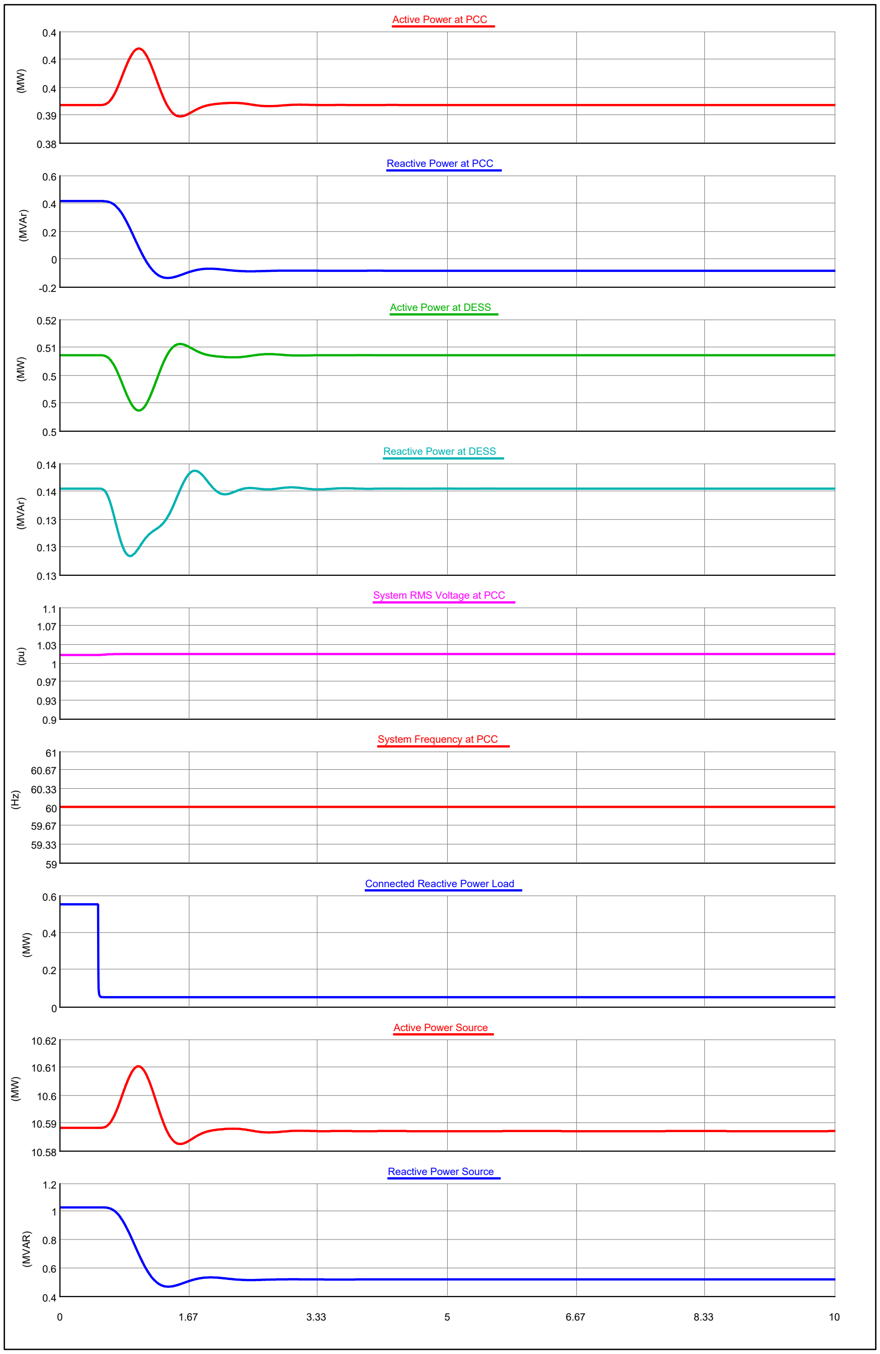

Figure A.34: System Response for Test 4.2.3

TEST 4.2.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 1.018 pu to 1.068 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected by the change.

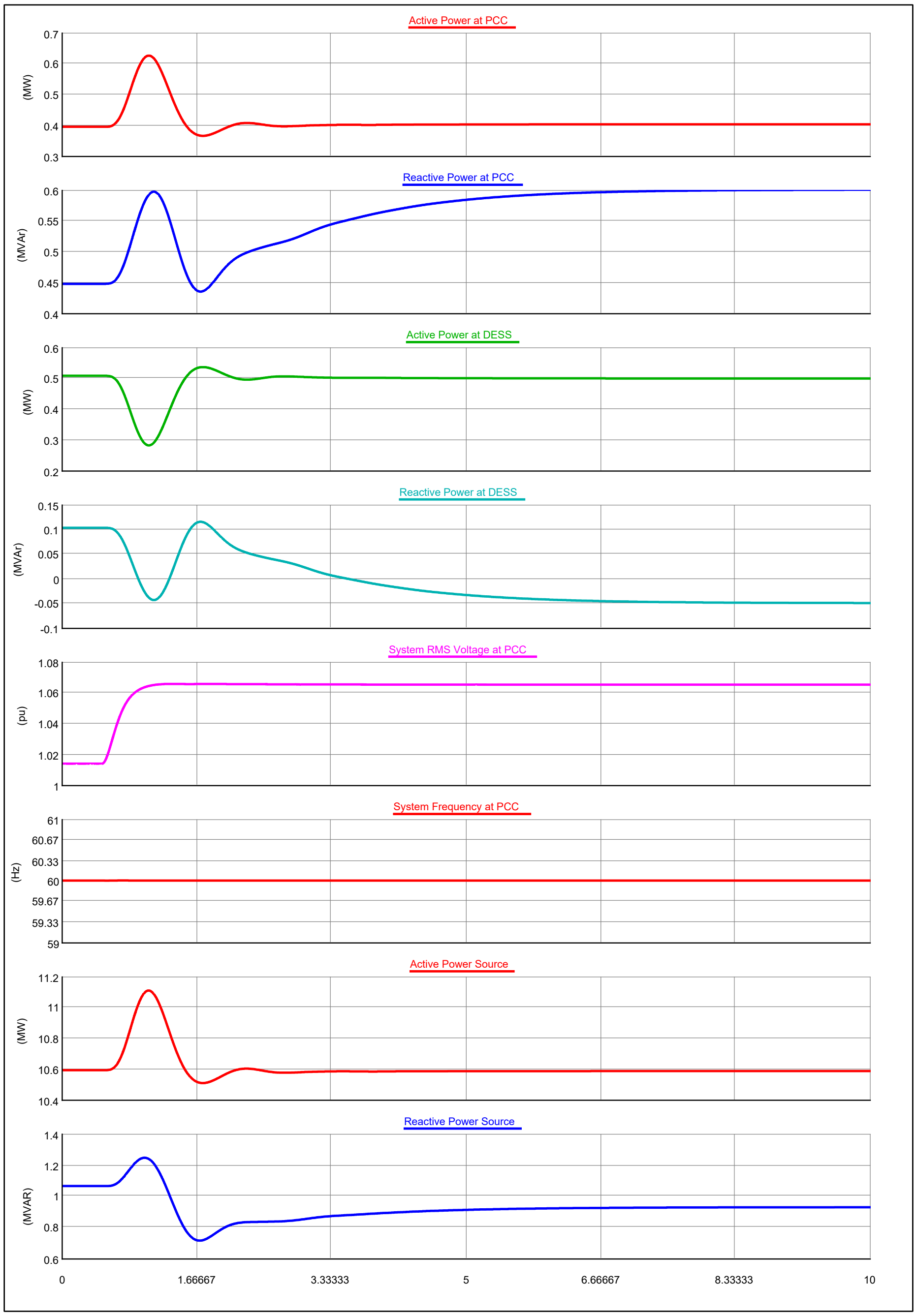

Figure A.35: System Response for Test 4.2.4

TEST 4.2.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 1.018 pu to 0.968 pu, the reactive power output of the DER increased and produced more reactive power to maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected by the change at steady state.

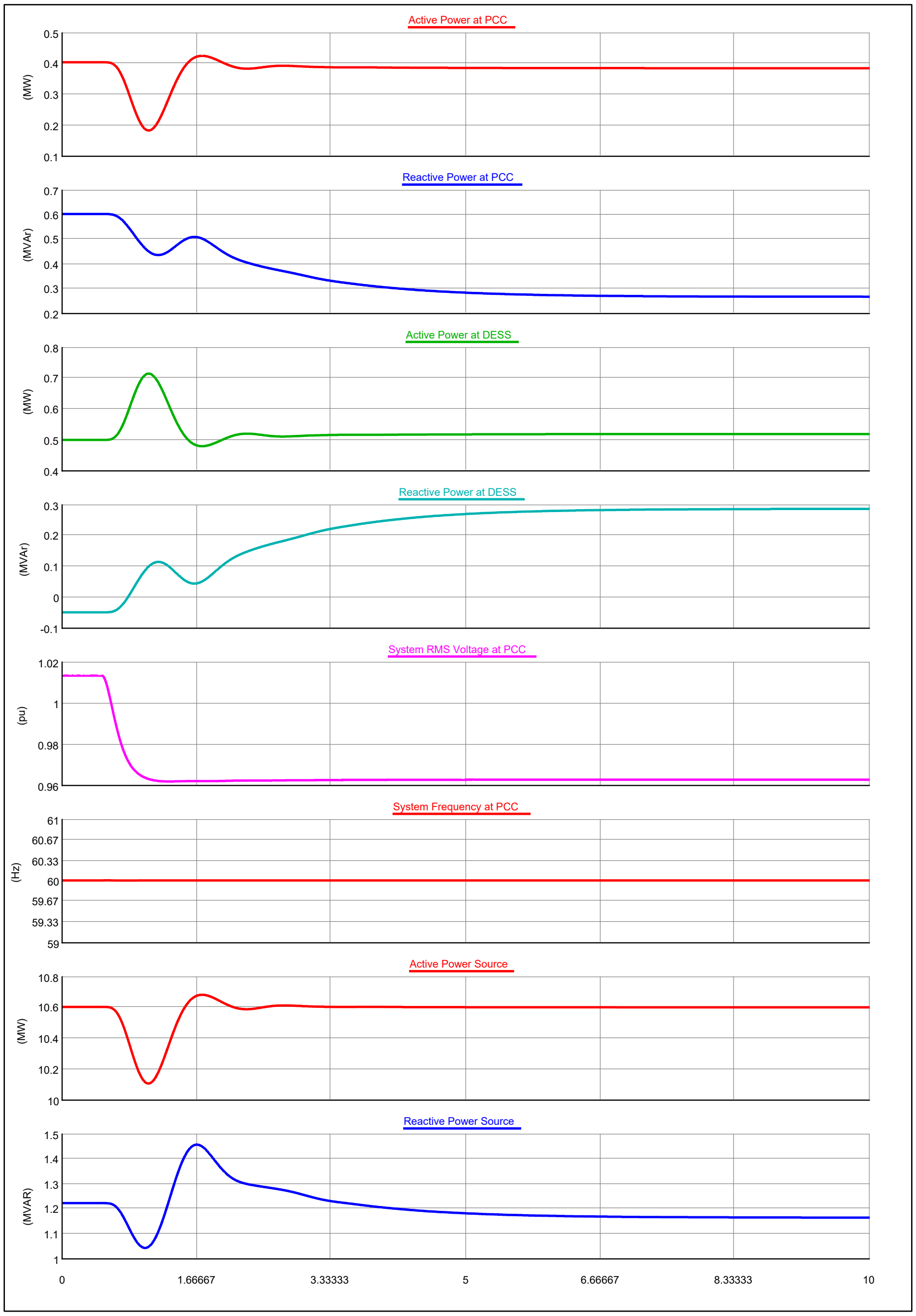

Figure A.36: System Response for Test 4.2.5

TEST 4.2.6: VARY THE SYSTEM VOLTAGE

The voltage profile at the PCC was varied, as shown in Figure A.28. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

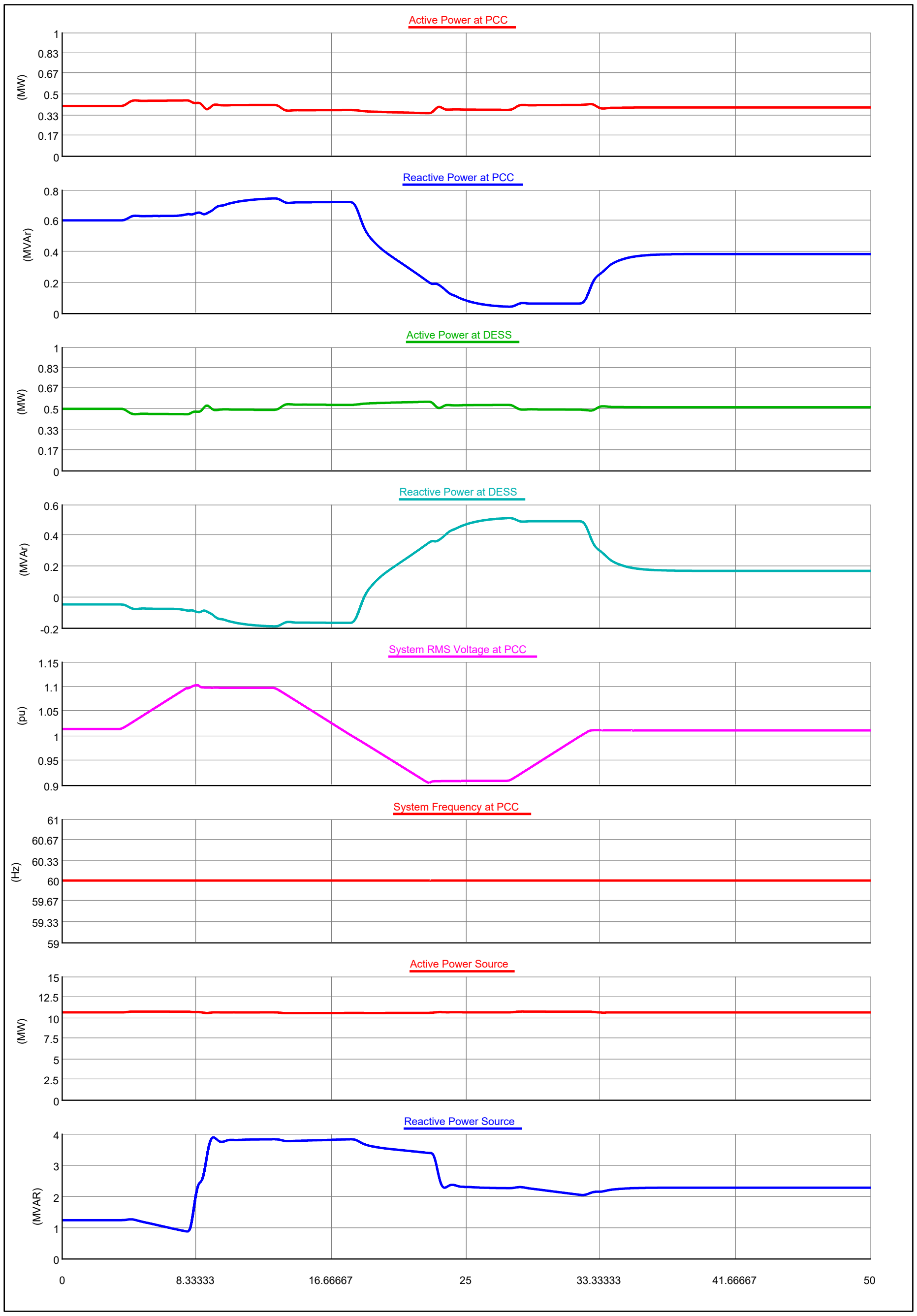

Figure A.37: System Response for Test 4.2.6

TEST 4.2.7: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to the power flow but settled back to 1.018 pu in steady state.

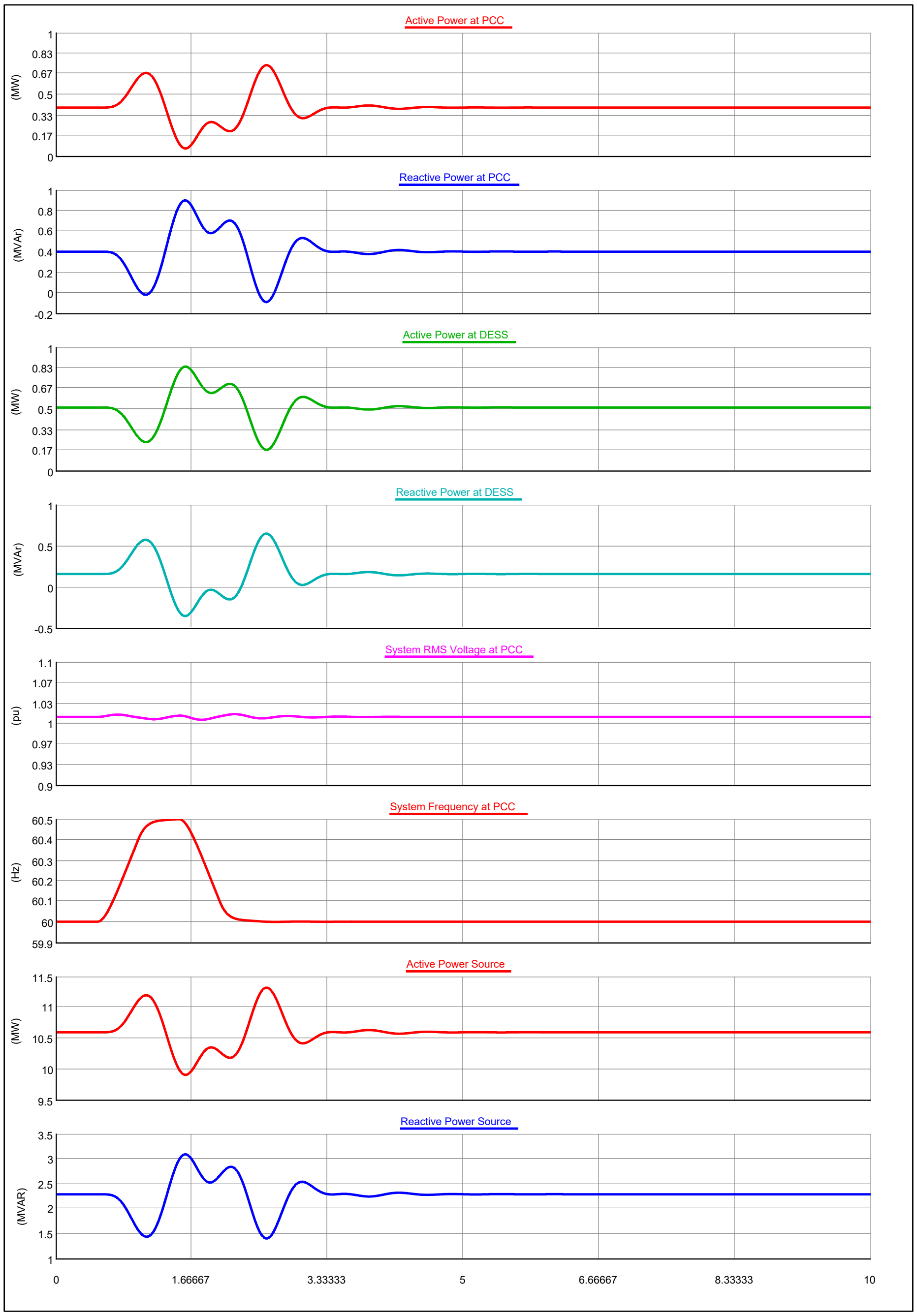

Figure A.38: System Response for Test 4.2.7

Test 4.2.8: Decrease the System Frequency by 0.5 Hz for 1 Second

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.018 pu in steady state.

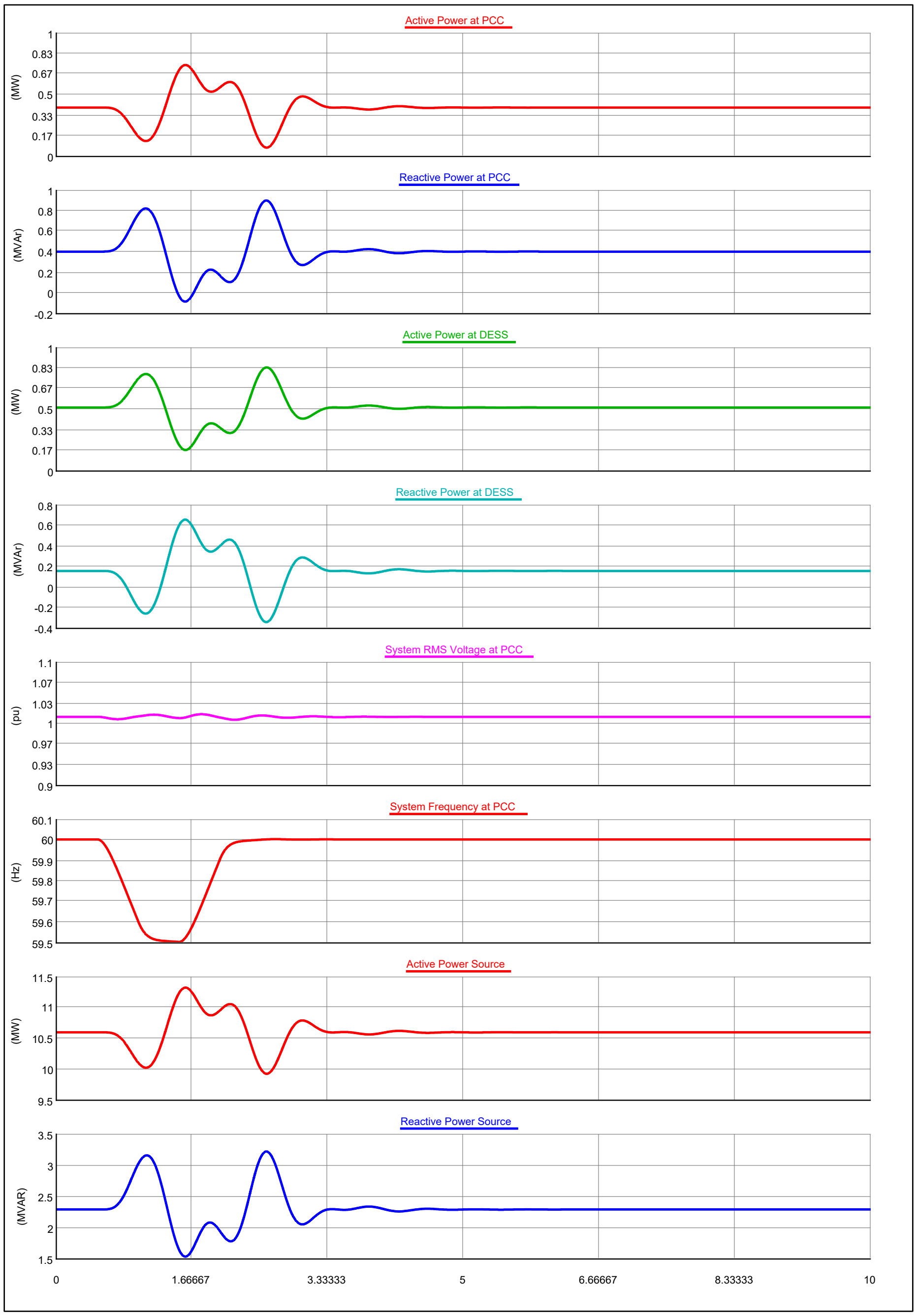

Figure A.39: System Response for Test 4.2.8

Scenario 3: DER at the End of a Long Feeder

TEST 4.3.1: MODE ACTIVATION WITH REACTIVE POWER SET POINT OF 200 KVAR

The initial set point of the DER was at 500 kW and 200 kVAR. The active and reactive power load were at 900 kW and 550 kVAR, respectively. When the mode was activated, the reactive power input of the DER did not change because the voltage at the PCC is at 1.002 pu, and therefore the DER maintained its reactive power output to maintain the terminal voltage at the same value. The active power dispatch of the DER remained unaffected, and hence it did not change across the PCC and the source. The system voltage and frequency did not change with the activation of the mode.

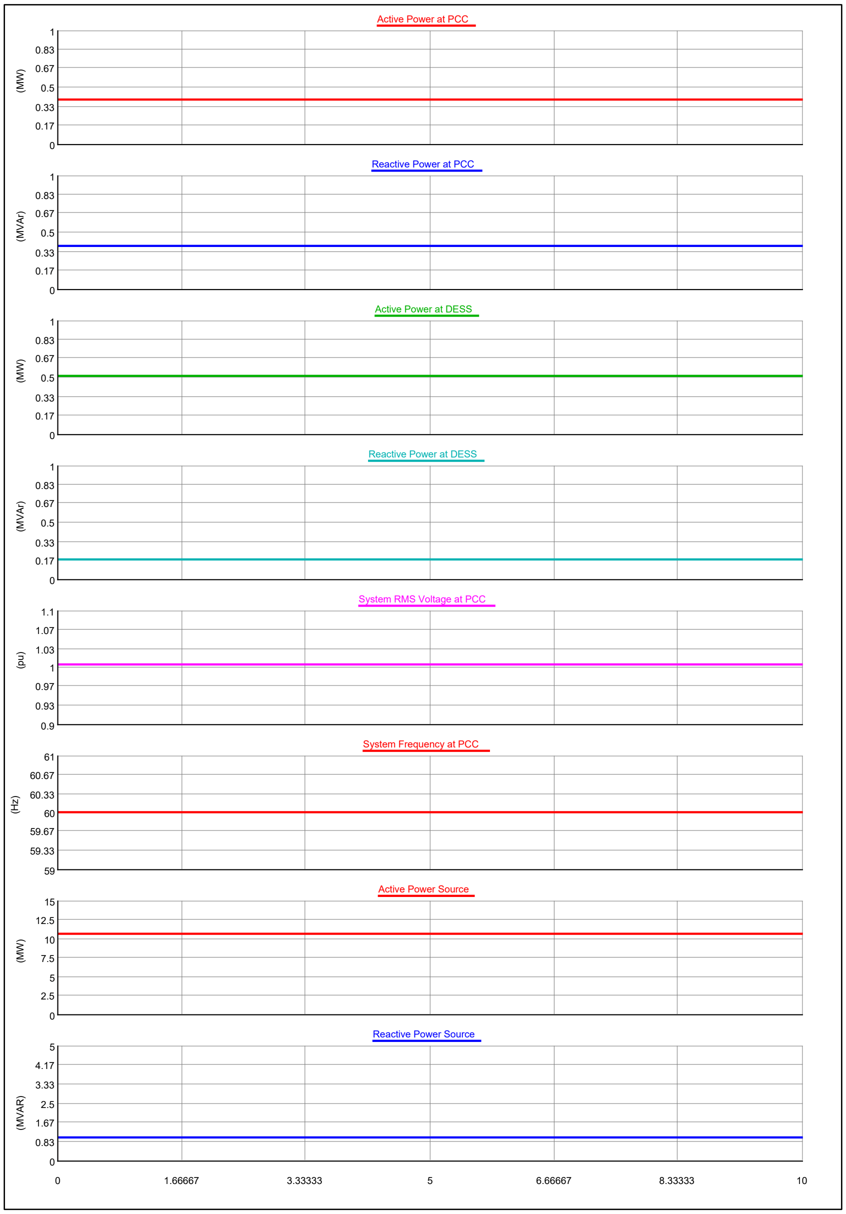

Figure A.40: System Response for Test 4.3.1

TEST 4.3.2: INCREASE THE SYSTEM LOAD BY 500 KVAR

On increasing the reactive power load by 500 kVAR to 1050 kVAR at the PCC, the reactive power at the DER remained unchanged at steady state because the reactive power set point at the DER was determined by the system voltage, which was not affected significantly during the load variation. The system voltage decreased minimally because of the inflow of the reactive power from the grid. The additional reactive power load was supported by the PCC to keep the node voltage constant. The frequency and the real power at the DER and PCC remained unaffected as well.

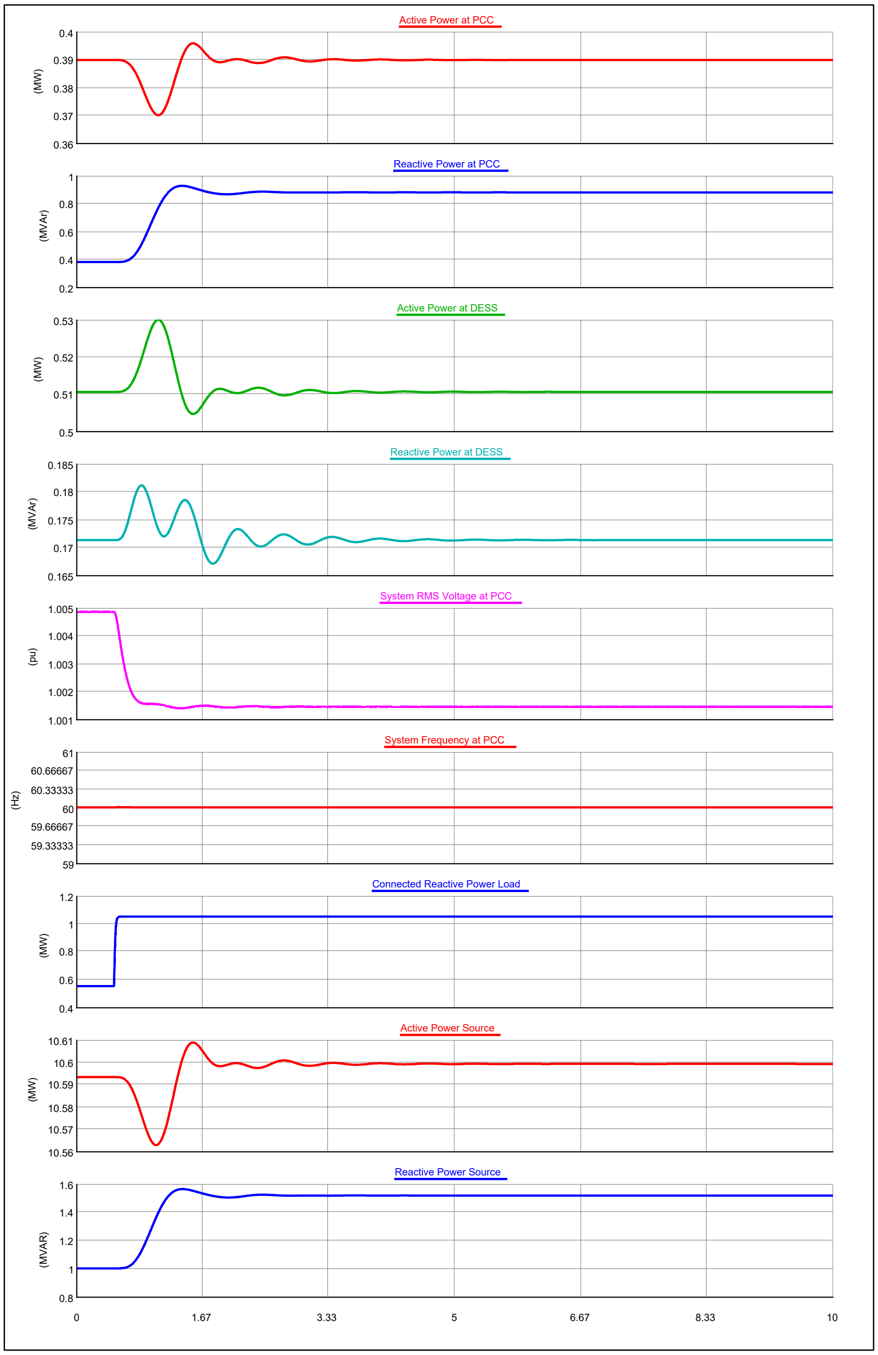

Figure A.41: System Response for Test 4.3.2

TEST 4.3.3: DECREASE THE SYSTEM LOAD BY 500 KVAR

On decreasing the reactive power, the load decreased from 550 kVAR to 50 kVAR. Like the observations from Test 4.3.2, the reactive power at the DER remained unaffected, while the grid drew power from the DER to maintain the load voltage at the PCC constant. The real power and frequency remained unaffected by the VAR changes, while the system voltage increased slightly because of the excess reactive power being generated that was injected into the grid through the PCC.

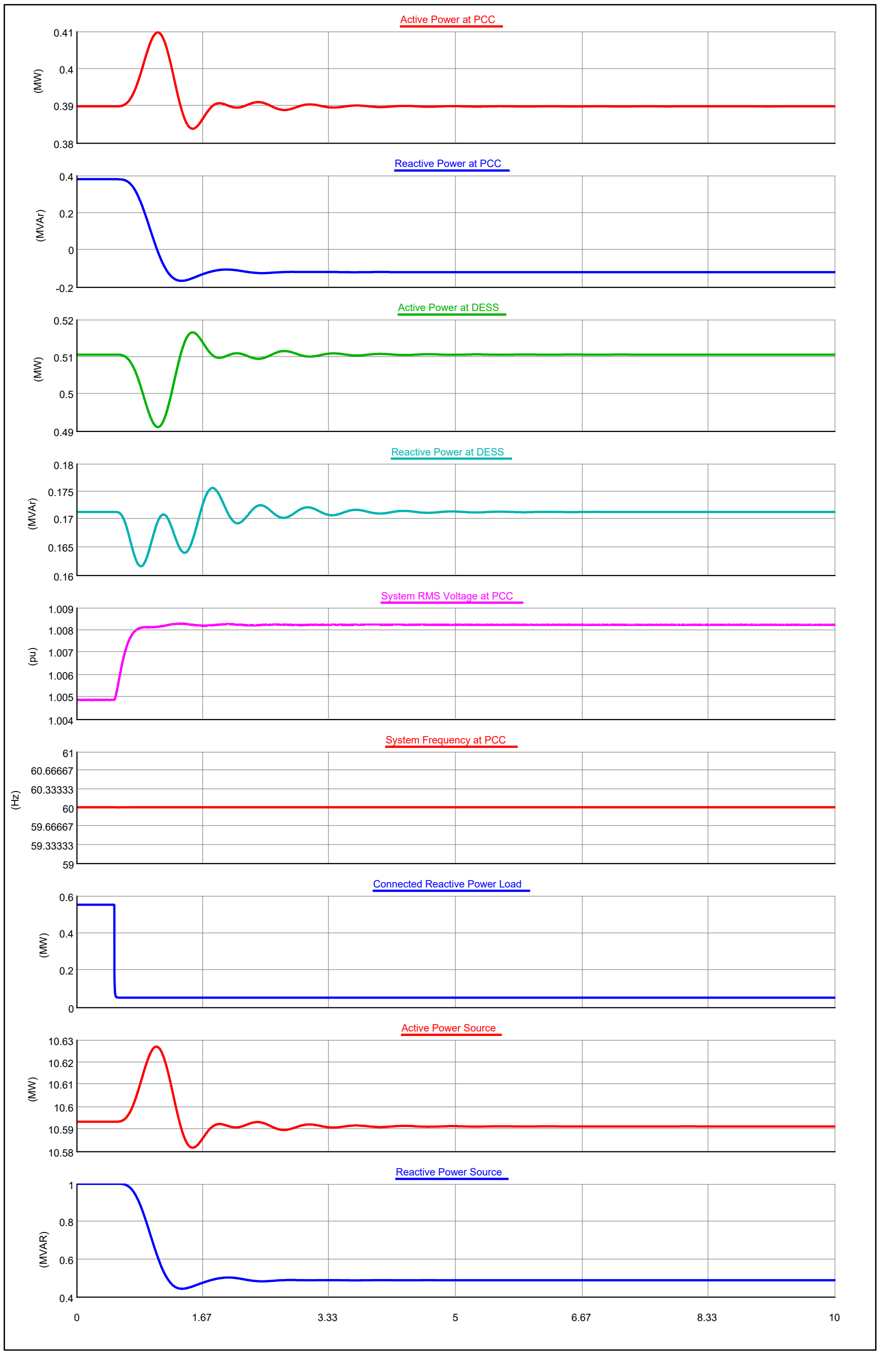

Figure A.42: System Response for Test 4.3.3

TEST 4.3.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage at the PCC from 1.002 pu to 1.052 pu, the reactive power output of the DER decreased and drew more reactive power from the grid through the PCC to maintain the node voltage at the PCC constant. The frequency and real power at the PCC and DER remained unaffected by the change.

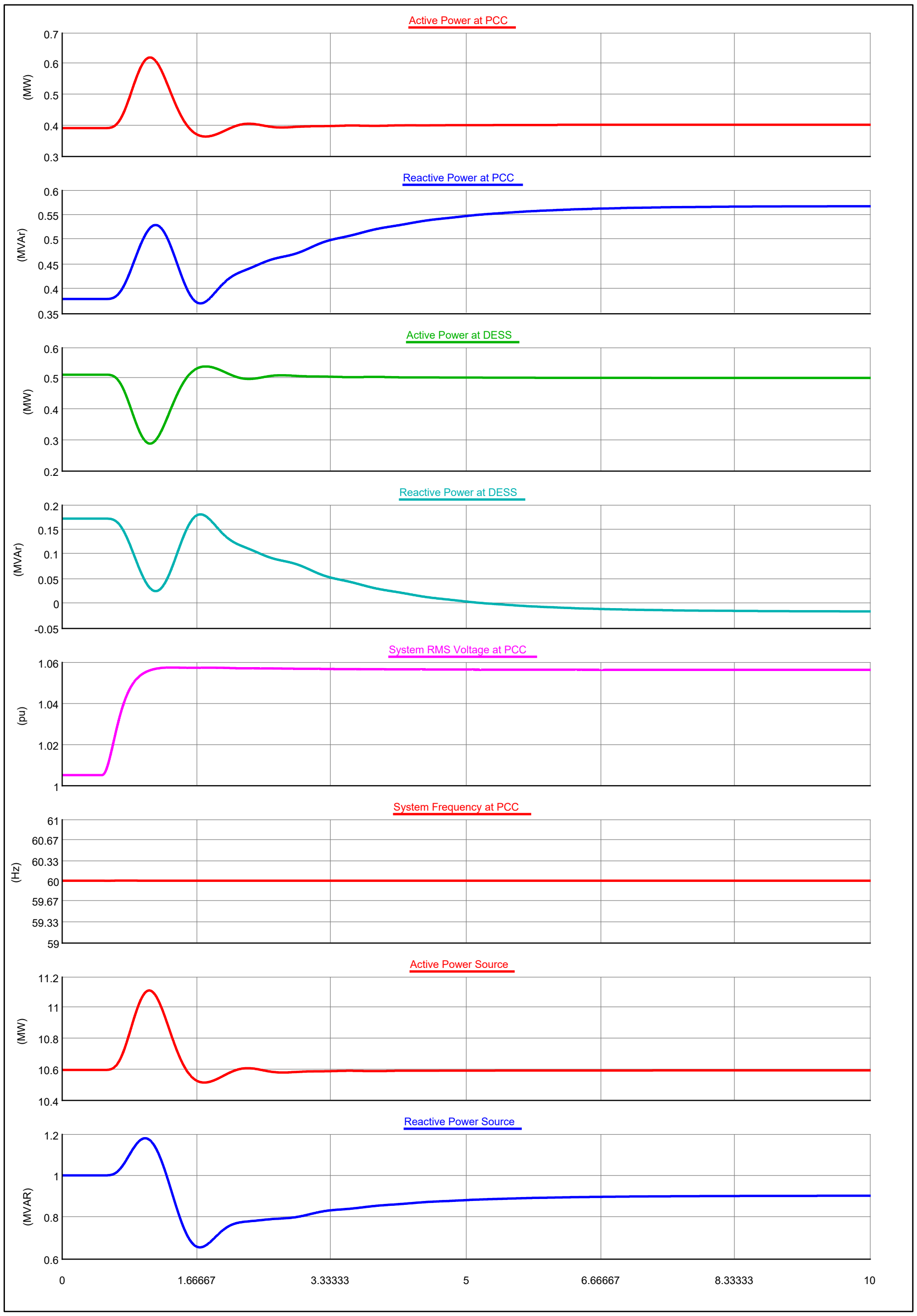

Figure A.43: System Response for Test 4.3.4

TEST 4.3.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage at the PCC from 1.002 pu to 0.952 pu, the reactive power output of the DER increased and produced more reactive power maintain the node voltage at the PCC constant. The frequency and the real power at the PCC and DER remained unaffected by the change at steady state.

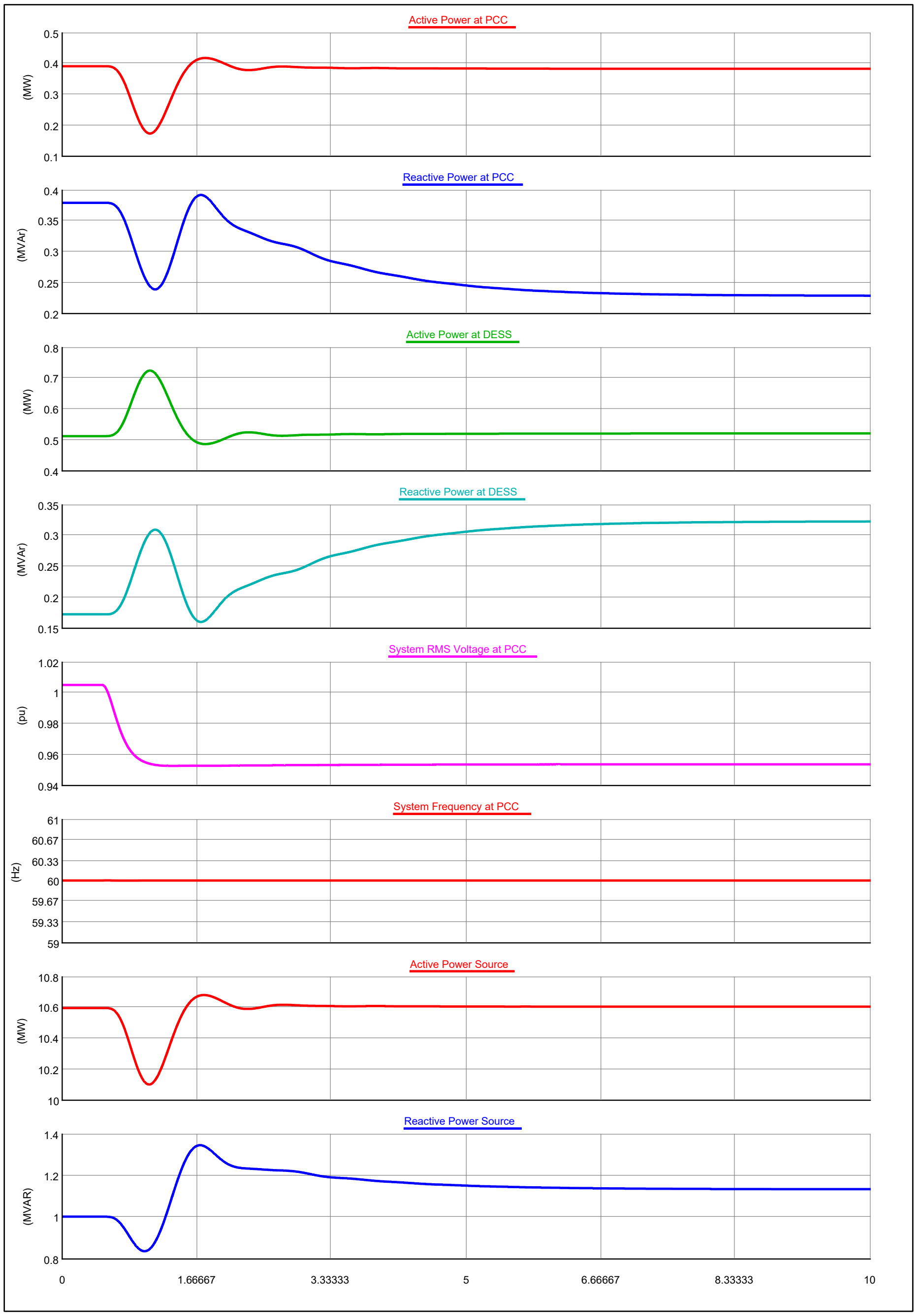

Figure A.44: System Response for Test 4.3.5

TEST 4.3.6: VARY THE SYSTEM VOLTAGE

The voltage profile at the PCC was varied, as shown in Figure A.28. The real power and reactive power at the DER and PCC settled at its prior set point post the transition in the voltage. The system frequency remained unaffected by the change in voltage.

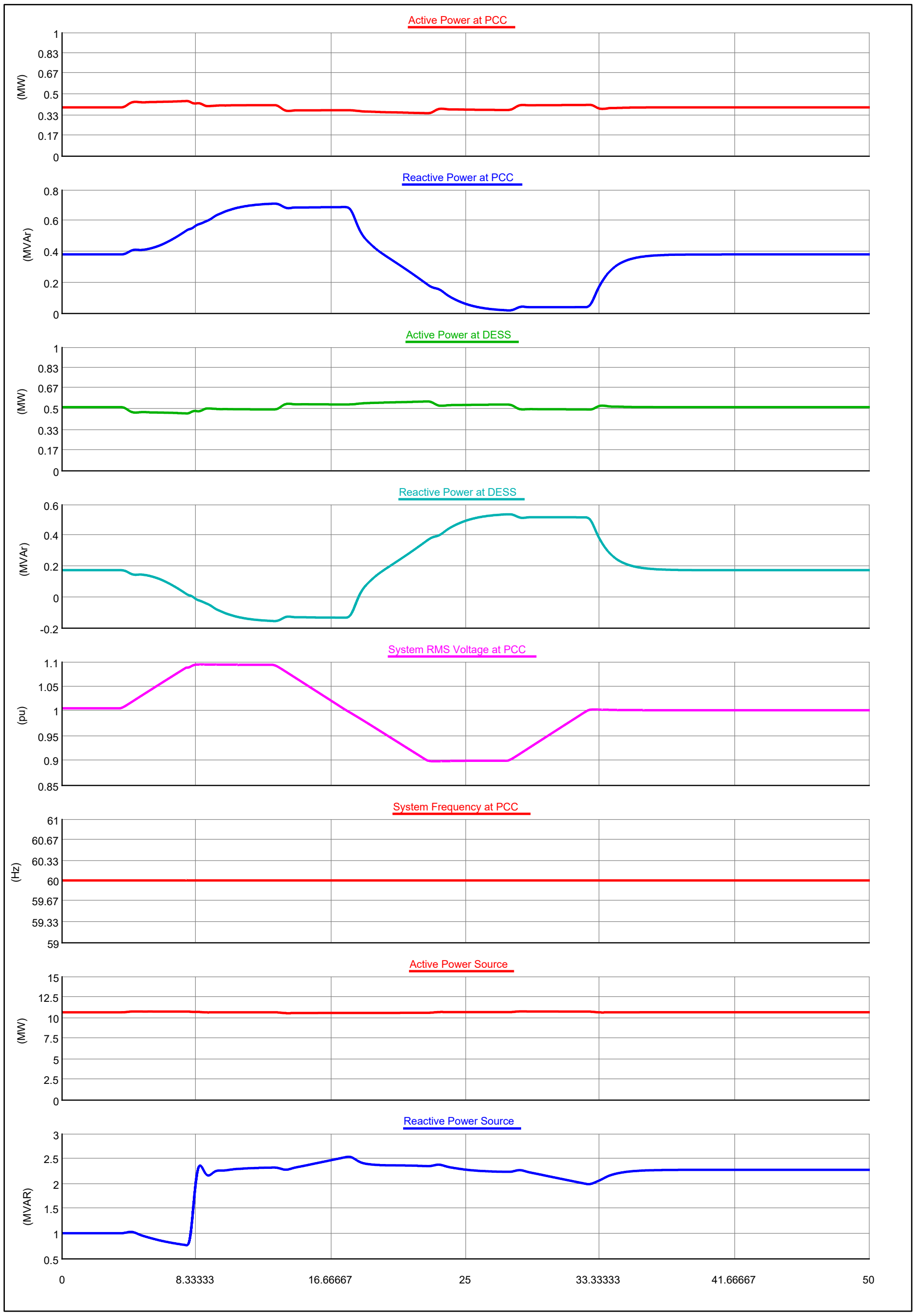

Figure A.45: System Response for Test 4.3.6

TEST 4.3.7: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode; hence, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

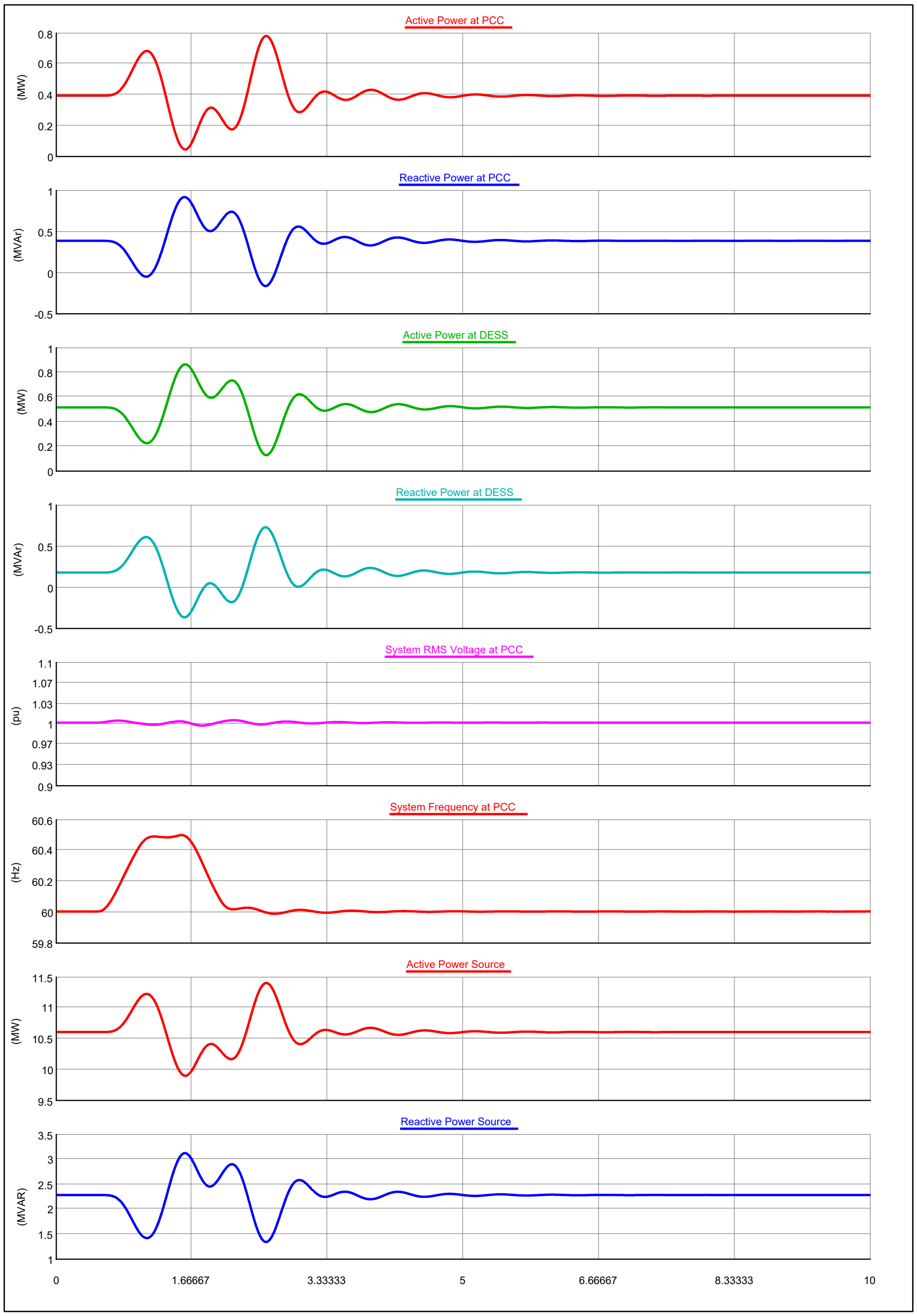

Figure A.46: System Response for Test 4.3.7

TEST 4.3.8: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER, in this mode, reacted to the change, rode through, and returned to steady state. The real and reactive power flow at the PCC and DER settled at their previous set points. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

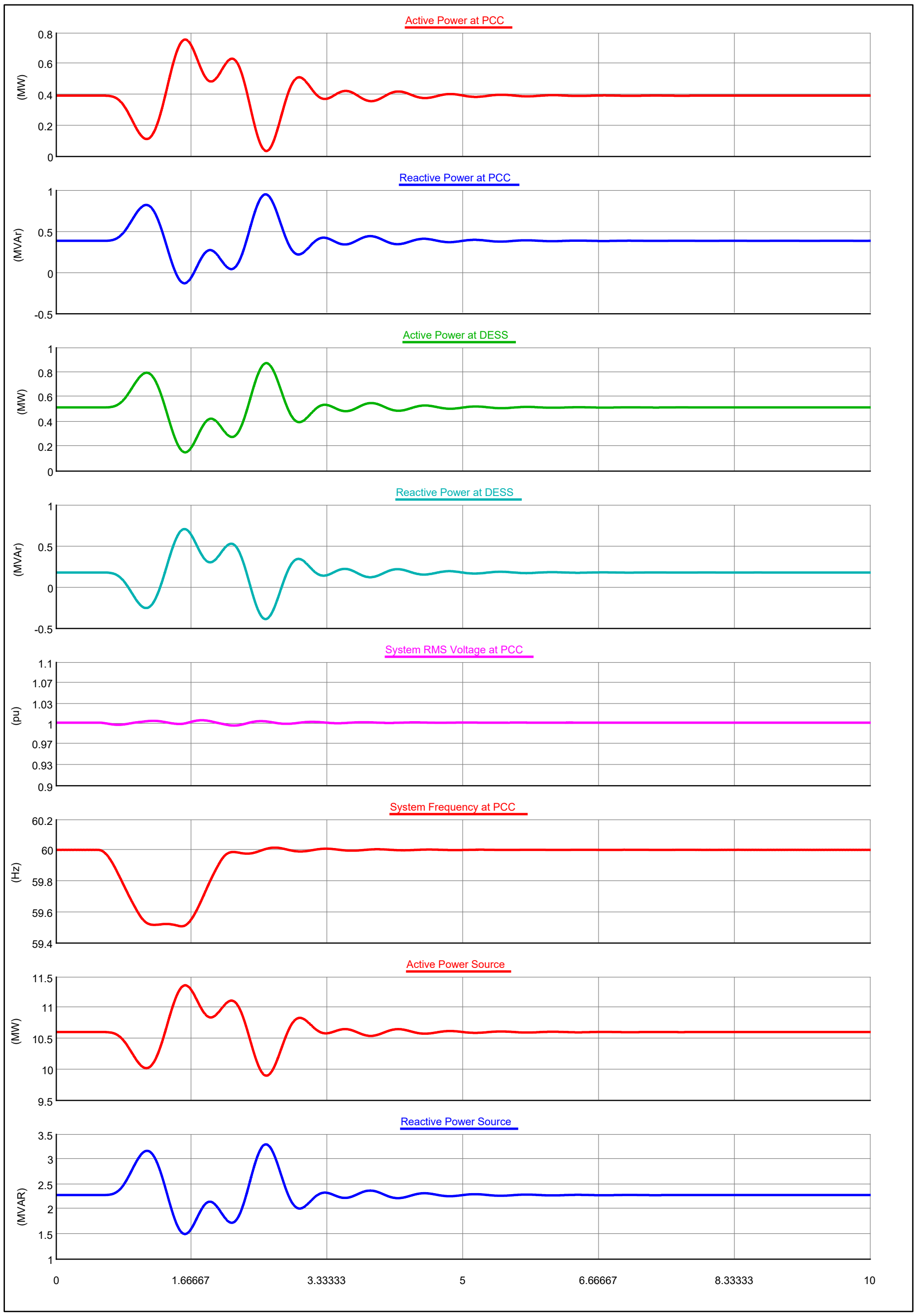

Figure A.47: System Response for Test 4.3.8

TEST 5 – FREQUENCY-WATT

This function is intended to provide a mechanism through which a DER may be configured to manage its own active power output in response to the fluctuations in the system frequency. This function involves the dynamic production of active power to resist variations in the system frequency.

The objective is to counter any changes in the frequency by varying the output power. When the DER is in frequency-watt mode, it attempts to maintain the frequency of the system to 60 Hz by regulating active power.

The procedure for testing was as follows:

Step 1. Vary the system frequency beyond the nominal values in a stepped and/or transient manner to observe the behavior of the DER (the DER should respond in such a way that the system frequency is maintained within the nominal values).

Step 2. Change the system frequency by changing the load in steps or by changing the grid frequency (when the DER is put into frequency-watt mode, the system frequency should revert in to the nominal band because of the DER active power regulation).

Compare the results with the baseline case and develop the conclusions based on these findings.

Table A.3 lists the tests that will be conducted.

Table A.3: DER Frequency-Watt Test Cases

Test	Test Description	Expected Response
Test 5. x.1	Mode activation with active power set point of 500 kW	DER dispatches 500kW at steady state
Test 5. x.2	Increase the system load by 500 kW	DER dispatches 500kW at steady state
Test 5. x.3	Decrease the system load by 500 kW	DER dispatches 500kW at steady state
Test 5. x.4	Increase the system voltage by 5%	DER dispatches 500kW at steady state
Test 5. x.5	Decrease the system voltage by 5%	DER dispatches 500kW at steady state
Test 5. x.6	Increase the system frequency by 0.5 Hz for 1 s	DER decreases active power output to offset frequency increase. DER dispatches 500kW at steady state.
Test 5. x.7	Decrease the system frequency by 0.5 Hz for 1 s	DER increases active power output to offset frequency decrease. DER dispatches 500kW at steady state
Test 5. x.8	a) Ramp up the system frequency to 60.5 Hz at the rate of 0.1 Hz per second, and hold it for 5 s b) Ramp down the system frequency to 59.7 Hz at the rate of 0.1 Hz per second, and hold it for 5 s)	DER decreases its active power output to offset frequency increases and following that DER increases its active power output to offset frequency decrease. DER settles back at 500kW at steady state.
Test 5. x.9	Increase the system frequency by 0.5 Hz for 5 s	DER decreases active power output to offset frequency increase
Test 5. x.10	Decrease the system frequency by 0.5 Hz for 5 s	DER increases active power output to offset frequency decrease

Note: "x" denotes the scenario under test.

Scenario 2: DER on a Complex Circuit with a Multitude of Controllable Devices

TEST 5.2.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The active and reactive power dispatch of the DER were set at 500 kW and 200 kVAR, respectively. On activating the frequency-watt mode, there was no change on the graph because the system frequency is maintained at 60 Hz.

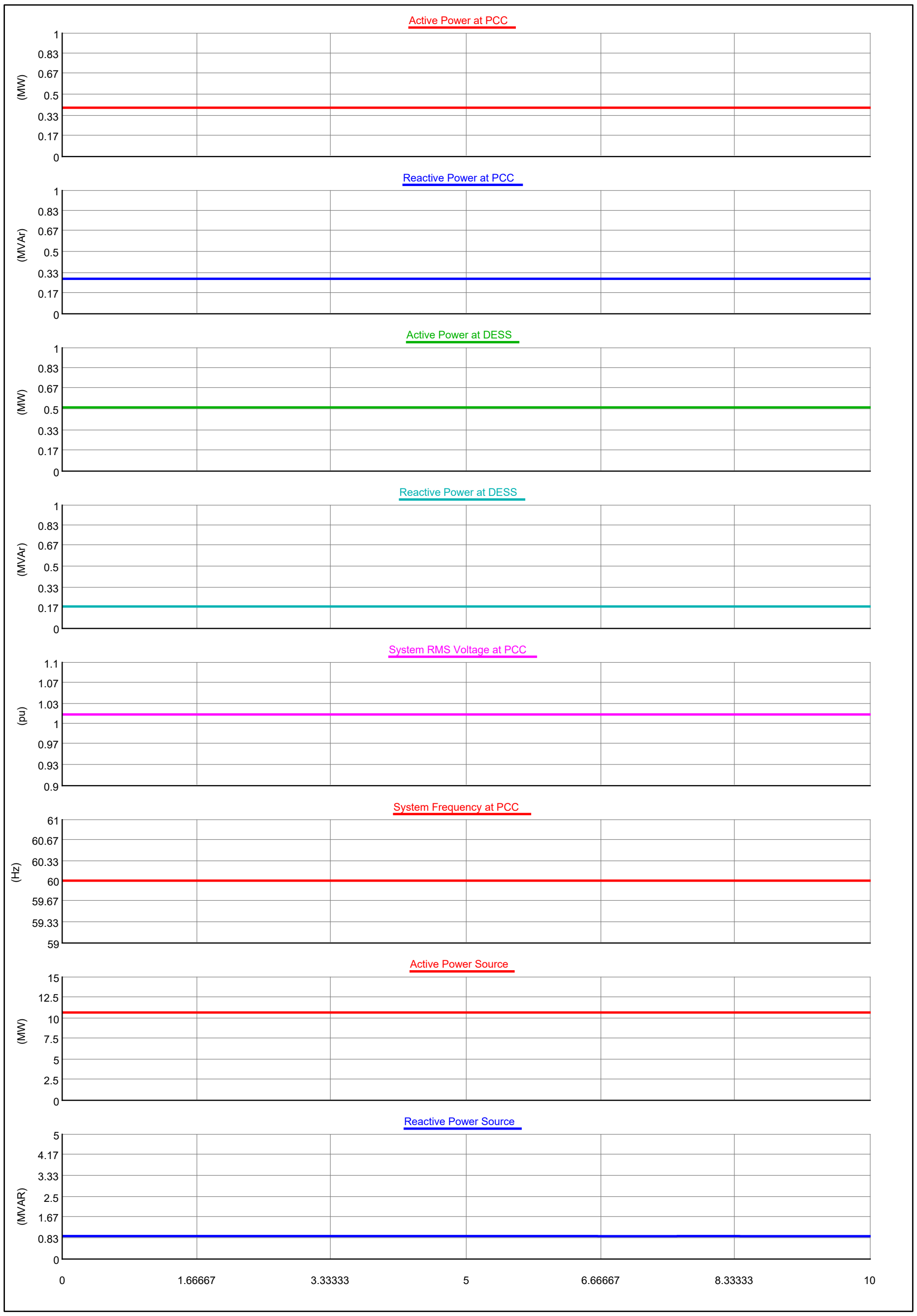

Figure A.48: System Response for Test 5.2.1

TEST 5.2.2 INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power output of the DER remained constant at 500 kW, while the additional load was fed by the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

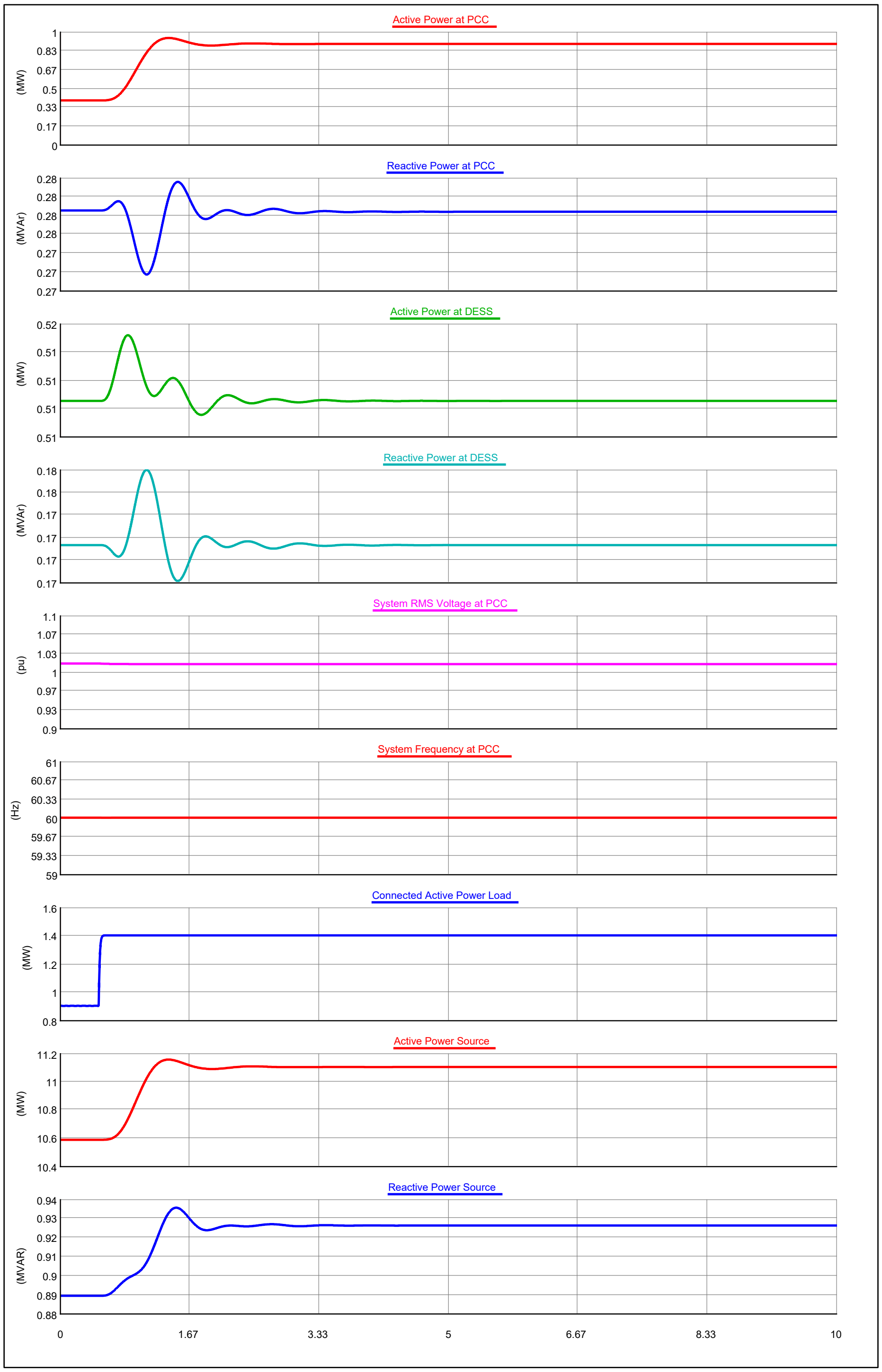

Figure A.49: System Response for Test 5.2.2

TEST 5.2.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power output of the DER remains constant at 500 kW, while the load is balanced by sending more active power into the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

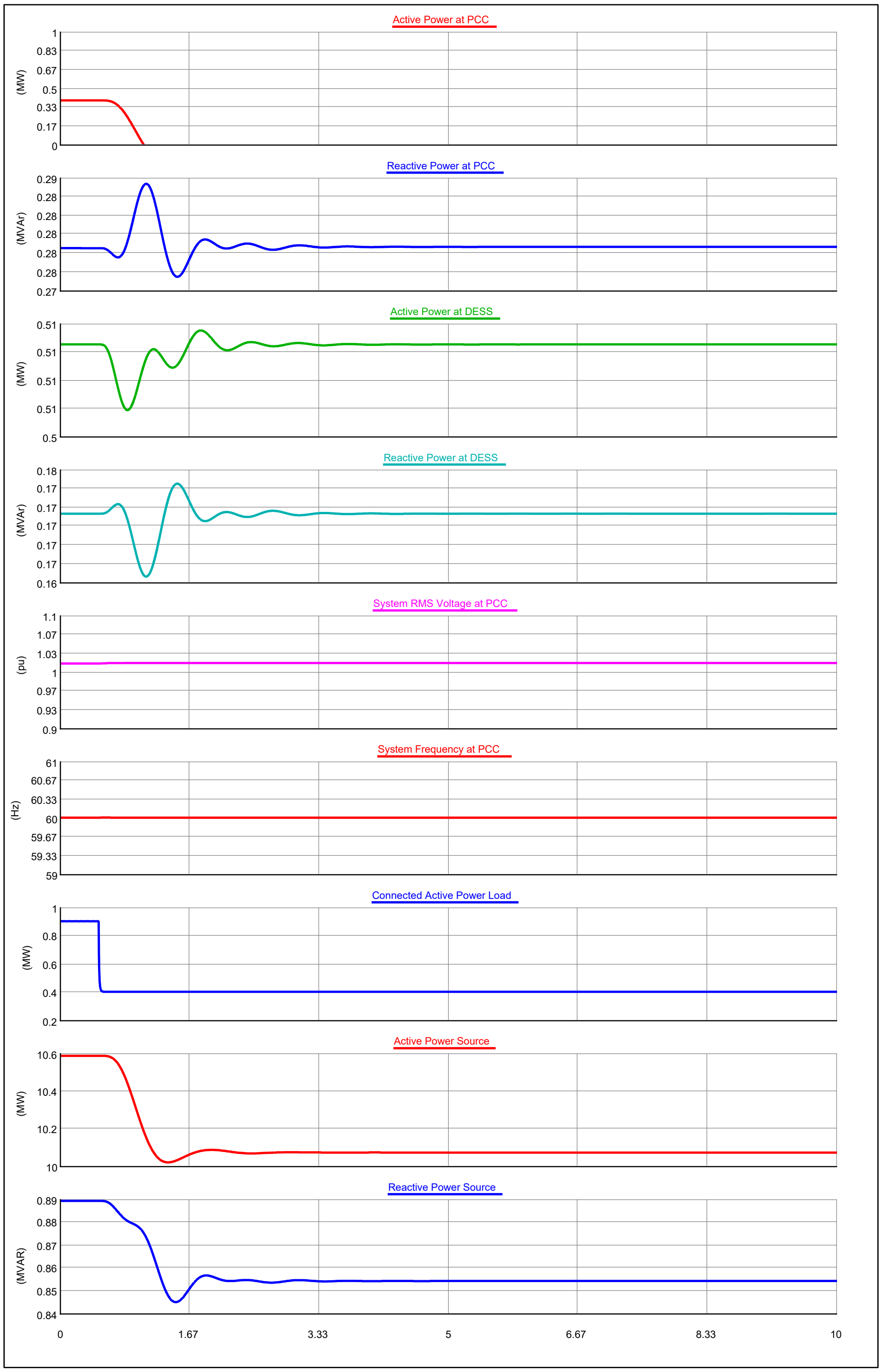

Figure A.50: System Response for Test 5.2.3

TEST 5.2.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage by 5 percent from 1.018 pu to 0.968 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

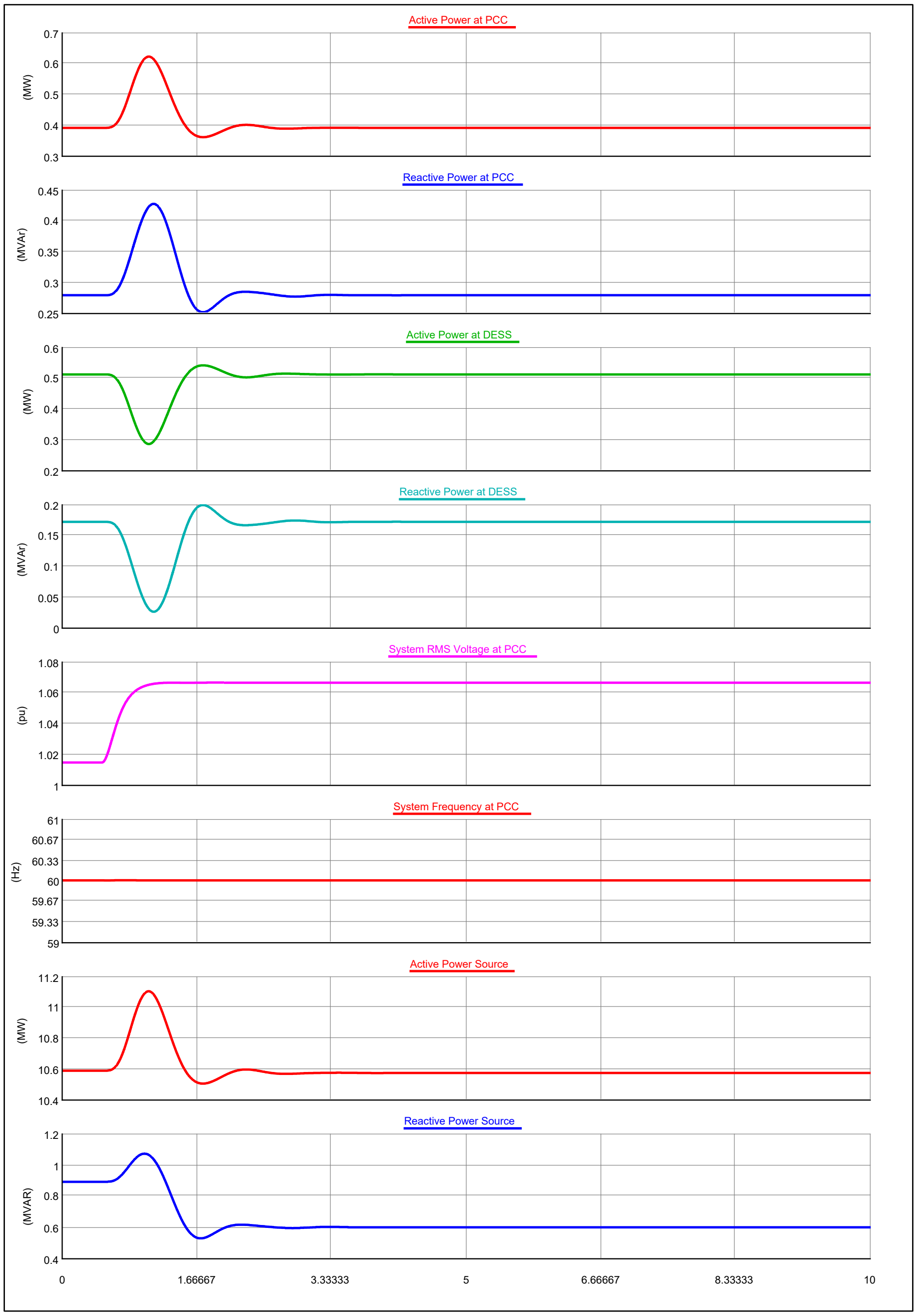

Figure A.51: System Response for Test 5.2.4

TEST 5.2.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage by 5 percent from 1.01 pu to 0.96 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

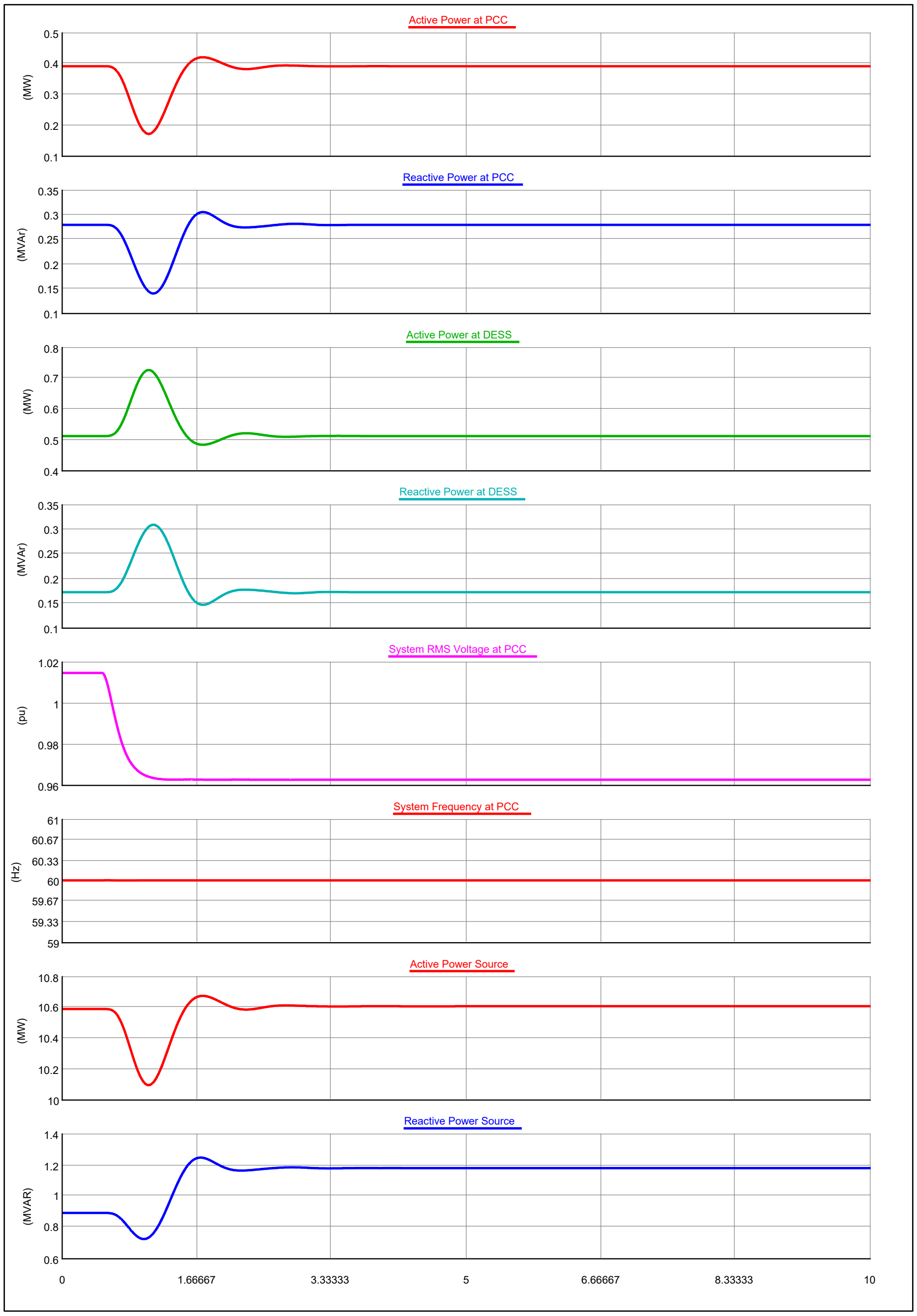

Figure A.52: System Response for Test 5.2.5

TEST 5.2.6: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

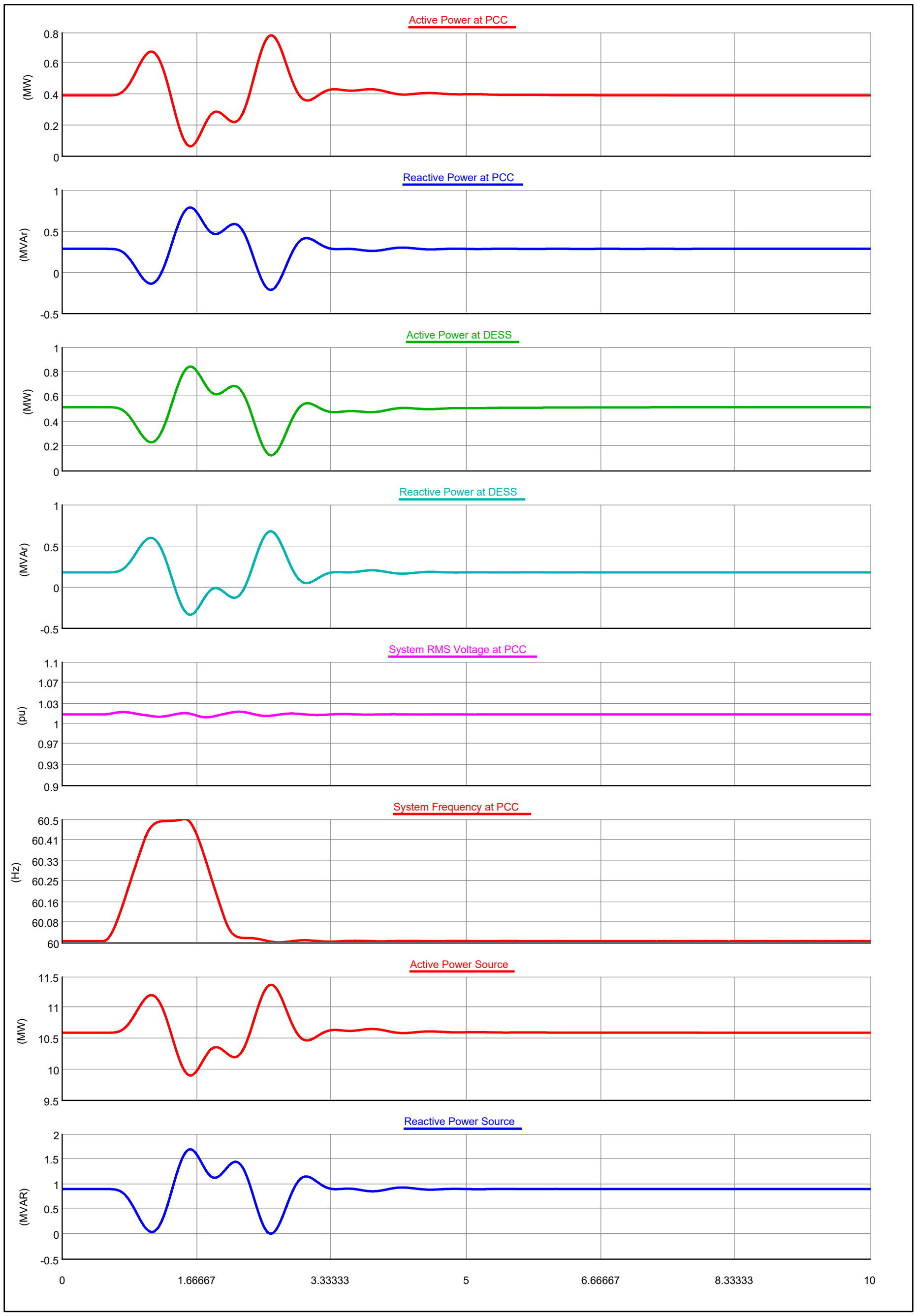

Figure A.53: System Response for Test 5.2.6

TEST 5.2.7: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

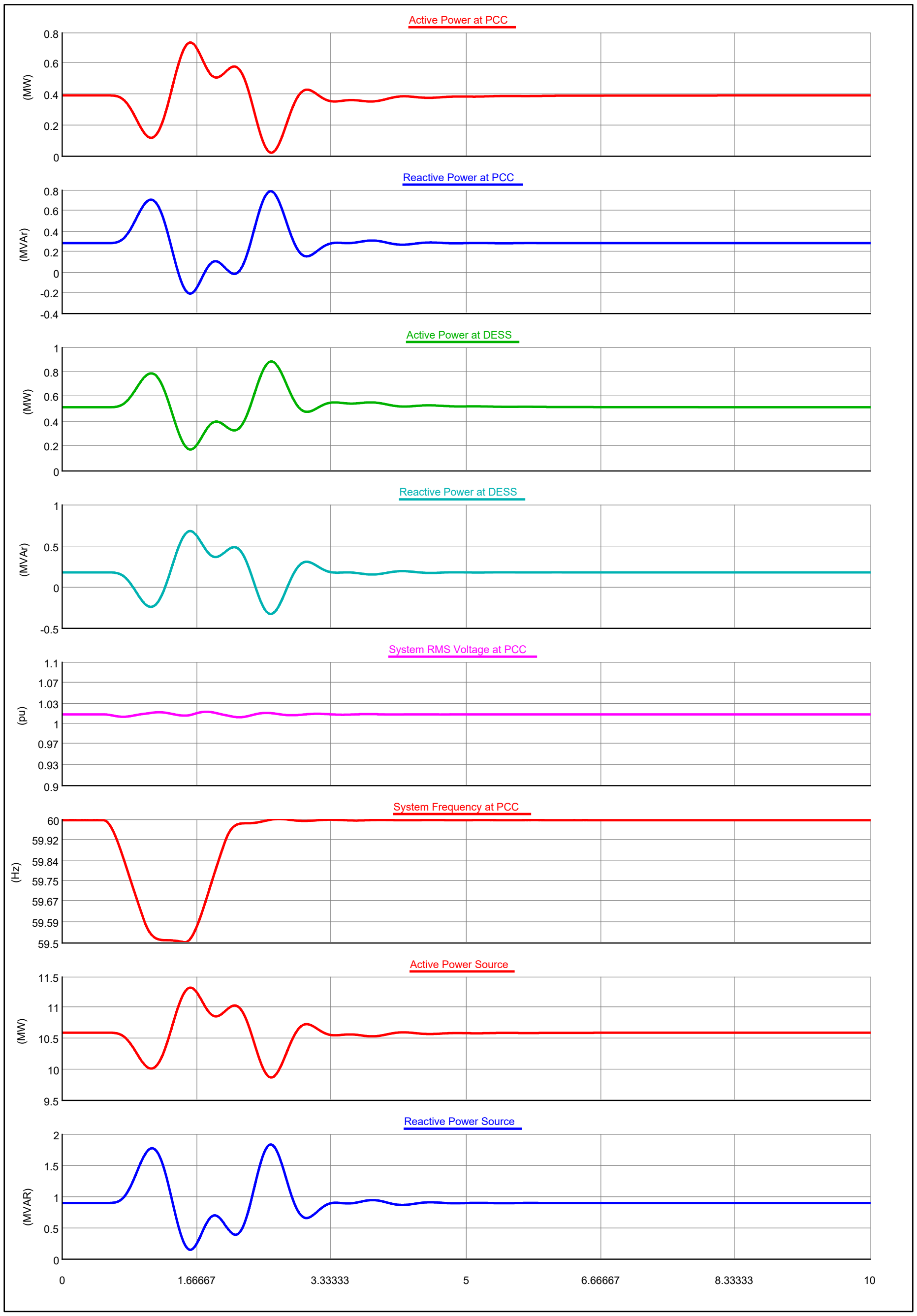

Figure A.54: System Response for Test 5.2.7

TEST 5.2.8: VARY THE SYSTEM FREQUENCY

On increasing the system frequency to 60.5 Hz at a ramp rate of 0.1 Hz per second (as shown in Figure 3.42), the real power across the DER reduced, while the active power import across the PCC increased. The frequency was held at 60.5 Hz for a period of 5 seconds, during which the active power across the PCC and DER began to settle. When the frequency began decreasing from 60.5 Hz to 59.7 Hz and was held for another 5 seconds, the active power output of the DER increased and the import across the PCC reduced. The active power settled at its previous set point of 500 kW during steady-state conditions following the disturbances. The reactive power was disturbed during this transition and settled at its previous set point during steady-state conditions. The system voltage was affected during this transition but returns to 1.01 pu during steady-state conditions.

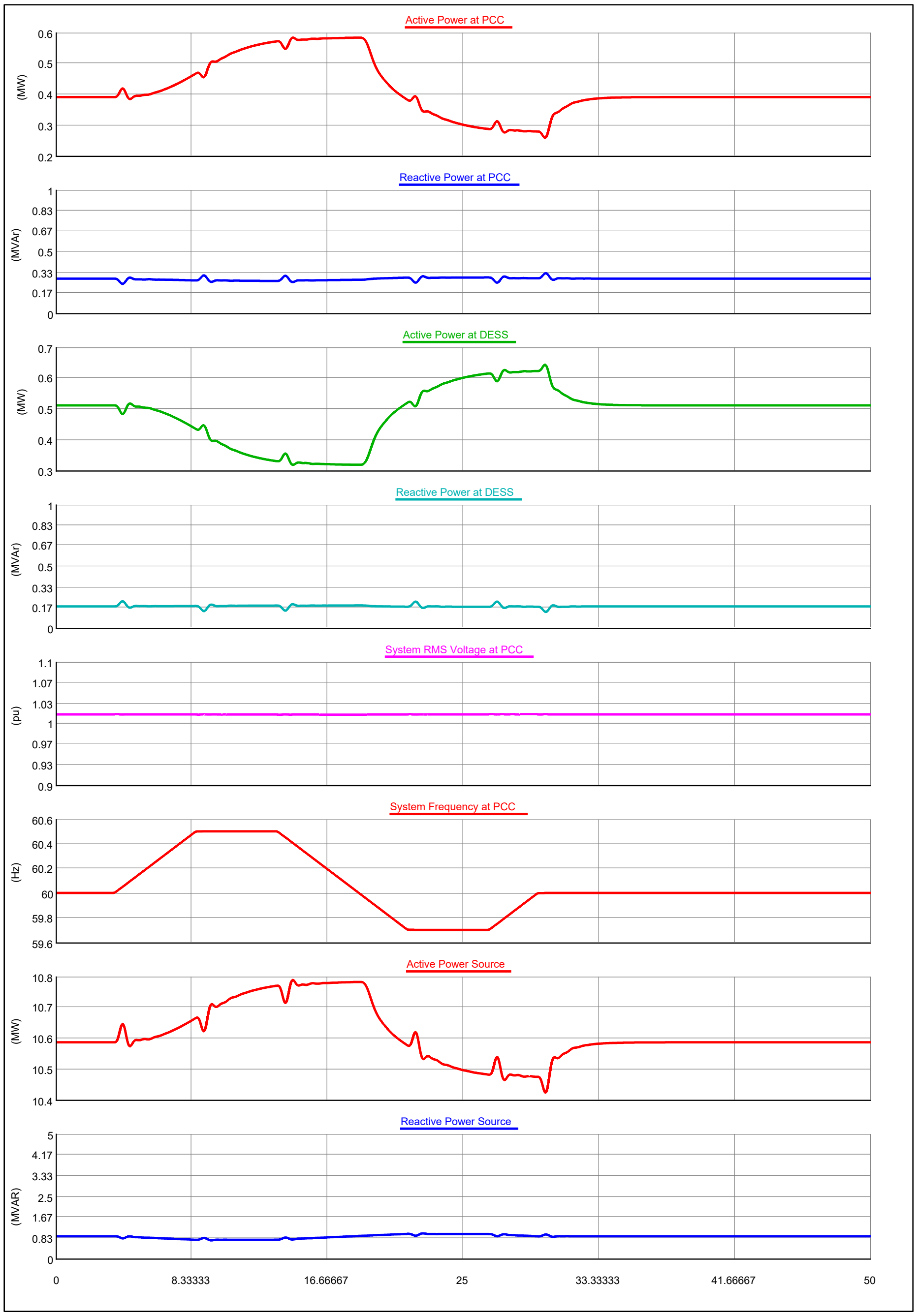

Figure A.55: System Response for Test 5.2.8

TEST 5.2.9: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On increasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by reducing its power output and settled at a new set point per the frequency-watt droop of the inverter. This caused more active power to be drawn from the grid. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1.025 pu at steady state.

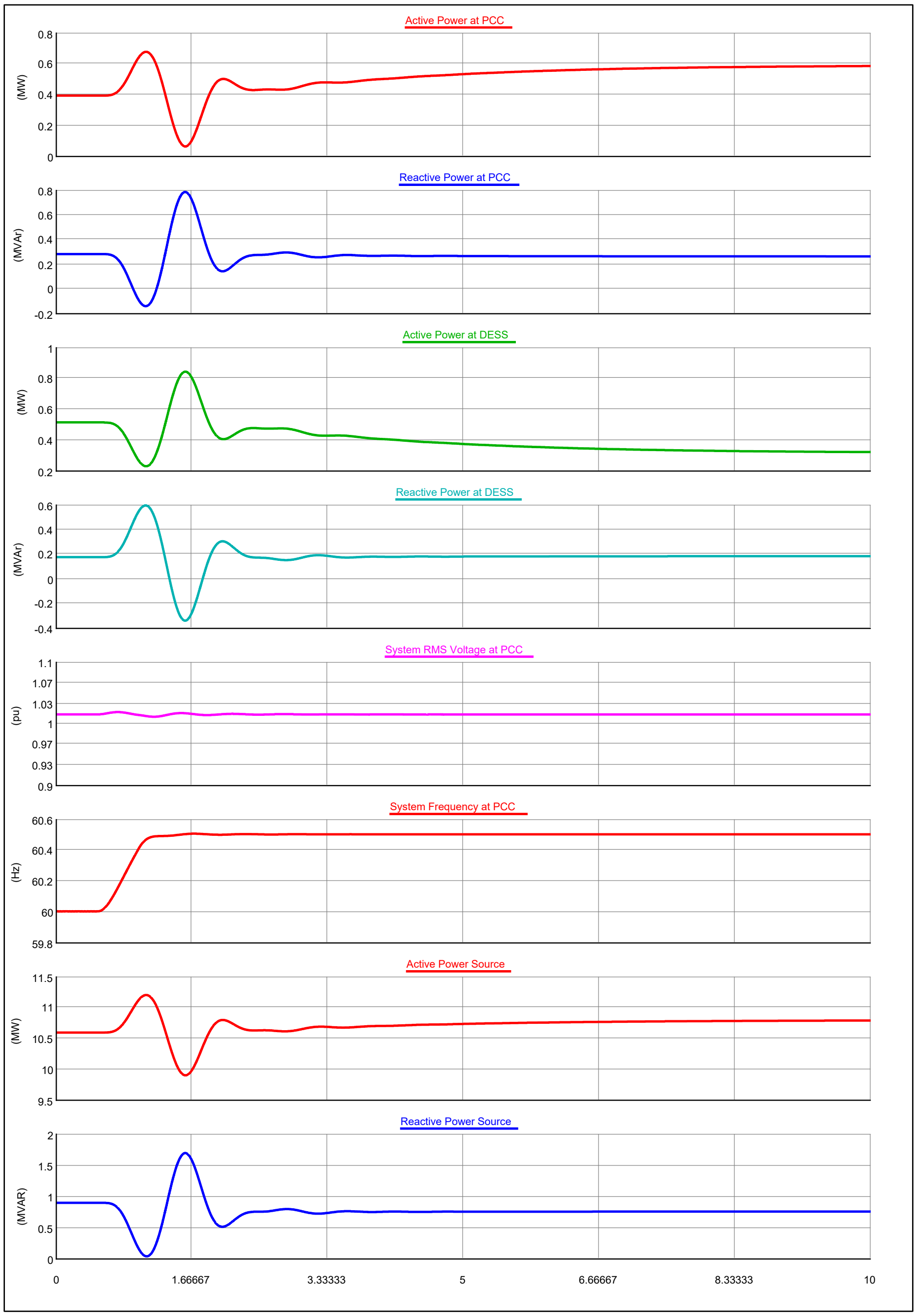

Figure A.56: System Response for Test 5.2.9

TEST 5.2.10: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On decreasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by increasing its power output and settled at a new set point per the frequency-watt droop of the inverter. This reduced the active power import from the grid through the PCC. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1.025 pu at steady state.

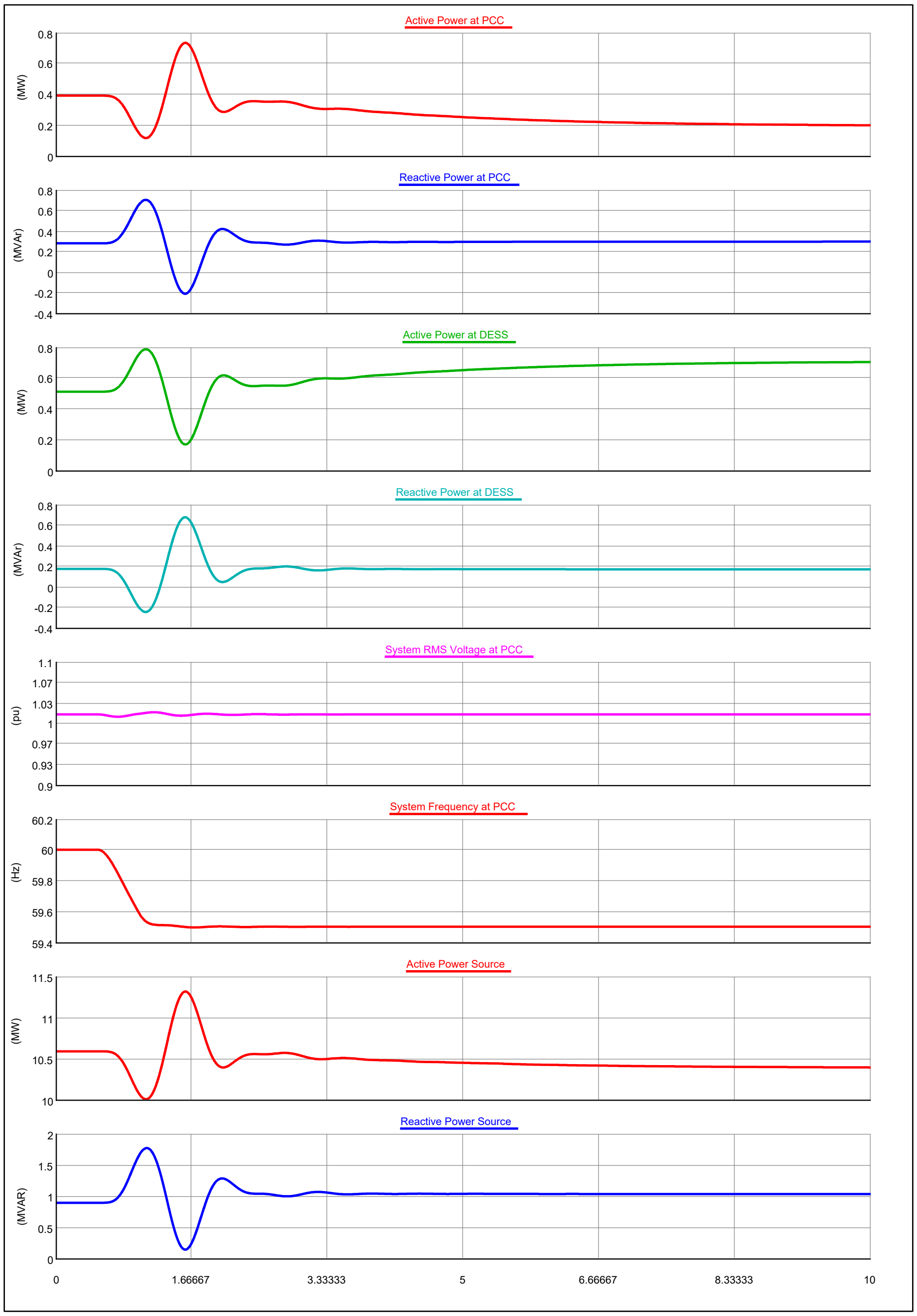

Figure A.57: System Response for Test 5.2.10

Scenario 3: DER at the End of a Long Feeder

TEST 5.3.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The active and reactive power dispatch of the DER were set at 500 kW and 200 kVAR, respectively. On activating the frequency-watt mode, there was no change on the graph because the system frequency was maintained at 60 Hz.

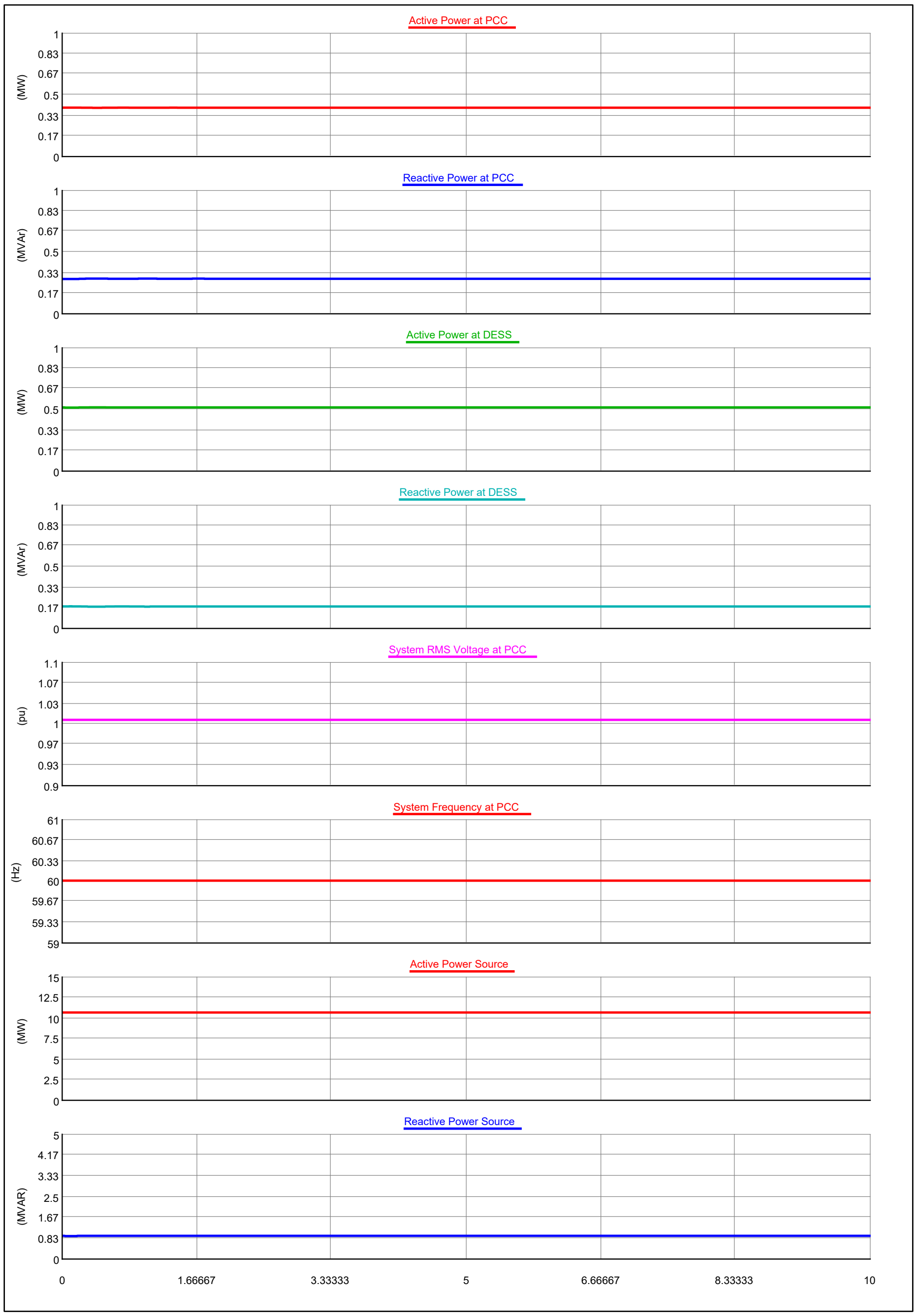

Figure A.58: System Response for Test 5.3.1

TEST 5.3.2: INCREASE THE SYSTEM LOAD BY 500 KW

On increasing the active power load by 500 kW, the real power output of the DER remained constant at 500 kW, while the additional load was fed by the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

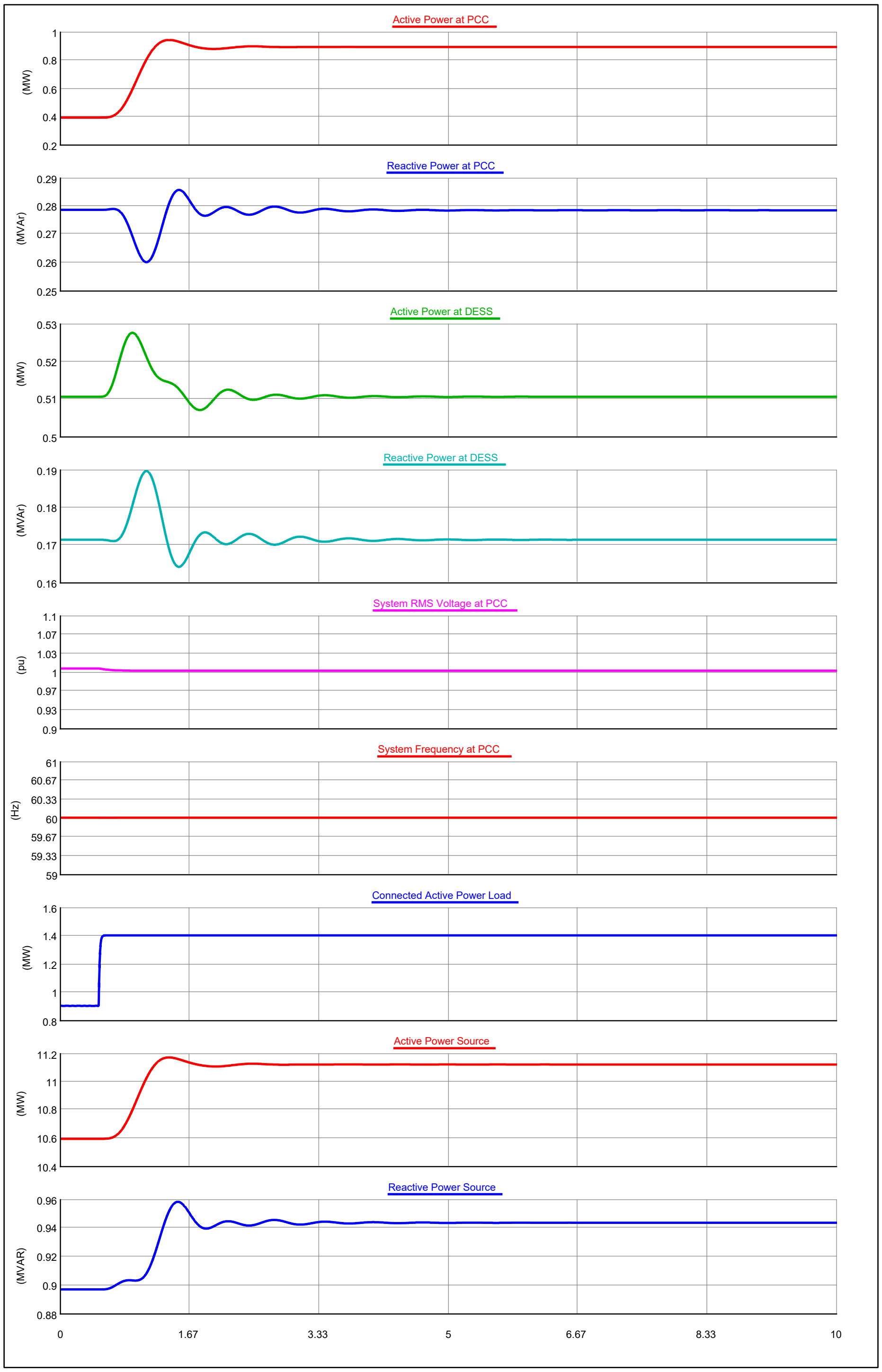

Figure A.59: System Response for Test 5.3.2

TEST 5.3.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power output of the DER remained constant at 500 kW, while the load was balanced by sending more active power into the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

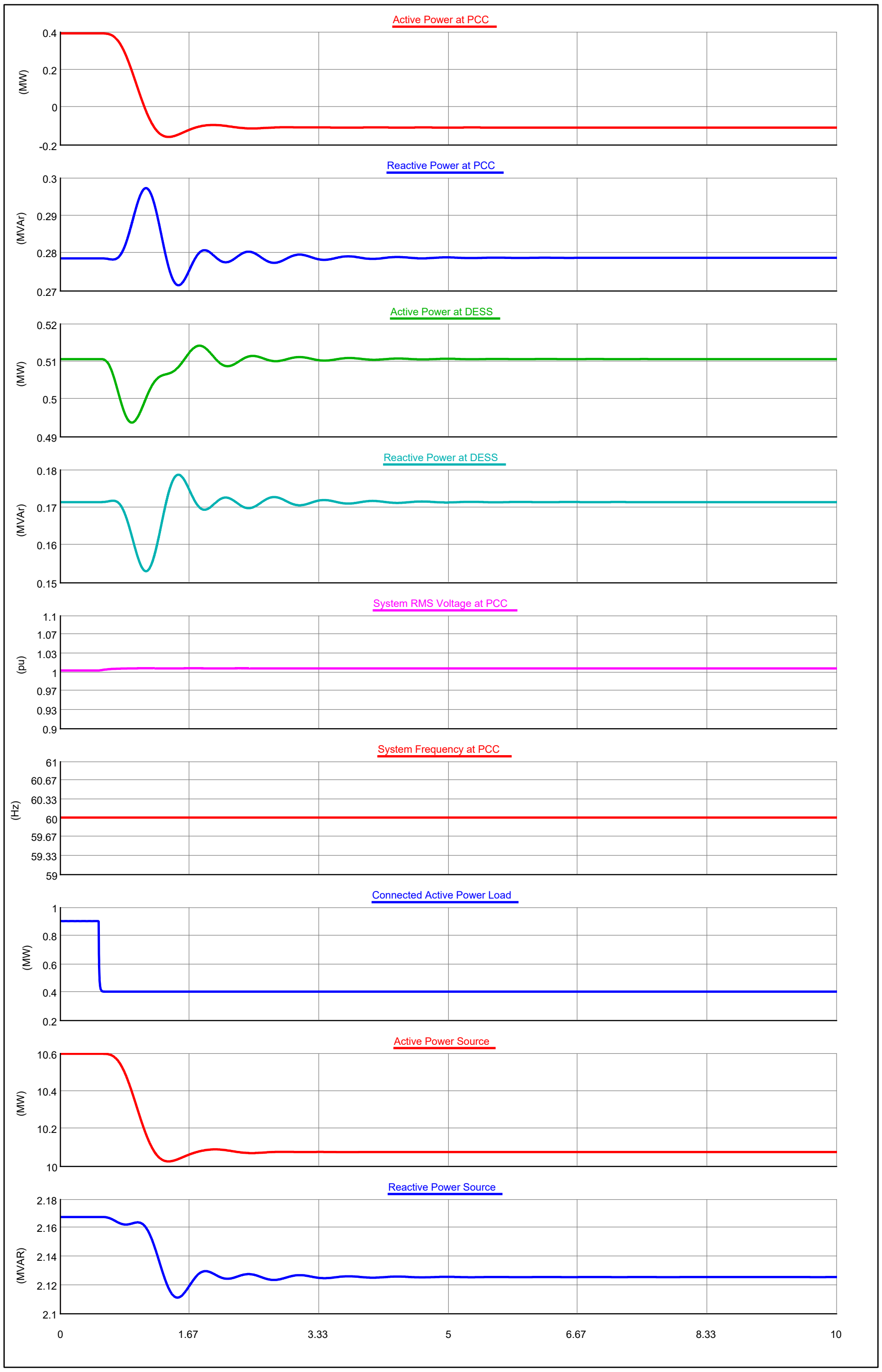

Figure A.60: System Response for Test 5.3.3

TEST 5.3.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage by 5 percent from 1.002 pu to 0.952 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

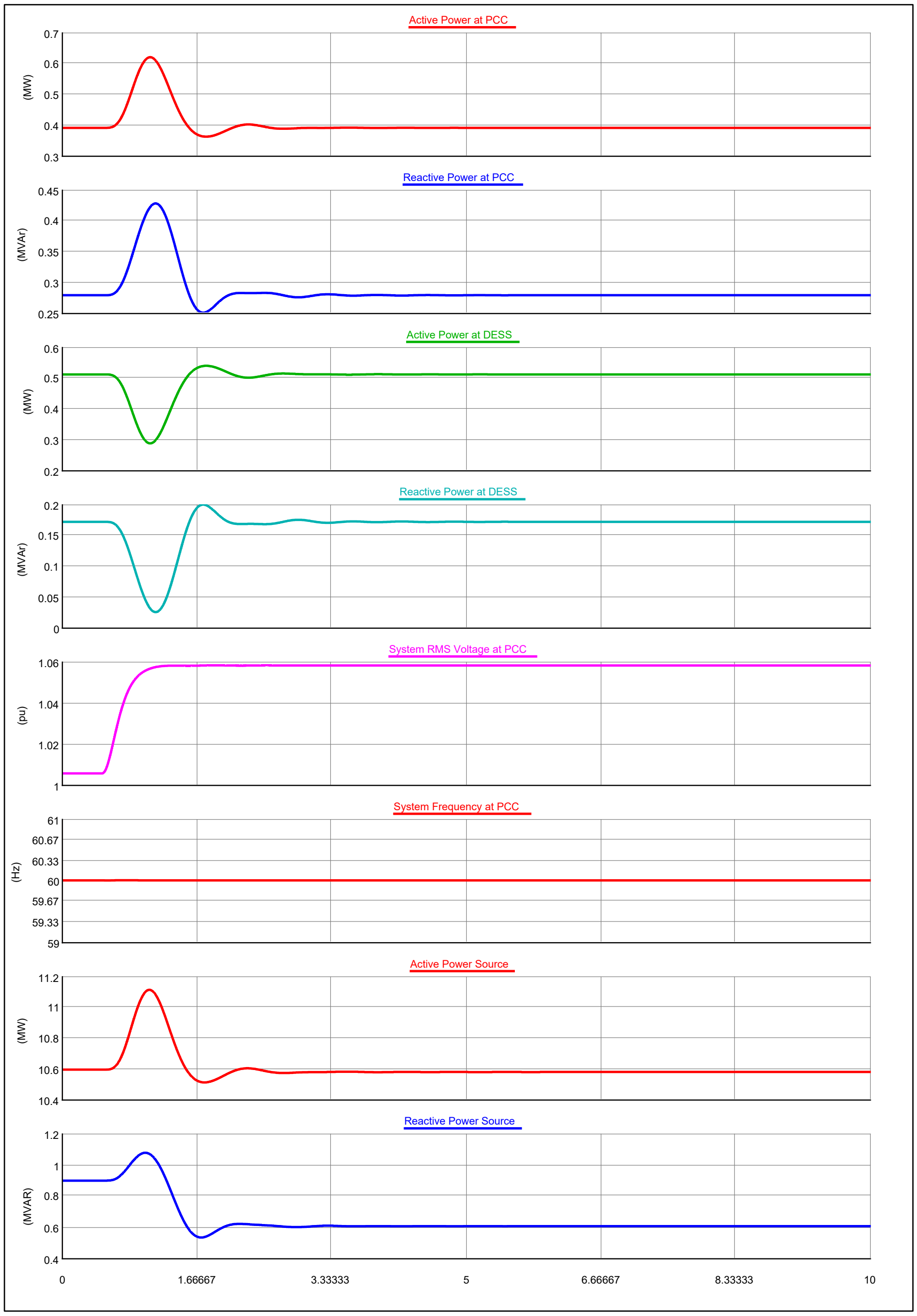

Figure A.61: System Response for Test 5.3.4

TEST 5.3.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage by 5 percent from 1.002 pu to 0.952 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

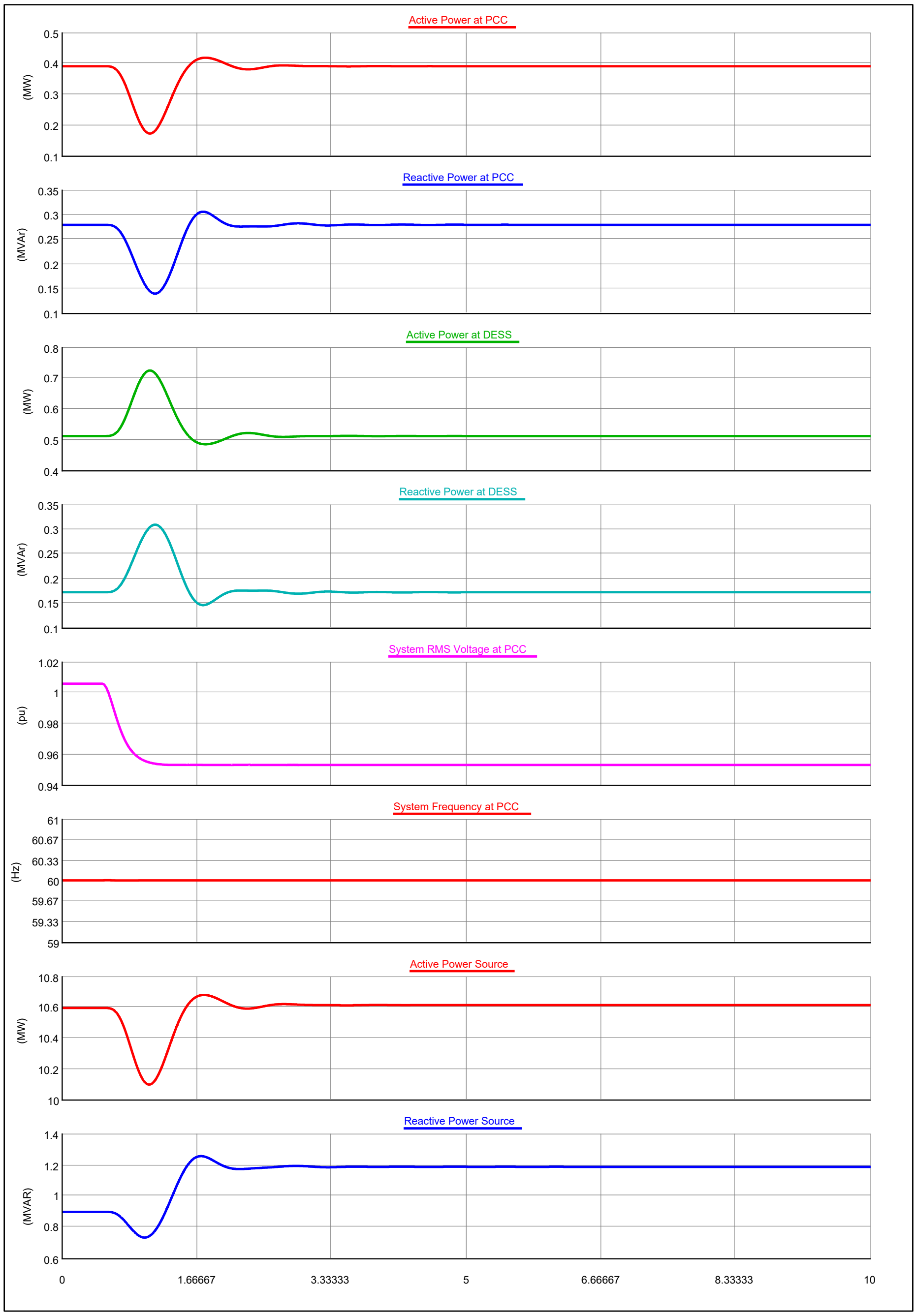

Figure A.62: System Response for Test 5.3.5

Test 5.3.6: Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

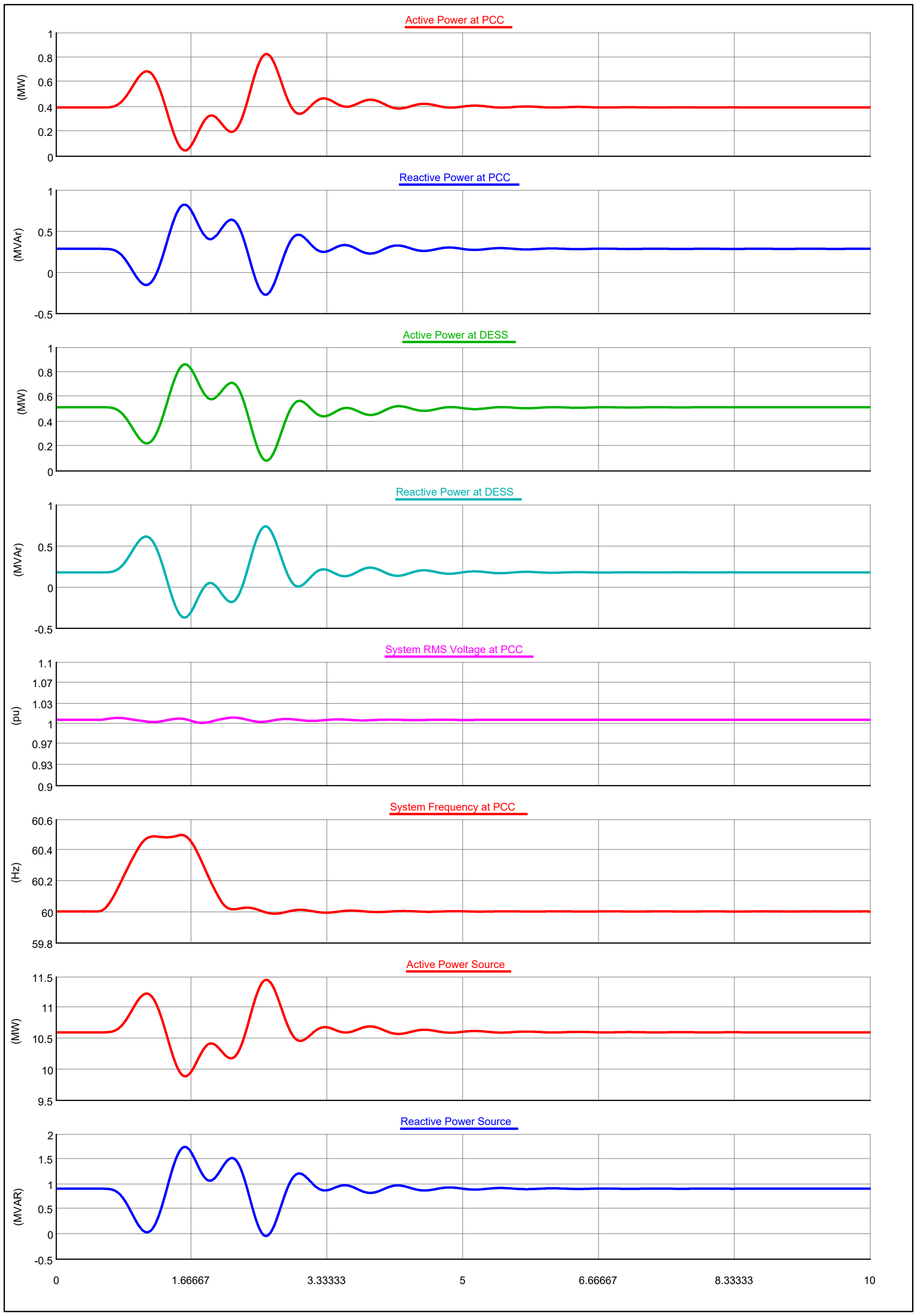

Figure A.63: System Response for Test 5.3.6

TEST 5.3.7: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.002 pu in steady state.

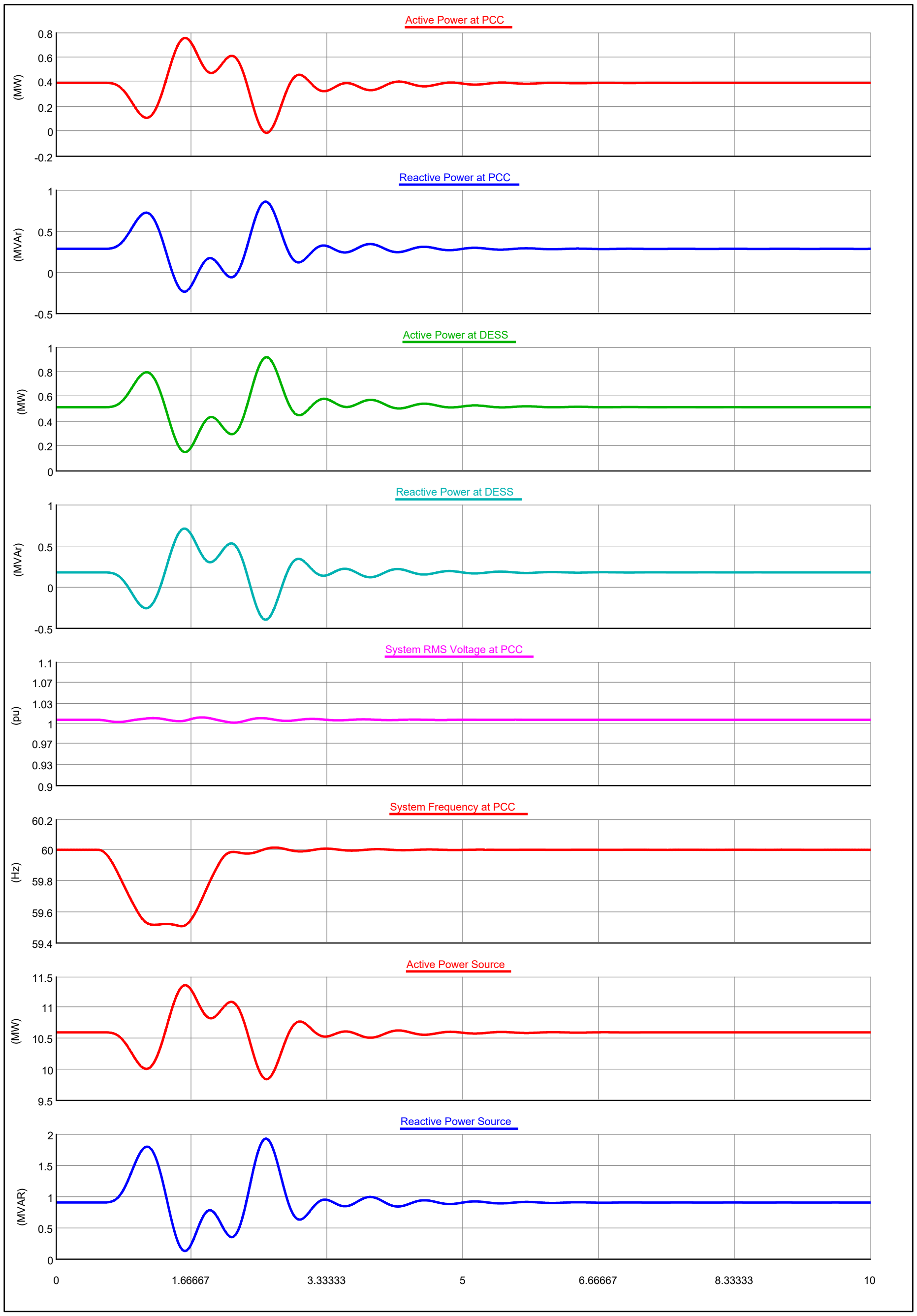

Figure A.64: System Response for Test 5.3.7

Test 5.3.8: Vary the System Frequency

The system frequency was changed as shown in Figure 3.42. The reactive power was disturbed during this transition and settled at its previous set point during steady-state conditions. The system voltage was affected during this transition but returned to 1.002 pu during steady-state conditions.

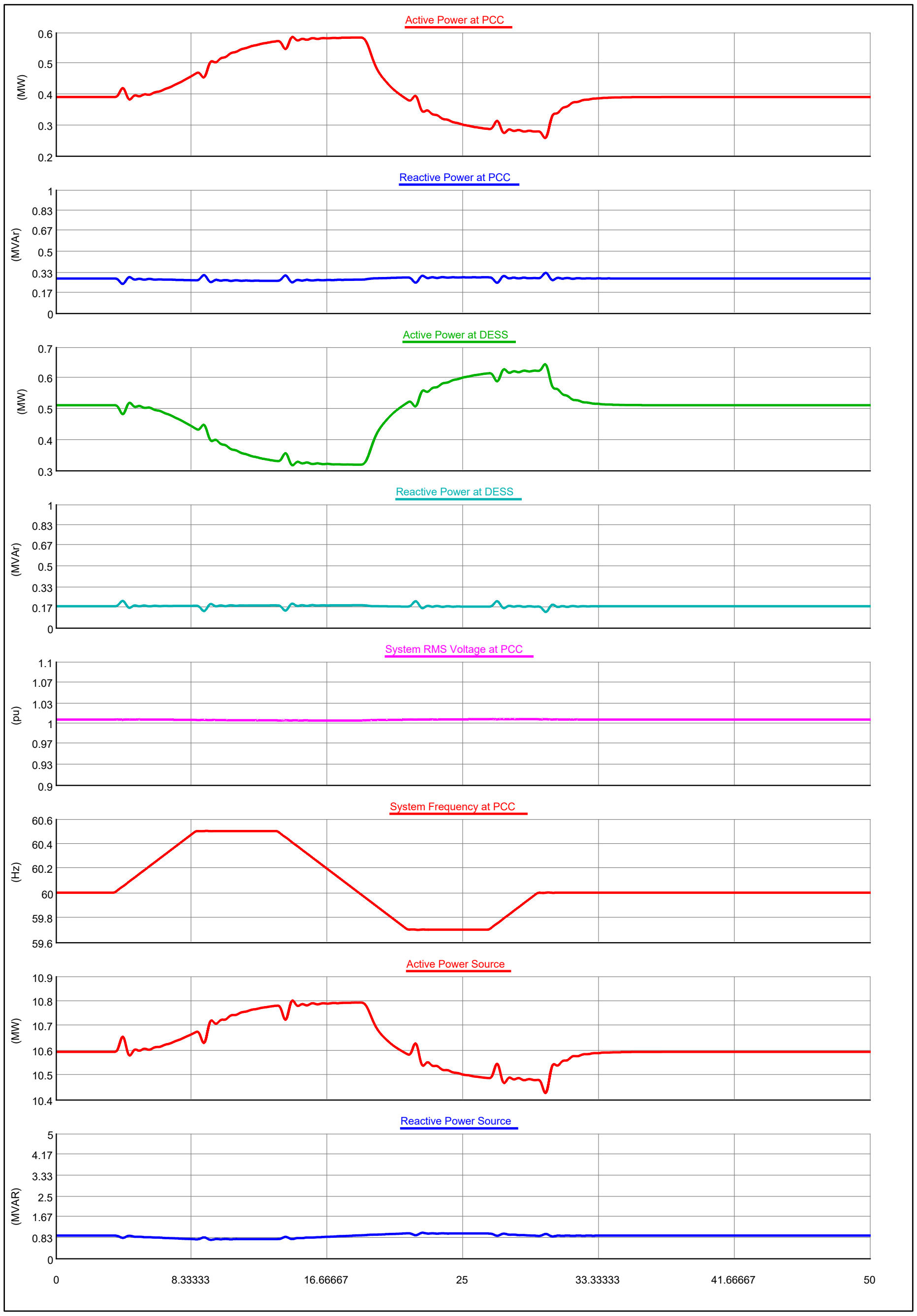

Figure A.65: System Response for Test 5.3.8

TEST 5.3.9 INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On increasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by reducing its power output and settled at a new set point per the frequency-watt droop of the inverter. This caused more active power to be drawn from the grid. The reactive power across the DER and PCC remained same, while the system voltage settled into 1.025 pu at steady state.

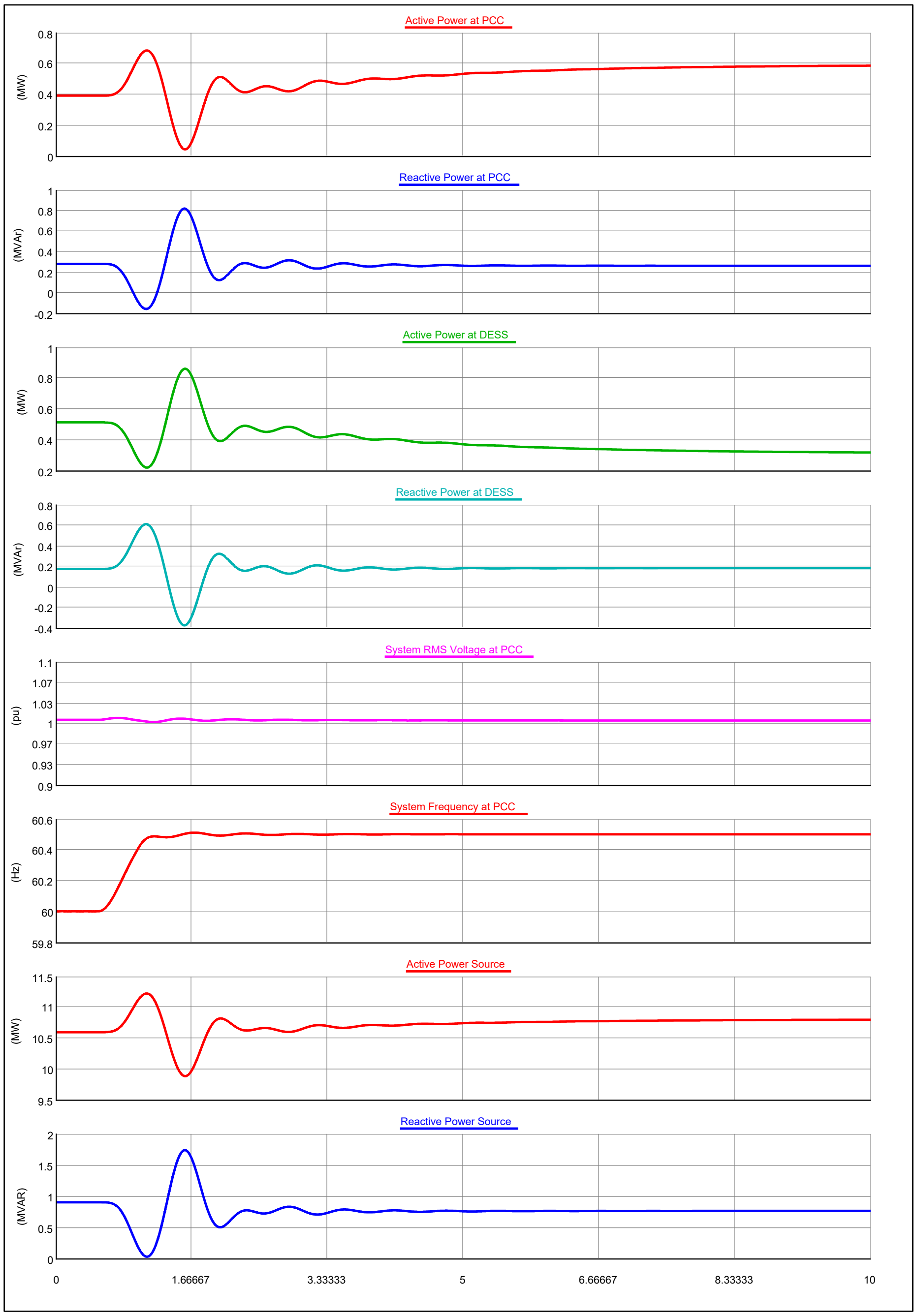

Figure A.66: System Response for Test 5.3.9

TEST 5.3.10: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On decreasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by increasing its power output and settled at a new set point per the frequency-watt droop of the inverter. This reduced the active power import from the grid through the PCC. The reactive power across the DER and PCC remained same, while the system voltage settled into 1.025 pu at steady state.

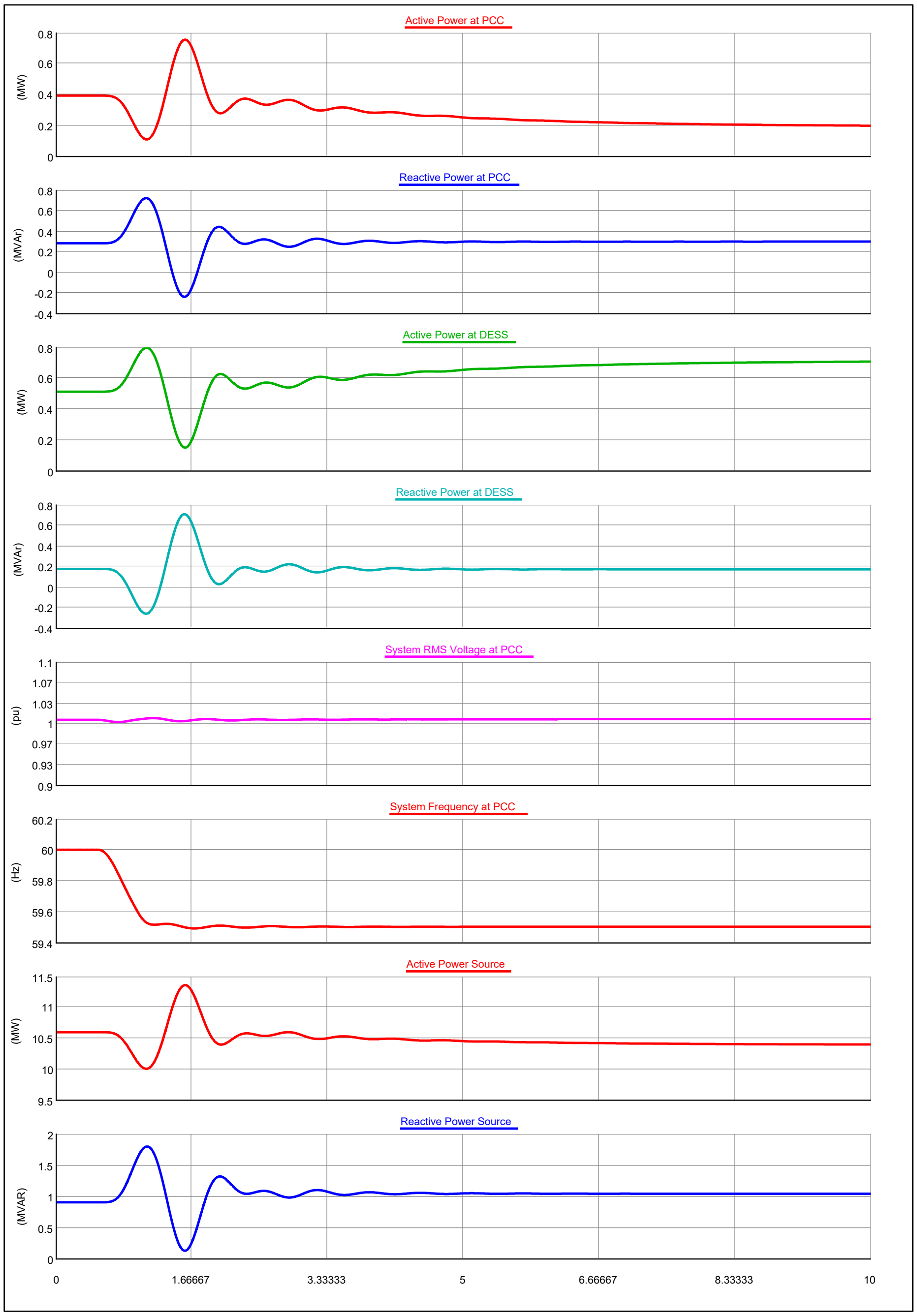

Figure A.67: System Response for Test 5.3.10

Scenario 4: Multiple Diverse Types of DER on the Same Circuit

TEST 5.4.1: MODE ACTIVATION WITH ACTIVE POWER SET POINT OF 500 KW

The active and reactive power dispatch of the DER were set at 500 kW and 200 kVAR, respectively. On activating the frequency-watt mode, there was no change on the graph because the system frequency was maintained at 60 Hz.

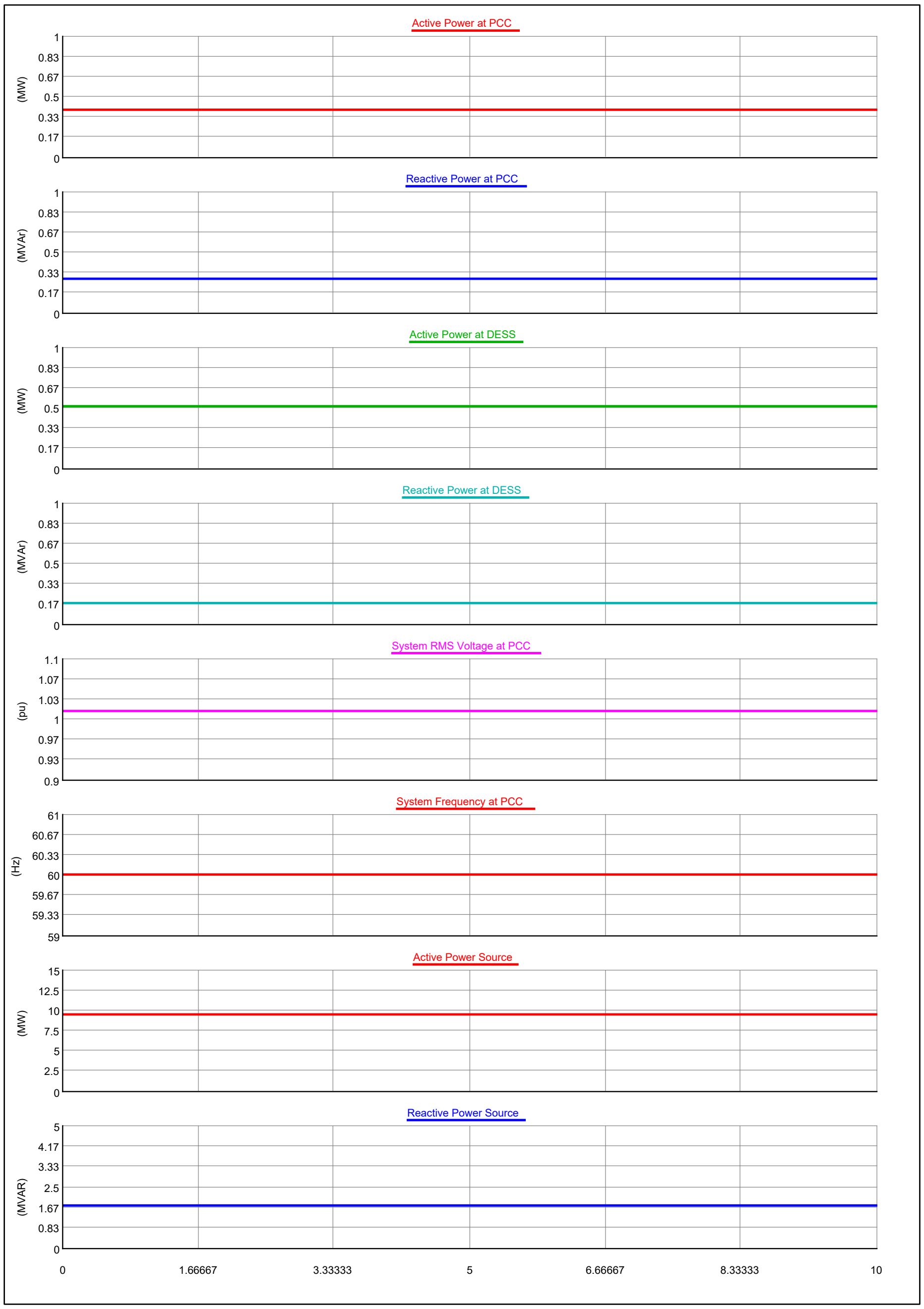

Figure A.68: System Response for Test 5.4.1

Test 5.4.2: Increase the System Load by 500 kW

On increasing the active power load by 500 kW, the real power output of the DER remained constant at 500 kW, while the additional load was fed by the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

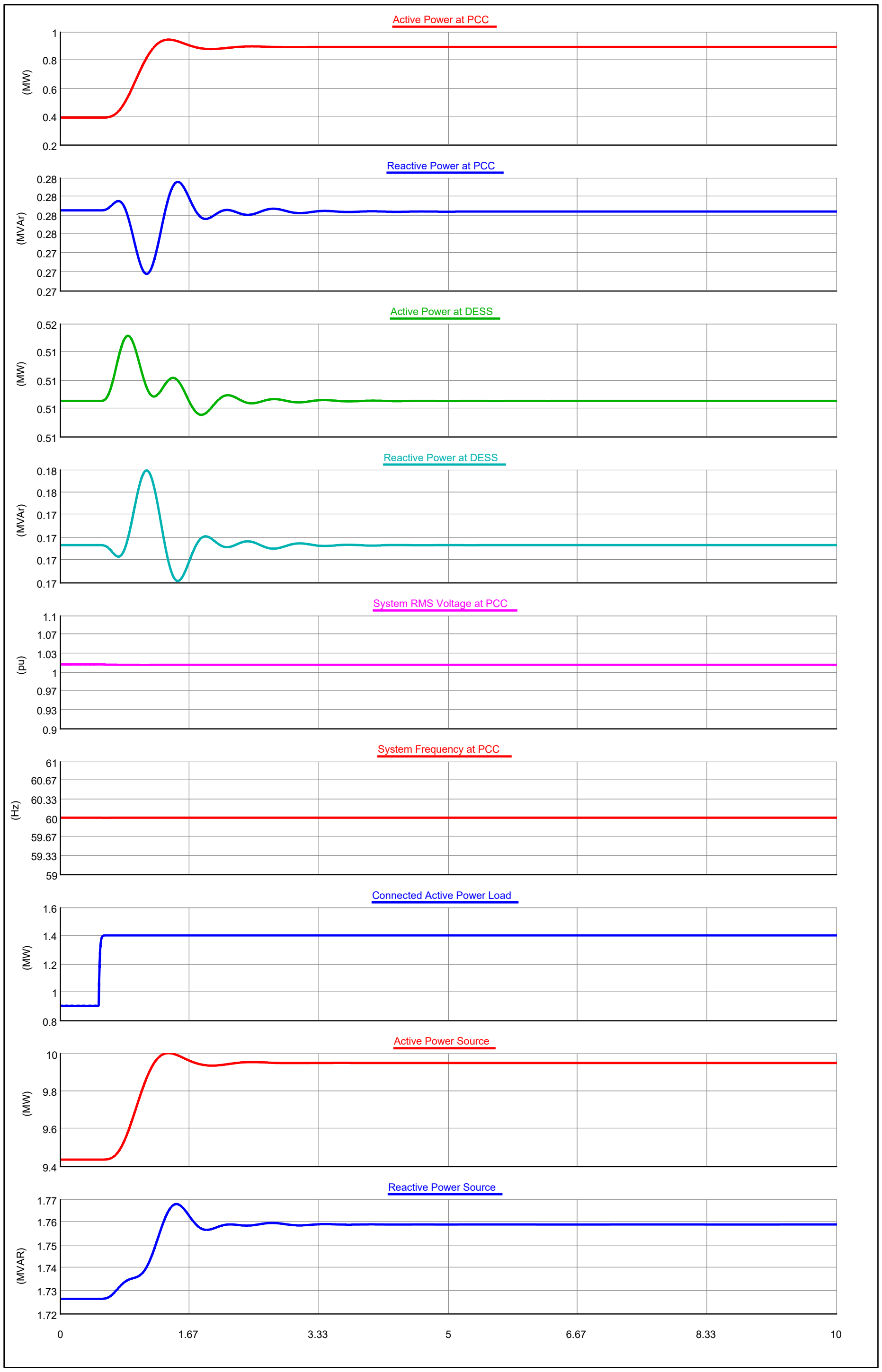

Figure A.69: System Response for Test 5.4.2

TEST 5.4.3: DECREASE THE SYSTEM LOAD BY 500 KW

On decreasing the active power load by 500 kW, the real power output of the DER remained constant at 500 kW, while the load was balanced by sending more active power into the grid through the PCC. The reactive power from the DER and across the PCC settled to their prior set points at steady state, while the system frequency and voltage were not affected by the change.

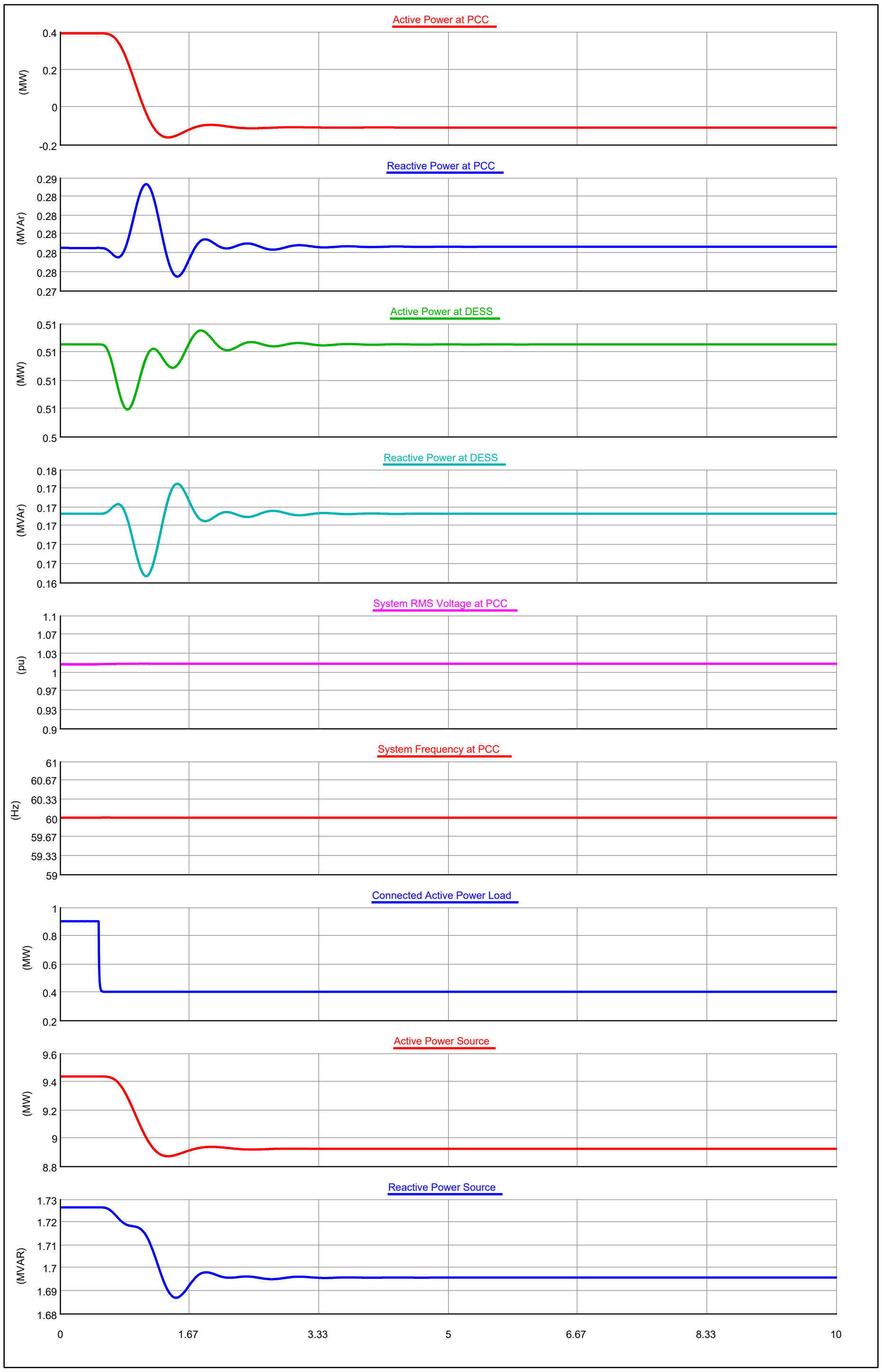

Figure A.70: System Response for Test 5.4.3

TEST 5.4.4: INCREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On increasing the system voltage by 5 percent from 1.01 pu to 0.96 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

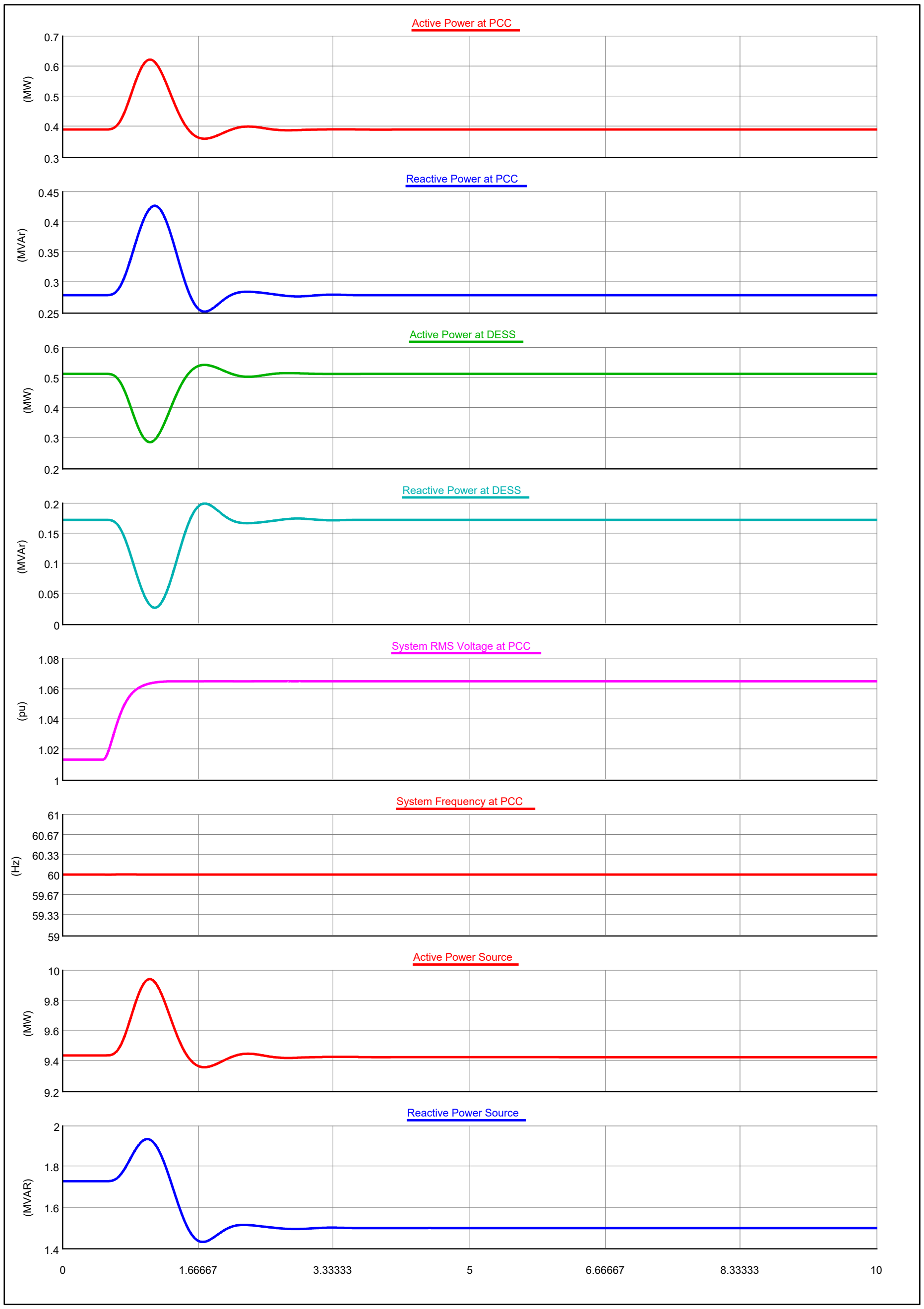

Figure A.71: System Response for Test 5.4.4

TEST 5.4.5: DECREASE THE SYSTEM VOLTAGE BY 5 PERCENT

On decreasing the system voltage by 5 percent from 1.01 pu to 0.96 pu, the DER rode through the disturbance. The real power and reactive power at the DER and PCC did not change at steady state, while the system frequency was unaffected.

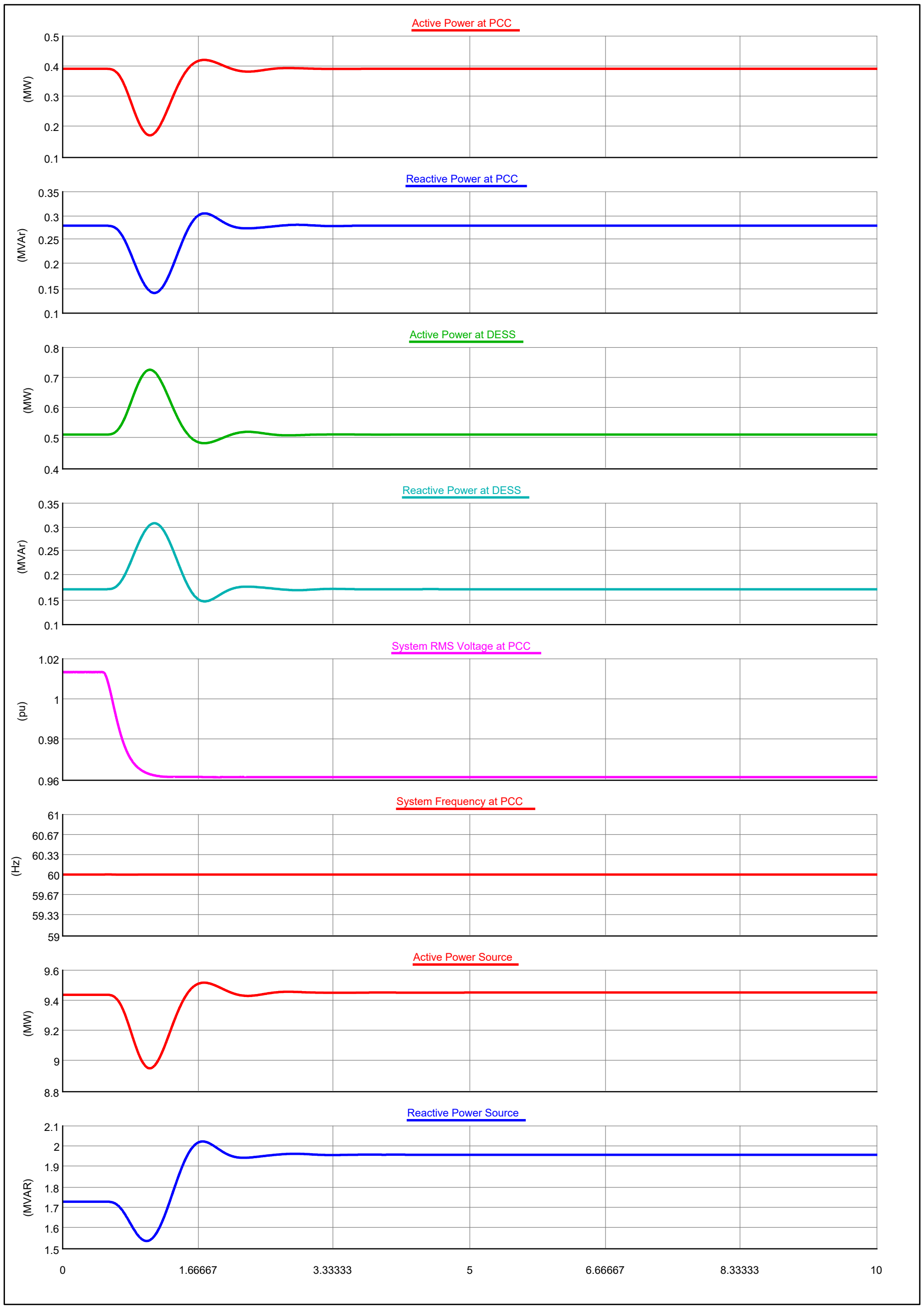

Figure A.72: System Response for Test 5.4.5

Test 5.4.6 Increase the System Frequency by 0.5 Hz for 1 Second

The system frequency was increased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

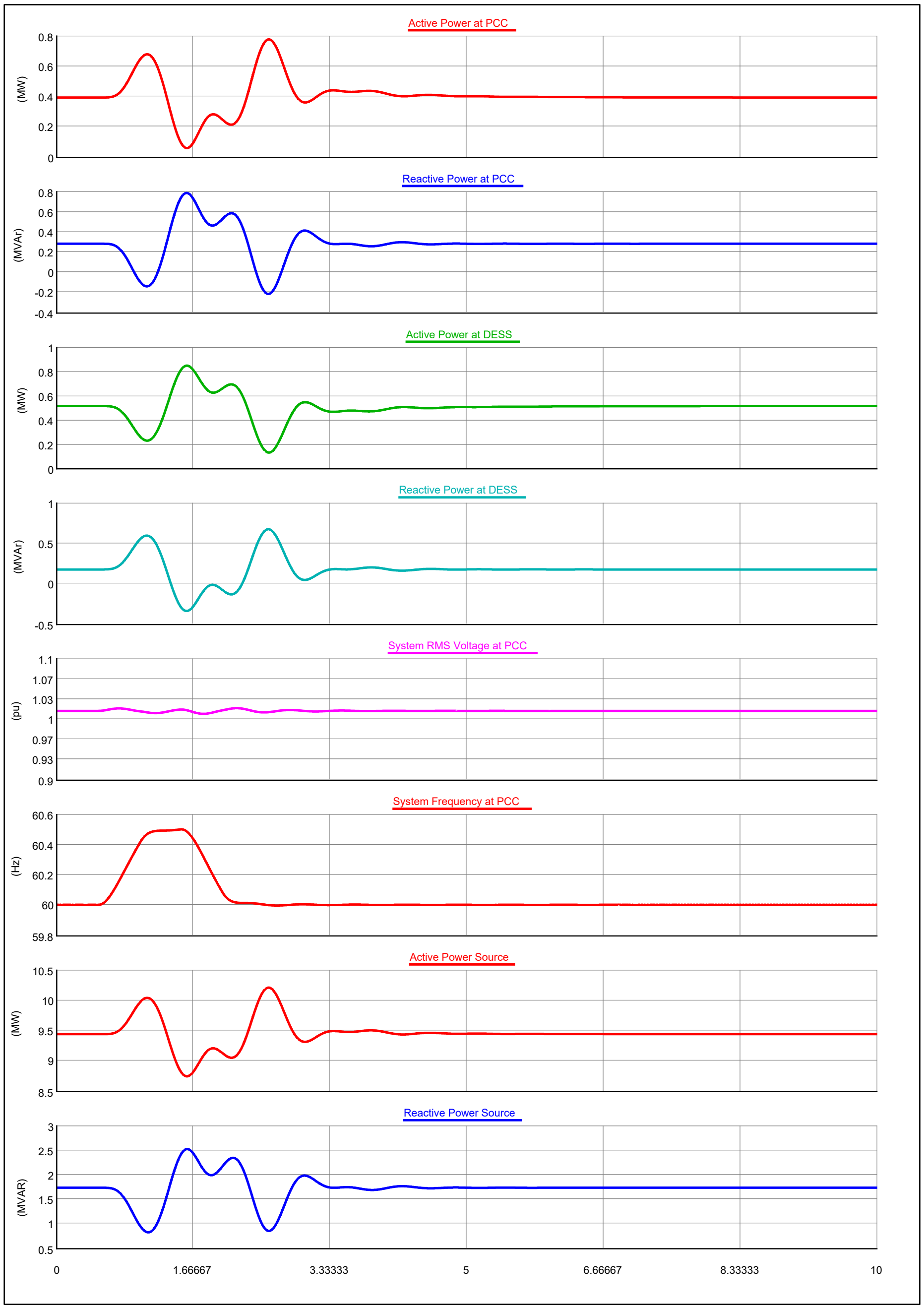

Figure A.73: System Response for Test 5.4.6

TEST 5.4.7: DECREASE THE SYSTEM FREQUENCY BY 0.5 HZ FOR 1 SECOND

The system frequency was decreased by 0.5 Hz for 1 second at a ramp rate of 1 Hz per second. The DER responded to the change in frequency by increasing its active power output correspondingly and settled at its prior set point at steady state. The reactive power flow at the PCC and DER settled at its prior set point. The voltage was disturbed by the frequency change due to power flow but settled back to 1.01 pu in steady state.

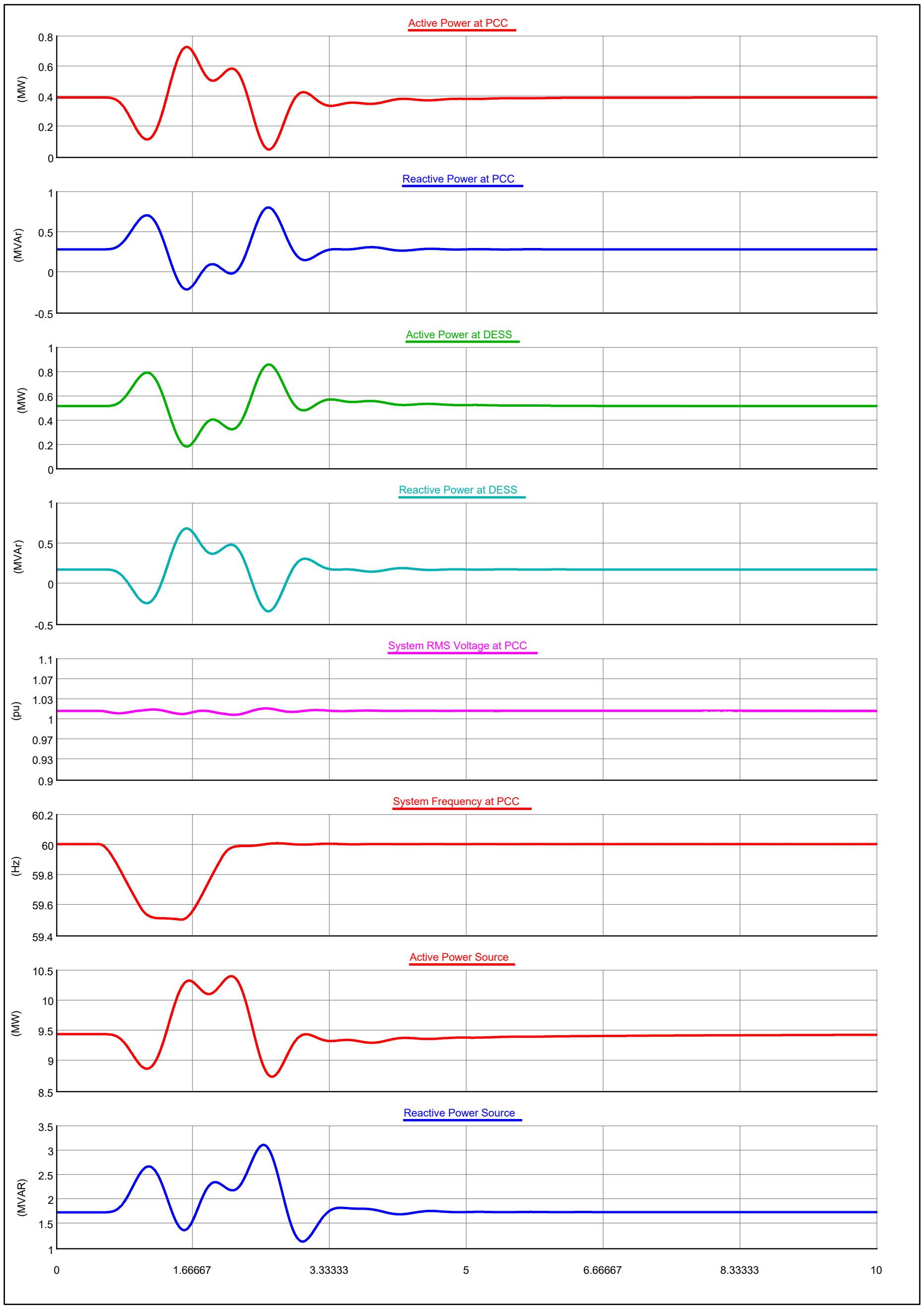

Figure A.74: System Response for Test 5.4.7

Test 5.4.8: Vary the System Frequency

The system frequency was changed as shown in Figure 3.42. The reactive power was disturbed during this transition and settled at its previous set point during steady-state conditions. The system voltage was affected during this transition but returned to 1.01 pu during steady-state conditions.

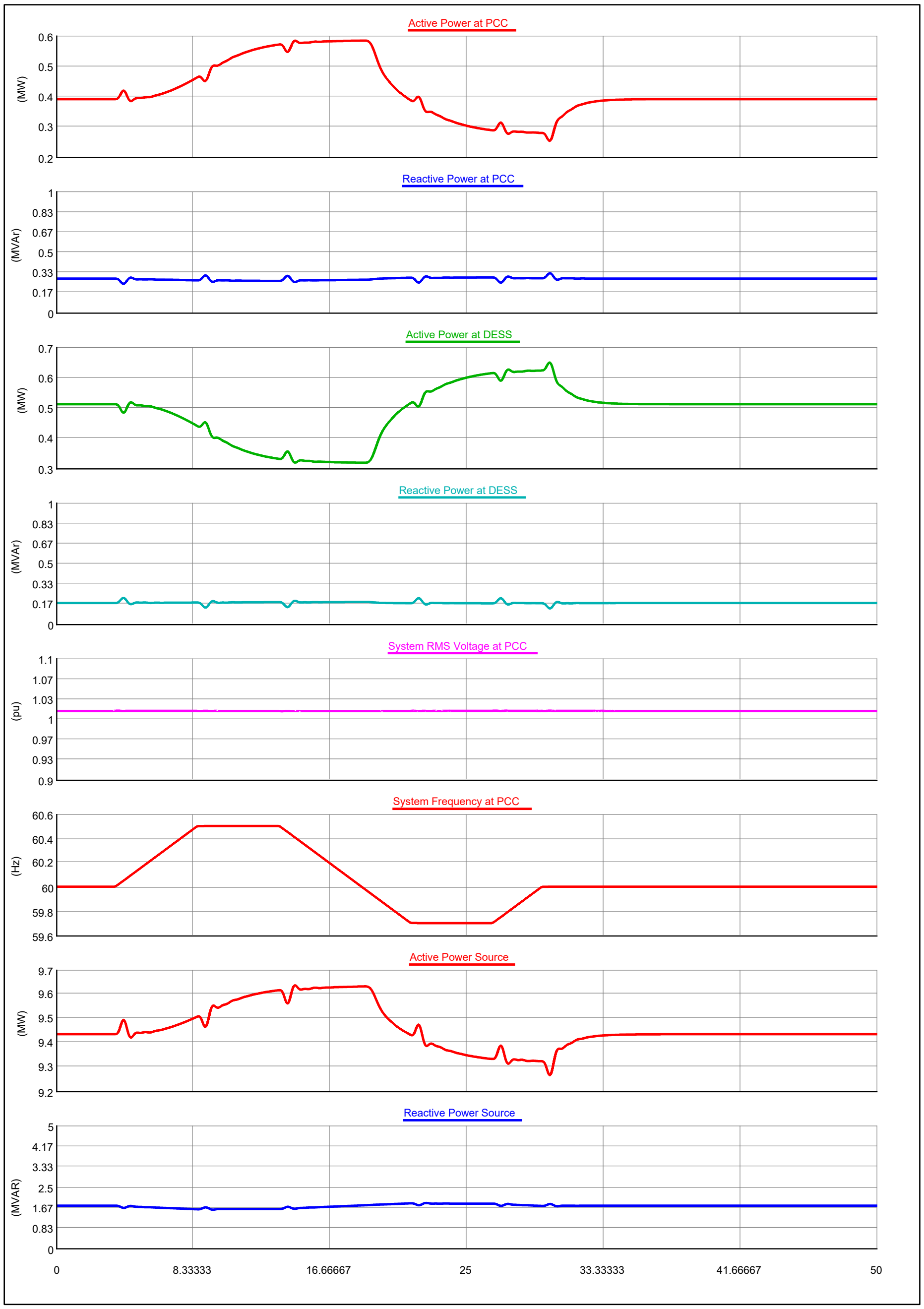

Figure A.75: System Response for Test 5.4.8

TEST 5.4.9: INCREASE THE SYSTEM FREQUENCY BY 0.5 HZ

On increasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by reducing its power output and settled at a new set point per the frequency-watt droop of the inverter. This caused more active power to be drawn from the grid. The reactive power across the DER and PCC remained same, while the system voltage settled into 1.025 pu at steady state.

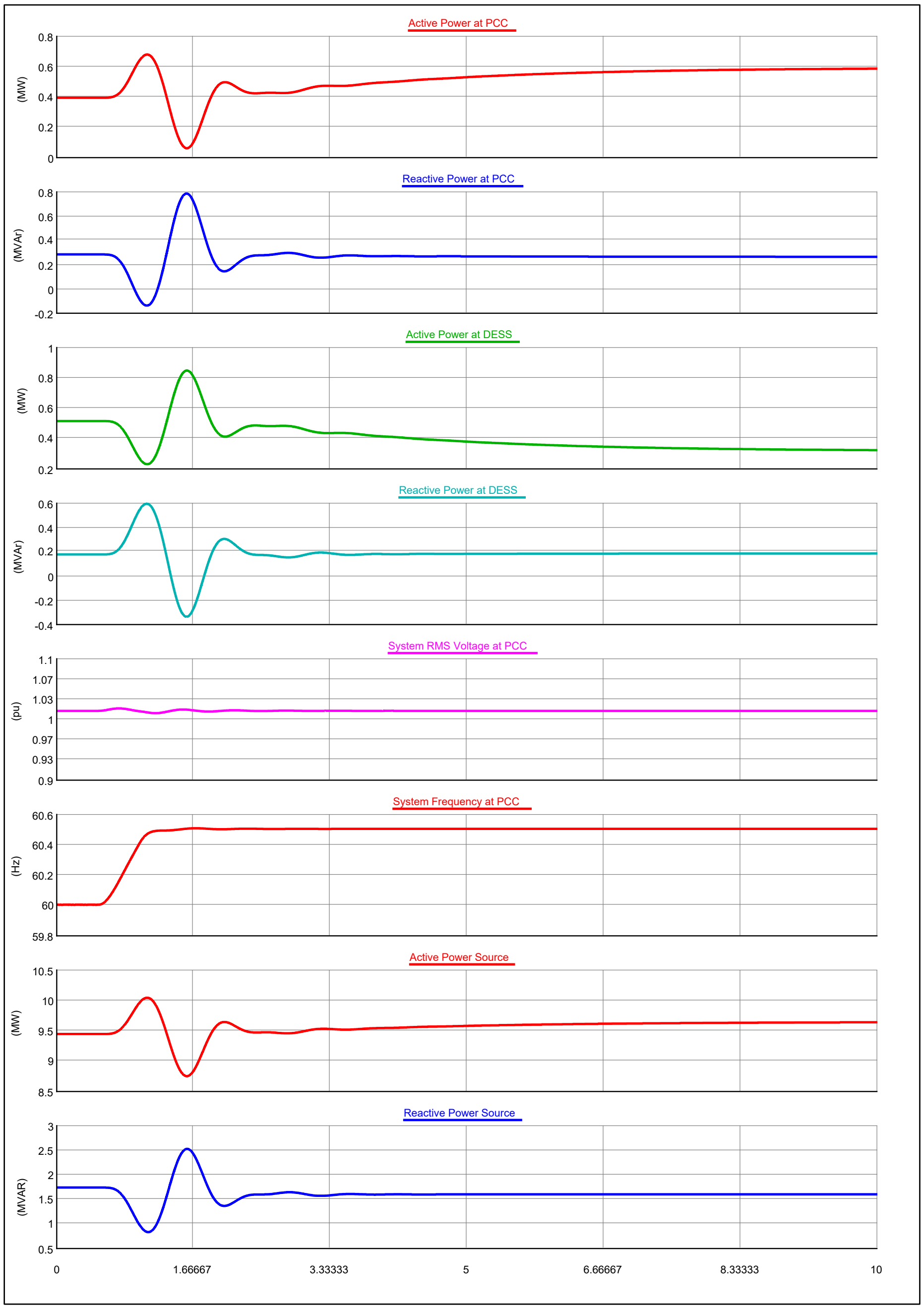

Figure A.76: System Response for Test 5.4.9

Test 5.4.10: Decrease the System Frequency by 0.5 Hz for 5 Seconds

On decreasing the system frequency by 0.5 Hz, the DER responded to the frequency changes by increasing its power output and settled at a new set point per the frequency-watt droop of the inverter. This reduced the active power import from the grid through the PCC. The reactive power across the DER and PCC remained the same, while the system voltage settled into 1.025 pu at steady state.

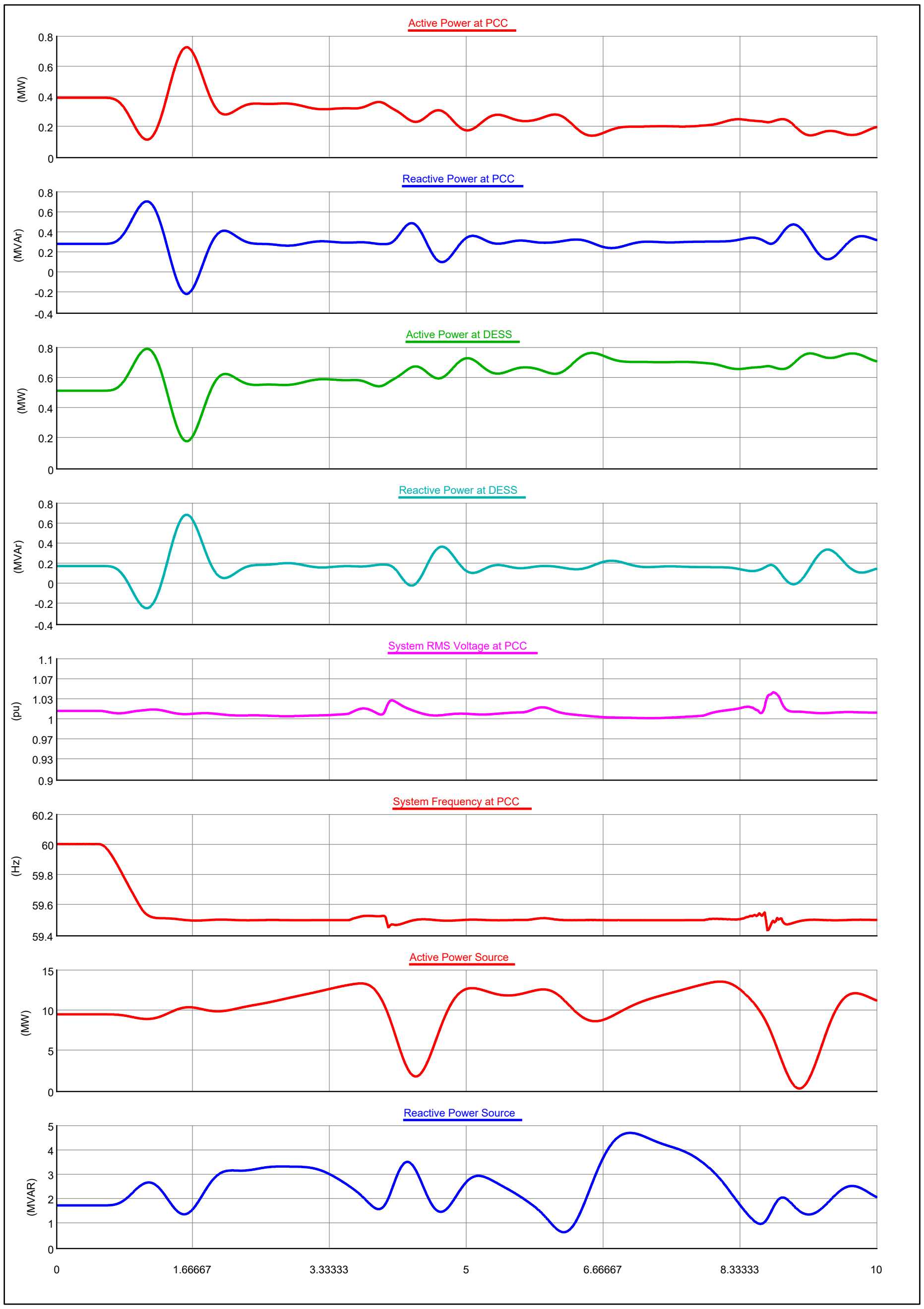

Figure A.77: System Response for Test 5.4.10

TEST 7 – SPINNING RESERVE

The objective of this test is to assess the benefits of the battery storage system in functioning as a spinning reserve in different system conditions, compared to traditional sources, such as diesel generators. The DER will be compared against the traditional backup diesel generator as a source of spinning reserve in terms of response time, standby losses, durability of support, and availability.

Test Procedure

The DER used for testing is modeled as a frequency-watt controlled and volt-VAR controlled DER when it is connected to the grid, and it works as a volt-frequency controlled device in island condition. Thus, the voltage and frequency of the DER is controlled during the grid connected mode as well as during island mode. The DER acts as a spinning resource providing support for the grid during periods of fluctuation in system voltage and/or frequency.

The procedure for testing was as follows:

Step 1. Place the DER into idle mode with the state of charge (SOC) of the battery at the full level. During Idle mode, the DER does not generate or absorb active or reactive power from the grid.

Step 2. Create a contingency where a grid source is taken offline to simulate an under-frequency situation in the rest of the system connected by the DER. Set the DER in to voltage and frequency regulation modes after approximately 5 seconds to produce the deficit active and reactive power to support the rest of the system during this event. In the meantime, bring the additional backup generation online.

Step 3. On opening the Region 1 (Rgn1) breaker, the DER enters island mode, regulates the voltage and frequency across the islanded portion of the grid, and restores balance in the portion of the circuit isolated from the main circuit within few seconds. The net load in the region is supported by the DER completely if the system load is within its capacity. The active power dispatch of the DER is 845 kW, and the reactive power dispatch is 310 kVAR. One observation in Figure A.79 is that the frequency of the DER shoots up to 4000 Hz and more. This can be attributed to the metering error of the software, which creates random values for frequency of those nodes that have been opened.

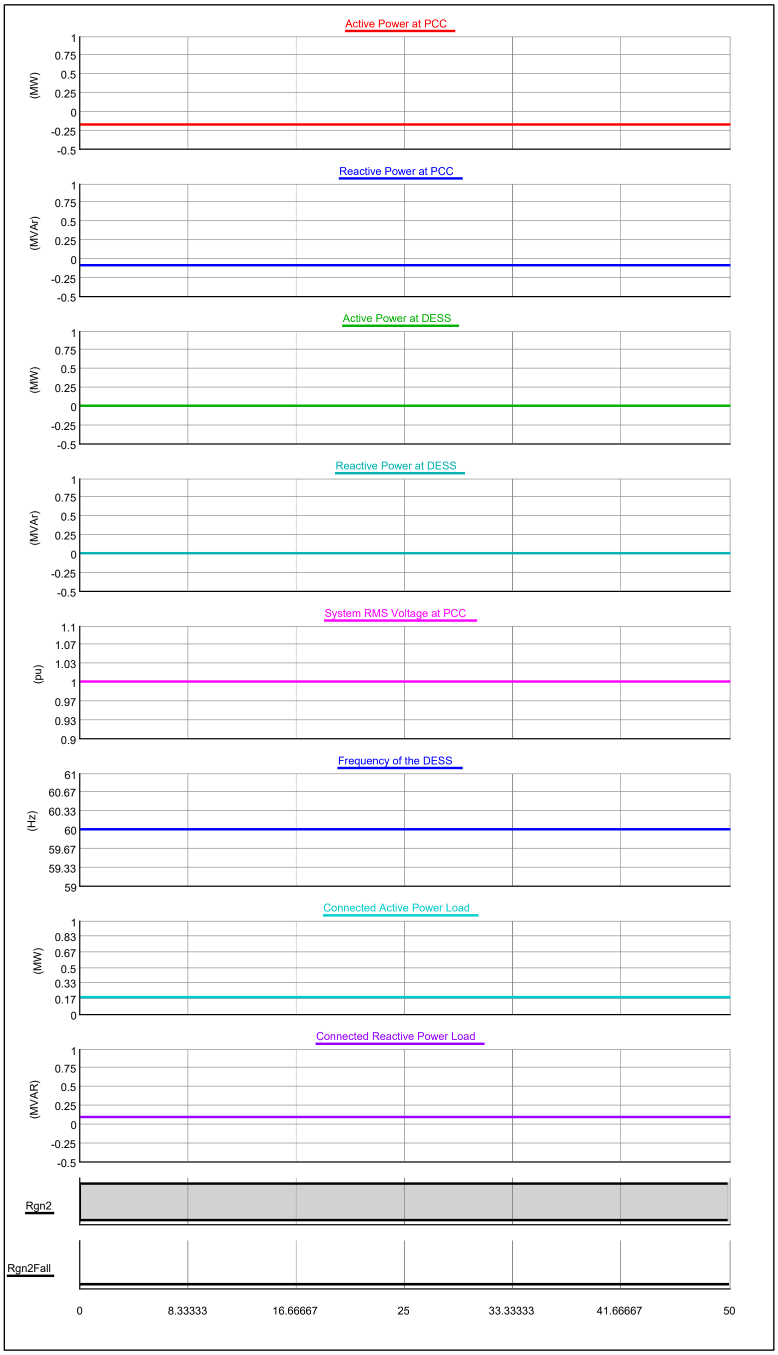

Figure A.78: Idle Grid Connected System With Frequency-Watt and Volt-VAR Modes

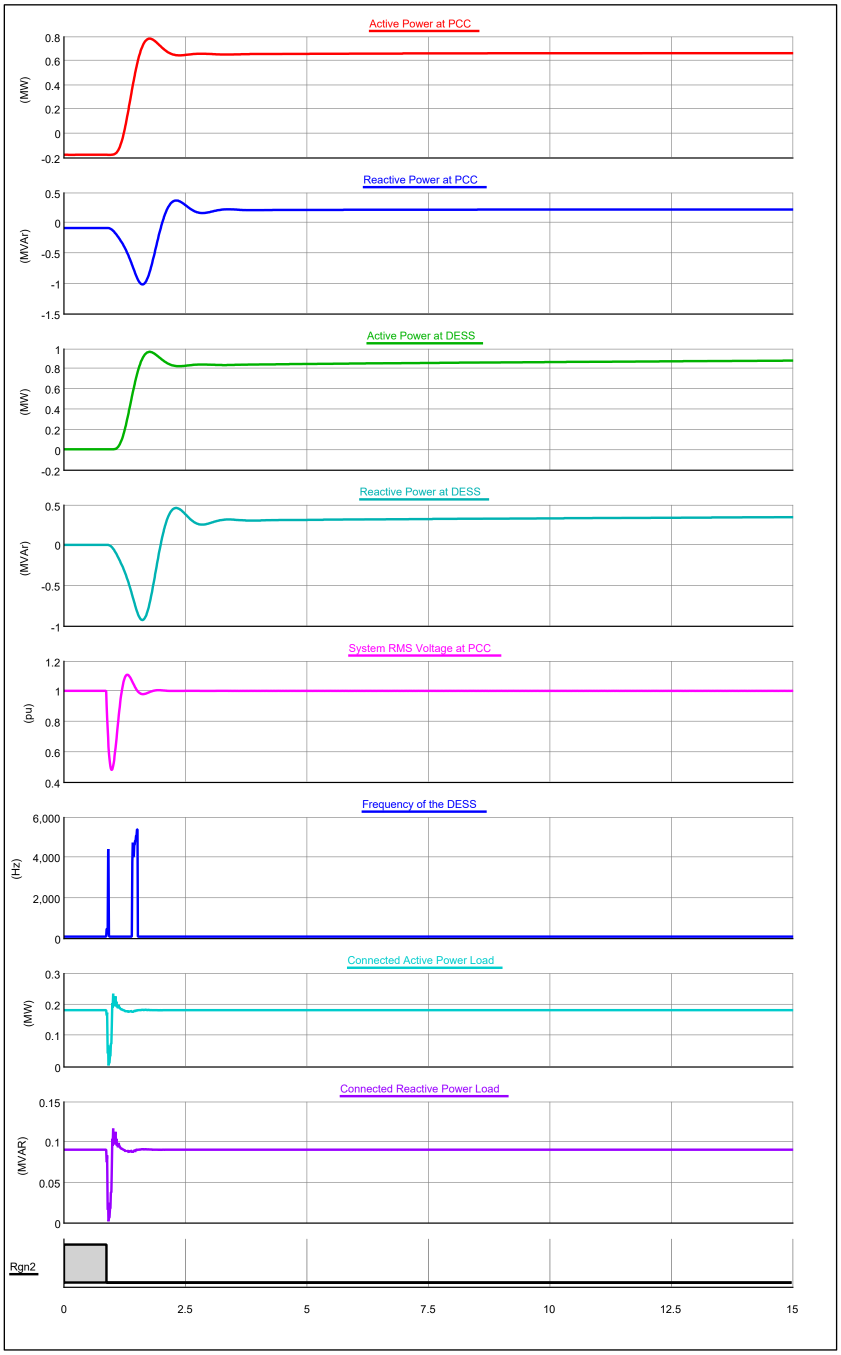

Figure A.79: System Response for DER Operating as Spinning Reserve Following Underfrequency Due to Islanding

Conclusion

On performing a comparative analysis in terms of economic benefits in fuel savings, ease of operation, response time, and reliability, it is evident that the use of a DER over diesel generators is considerably more beneficial, in terms of both cost and operation. The results from the comparative study in terms of various aspects are presented below.

COST

The capital cost of installing the DER is the only major cost involved in the battery storage system because the overall operation cost along with the idle charge losses is negligible. There is no fuel that needs to be replenished frequently as in a diesel generator, and hence the operational cost is considerably lower.

Compare the performance of the diesel generator of a similar rating of 1 MW, whose approximate fuel flow rate is specified as:

$$\text{Fuel flow (GPH)} = 1.1312 \bullet \text{MW (\% of the rated MW)} + 10.01$$

The total cost of the diesel generator based on the average cost of diesel of $2.562 per gallon.

Fuel cost during idle period for a period of 1 hour:

$$\text{Fuel cost} = \text{fuel flow (gallons per hour)} \bullet 1\text{ hour} \bullet \frac{\$2.562}{\text{gallon}}$$

$$\text{Fuel cost} = 10.01 \bullet \$2.562 = \$25.62$$

The fuel cost for a generation of 845.6 kW (0.8456 MW) for a period of 1 hour is calculated as follows:

$$\text{Fuel cost} = (1.1312 \bullet 0.8456 + 10.01) \bullet 1\text{ hour} \bullet \frac{\$2.562}{\text{gallon}} = \$28.096$$

$$\text{Total fuel cost} = \$53.71$$

The timelines considered here are solely for comparison; however, the actual idle runtime can exceed more than an hour, which increases the cost of operation rapidly. This cost is considerably higher than a negligible operational cost of the DER system, and hence a DER system is an economic source of spinning reserve than a diesel generator system because the idle loss of the diesel generator is almost half of the operation cost incurred by it.

RESPONSE TIME

The battery responds to changes in frequency and voltage due to islanding faster than a diesel generator. The response time of the battery to switch from grid connected mode to island mode was a period of 5 to 6 cycles, which is considerably faster than a diesel generator switching whose default ramp rate is around 40 percent of its rated capacity per minute, which means for an active power load of 85 percent of its rated capacity, the response is expected to be more than 120 seconds. This makes a DER an obvious choice for fast response.

OPERATION AND MAINTENANCE

A DER is relatively easier to operate and environmentally cleaner source compared to a diesel generator, which needs to be monitored frequently for changing operation and causes environmental pollution. Furthermore, a DER requires little or no maintenance compared to a traditional diesel generator, which needs frequent maintenance. This makes a DER an obvious choice of spinning reserve over diesel generators.

SPINNING RESERVE TEST RESULTS:

The purpose of this test is to assess the benefits of using the DER a source of spinning reserve to provide the active power support during different system conditions as compared to conventional diesel generators. The DER is connected near the end of the feeder (Scenario 3) in this test. The results of this test proved that the DER is quite effective in sustaining loads during periods of underfrequency, providing voltage and frequency support within a short period. In addition to being a fast spinning resource, it also proves to be more effective in terms of cost and efficiency and better in terms of environmental factors and ease of operation and maintenance.

TEST 8 – BLACK START

The battery storage system can be used to black start the system after complete system outage. The battery can operate in VSI mode to provide voltage and frequency support during the black start. Once the nominal voltage and frequency are established in the island, the loads can be picked up slowly and other renewable generation sources can be brought online to support the islanded load on the feeders.

The simplified test circuit for Scenario 3 for black start is shown in Figure A.80.

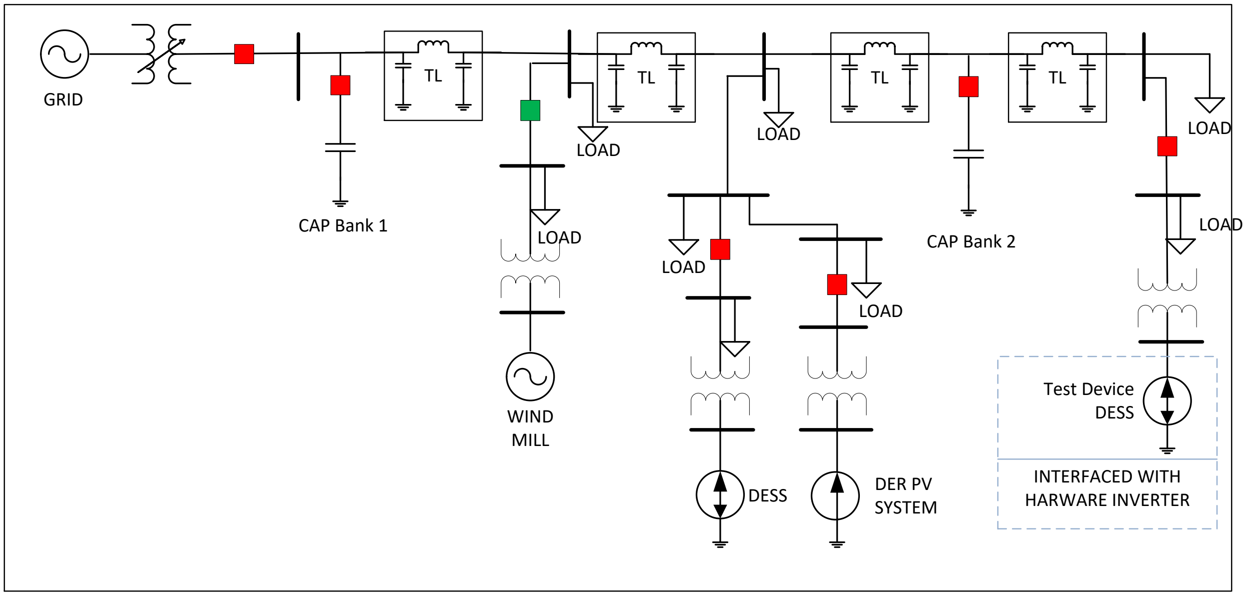

Figure A.80: DER at the End of a Long Feeder (Typical)

For the software testing, follow these steps:

- Step 1. While the system is running in steady-state conditions, open the grid circuit breaker, which should lead to a blackout in the system.
- Step 2. Identify the DER that can be used as a source to create an island. Disconnect the loads from the system so that the DER can feed enough load within its capacity without collapsing when brought online.
- Step 3. Once the island is formed, close the breakers connecting to other renewable sources in the system, such as the PV system and wind turbines.
- Step 4. Keeping in mind the available generation capacity, start closing the load breakers one by one.
- Step 5. Record the system voltage and frequency during the steps performed for the black start operation. Document the black start and load restoration procedure for analysis.

Test Procedure and Results

STEP 1: CLOSE THE TEST DER BREAKER TESTBKR

The grid breaker was opened, which caused a complete blackout in the system. All loads and DER were disconnected from the circuit. The total load of the system was brought down to 2 MW, which was within the capacity of the two DER put together. The circuit and the test the DER supplied active and reactive power to their local load in their respective islands. When the test inverter breaker (TESTBKR) was closed, the test DER was brought into the circuit. No loads were connected yet because the load breakers were still open, and hence the active and reactive power output of the test inverter and the circuit DER were not changed. The frequency and system voltage remained unaffected during this switching, while the power import across the PCC did not change as well.

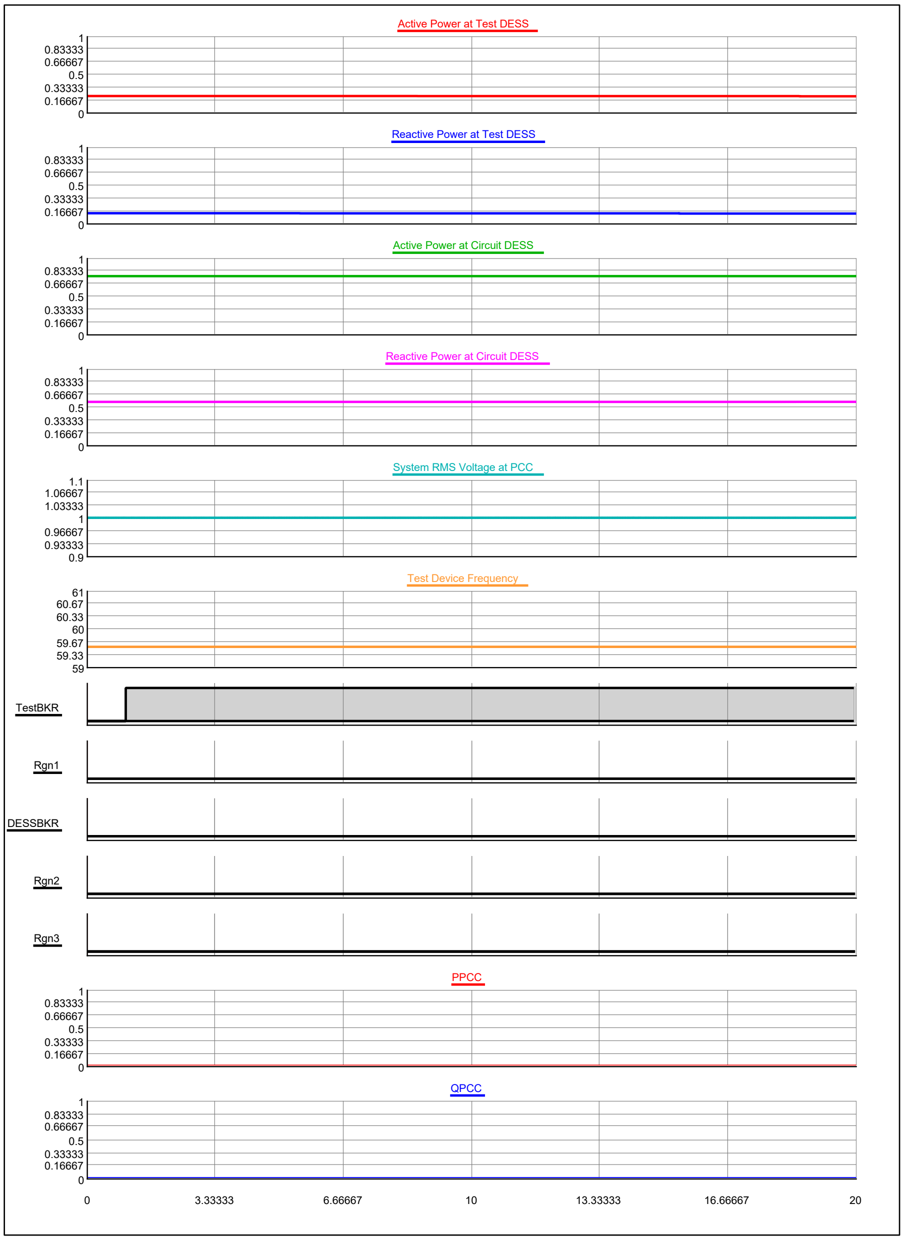

Figure A.81: System Response for Step 1

STEP 2: CLOSE THE LOAD REGION 1 BREAKER

When the load breaker for load Region 1 closed, the net load connected to the test DER increased, causing the active and reactive power output of the test DER to increase. This changes the power transfer across the PCC, which supplied power into the grid. The frequency across the DER had a minor fluctuation because of the switching transients but settled into the previous value during steady-state conditions. The active and reactive power output of the circuit DER did not change because it was still in its island mode and disconnected from the rest of the grid. The voltage remained unaffected by the change and was maintained approximately at 1 pu.

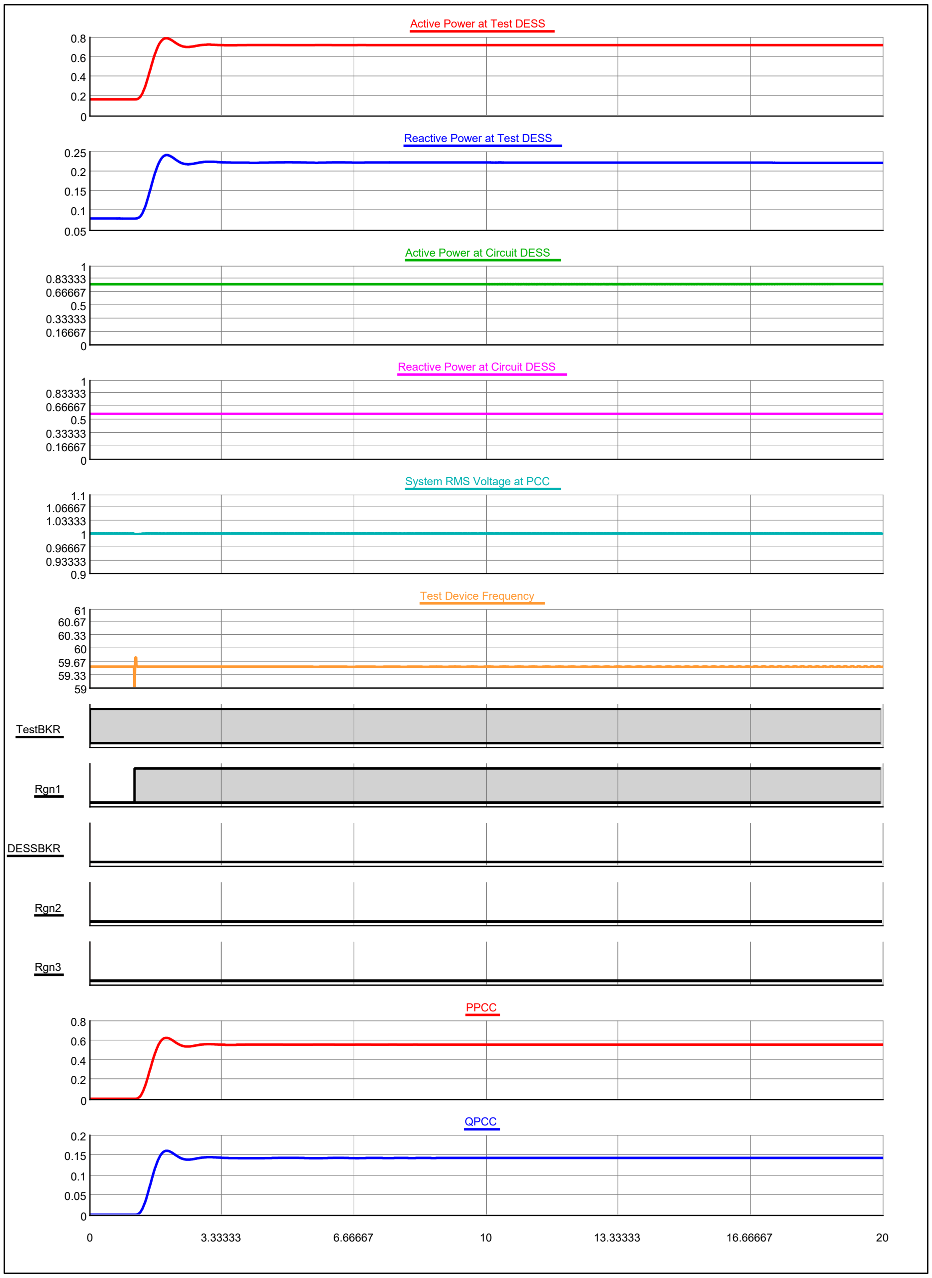

Figure A.82: System Response for Step 2

STEP 3: CLOSE THE CIRCUIT DER BREAKER (DESSBKR)

When the circuit DER was brought into the grid by closing the DESSBKR circuit breaker, the circuit DER output increased while the test DER output decreased to balance the existing loads in Region 1 between the two DER. This shift in power flow caused the power export across the PCC to reduce, resulting in the real and reactive power across the PCC to decrease. The system voltage and the frequency remained unaffected by the change.

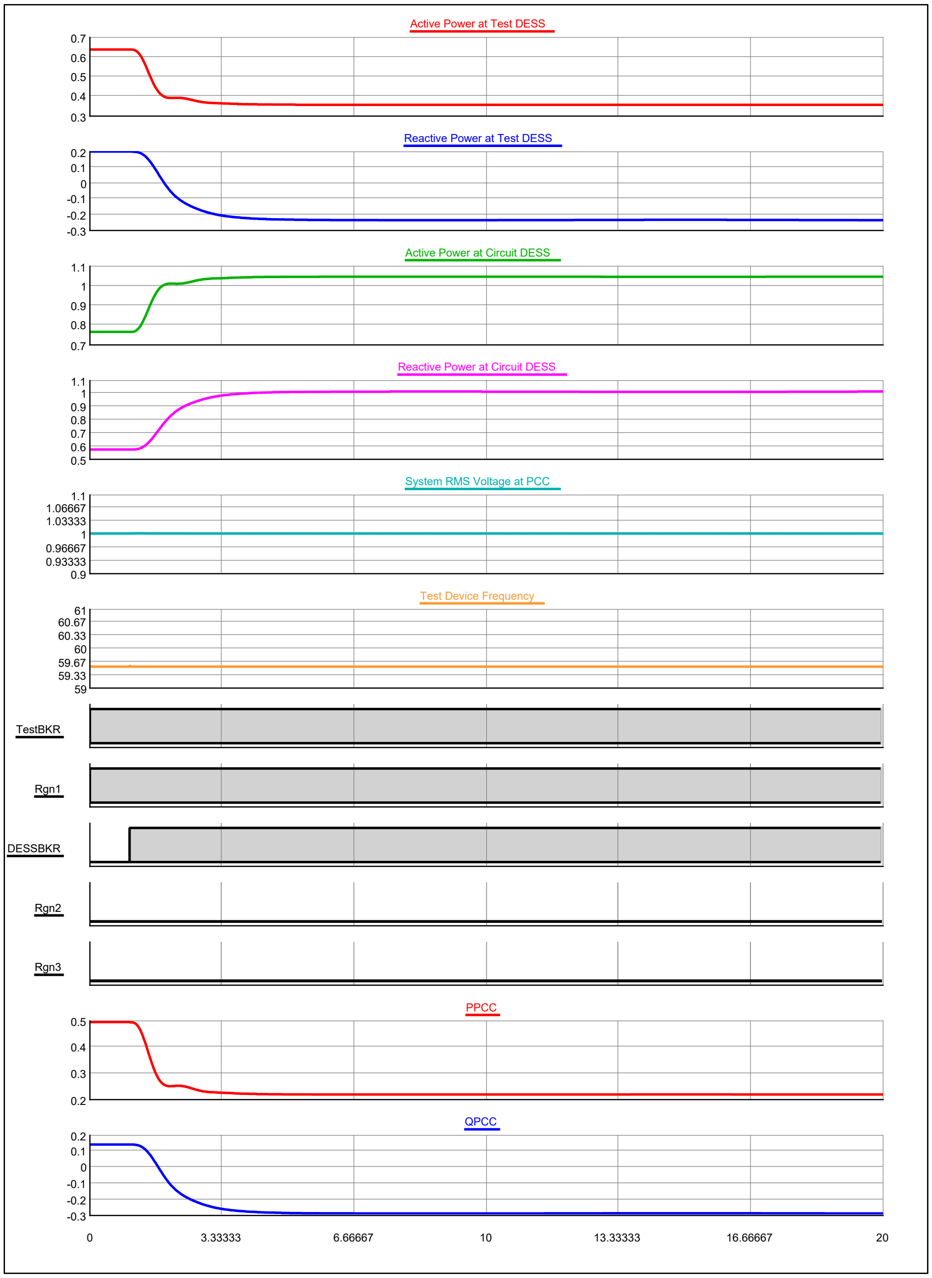

Figure A.83: System Response for Step 3

STEP 4: CLOSE LOAD REGION 2 BREAKER

When the load Region 2 breaker (Rgn2) closed, another set of loads were connected into the circuit fed by the two DER. This caused the active power output of both the test DER and circuit DER to increase, creating a shift in the reactive power output due to the shift in the load flow. The frequency and voltage had a minor disturbance but immediately settled back into steady-state conditions following the disturbance.

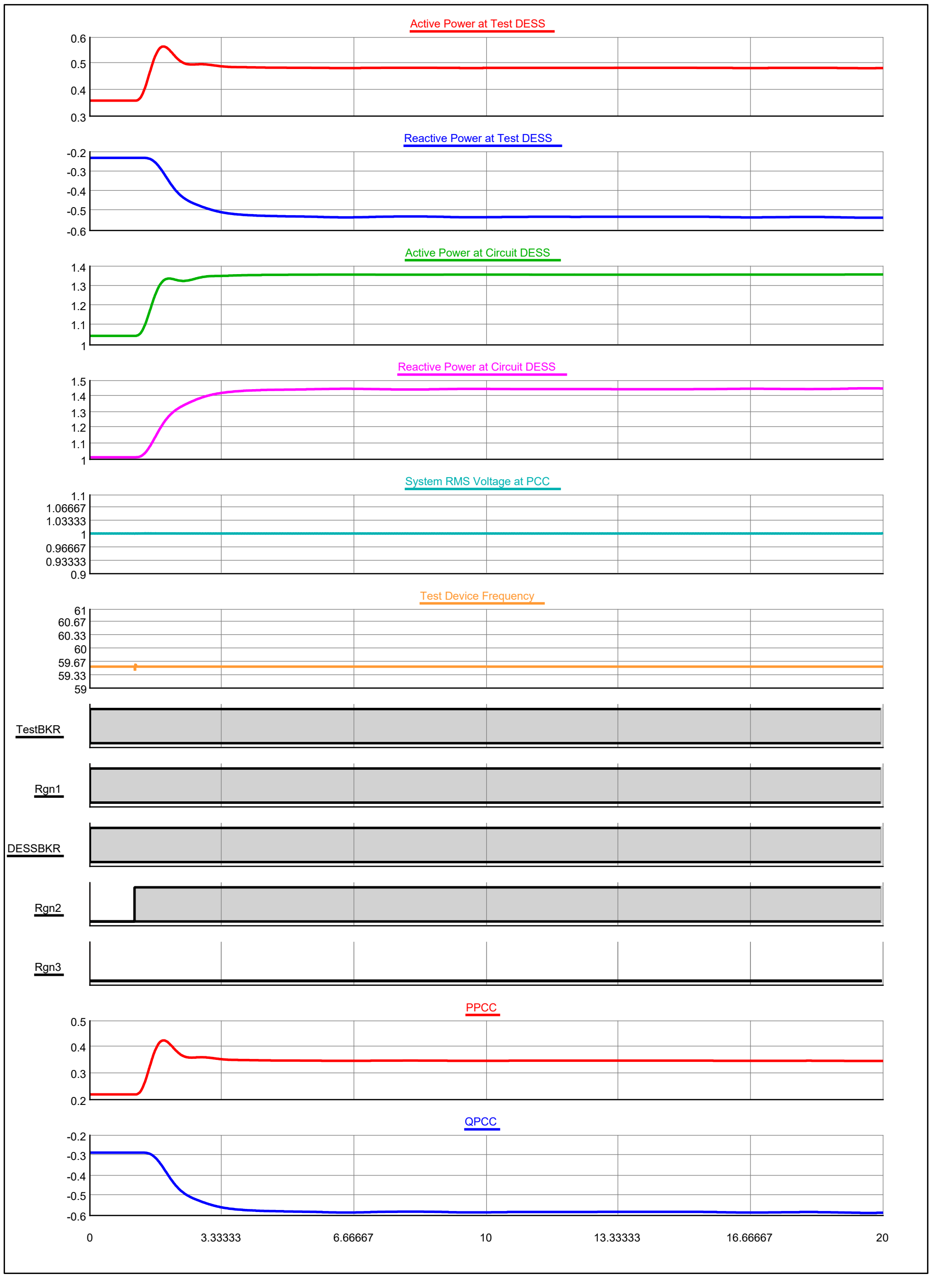

Figure A.84: System Response for Step 4

STEP 5: CLOSE LOAD REGION 3 BREAKER

When the load Region 3 breaker (Rgn3) closed, the last set of loads were connected into the rest of the circuit. This caused the active power output of both the test DER and circuit DER to increase, creating a shift in the reactive power output due to the shift in the load flow. The frequency and voltage had a minor disturbance but immediately settled back into steady-state conditions following the disturbance.

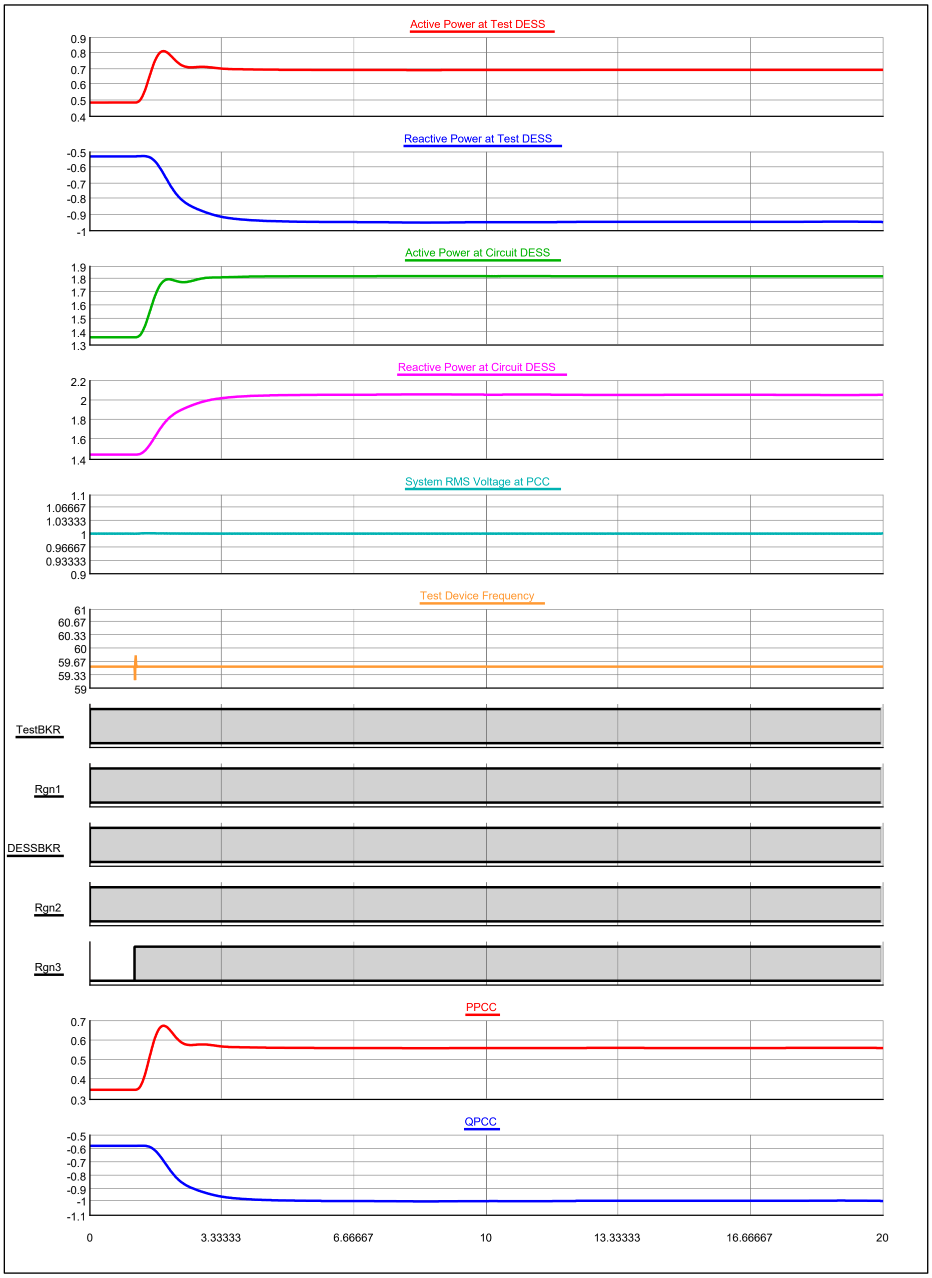

Figure A.85: System Response for Step 5

Conclusion

The purpose of this test is to assess the benefits of using the DER to black start the system after a complete system outage. The result of this test shows the effectiveness of using the DER to black start the system just like the traditional generation to bring the system online in the increment of loads and generations on the circuit. Once the grid breaker opens, causing the system to enter a blackout, the DER enters VSI mode creating reference for voltage and frequency. With the DER in VSI mode, additional load and generation sources can be connected in the system in the subsequent steps. The DER, like the PV system, need a voltage reference from the DER to initiate the startup process to feed the load. The only difference of using the DER as a black start source as opposed to the traditional generators is that the DER offers no inertia to the system.

APPENDIX B   DYNAMIC REDUCED MODEL ANALYSIS

A dynamic model of the distribution circuit is an equivalent reduced circuit with a synchronous source, transformer, load and the DER under test. This model was developed to study the actual response of the synchronous generator to load, voltage and frequency changes and its interaction with the test DER in PHIL environment. These tests served the same objective as that of software and PHIL tests conducted on the detailed model. Only core functions of the DER were demonstrated in this testing.

BUILDING THE MODEL

The source is replaced by the Synchronous generator with governor and exciter control models. The overall line load of the line is simplified to obtain an equivalent line impedance through equivalent impedance calculations. The dynamic model is a representation of the Scenario 3 of the test circuit. The tap changer is modeled as such. The net loads of the circuit are lumped together and is represented by a variable load changed using sliders. The two capacitors are lumped together to create one shunt capacitance.

The test DER is connected to the end of the feeder to study the interaction between the DER, synchronous source and the shunt capacitance for balancing the node voltage at the point of common coupling.

r

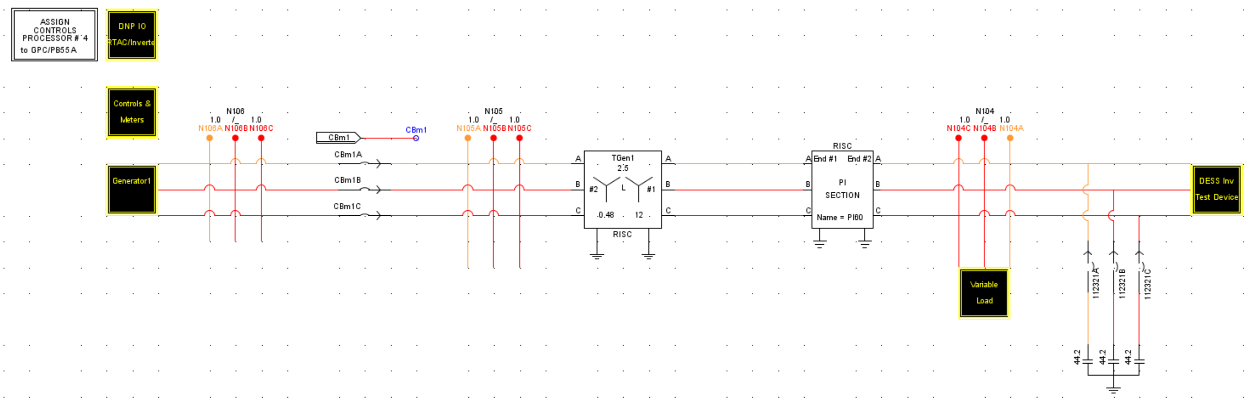

Figure B.86: Simplified Dynamic Equivalent Model of the Carmel Valley Circuit

TEST RESULTS

The dynamic model is particularly tested for the voltage and frequency based tests to test the more realistic response of the synchronous generator. The tests that are conducted with the dynamic model and the system responses are shown in this section:

Test 2 – Schedule Active Power Output

TEST 2.1: CHANGING THE ACTIVE POWER DISPATCH FROM 1MW TO -1MW

On changing the active power set point, the DER absorbed 1MW instead of producing a 1MW active power dispatch. This change in DER output affected the source generator output because of which it increased the active power dispatch. Because of increased megawatt production by the synchronous generator, the system frequency fell momentarily but stabilized in the steady state. The system voltage dropped minimally due to the increased power output from the generator.

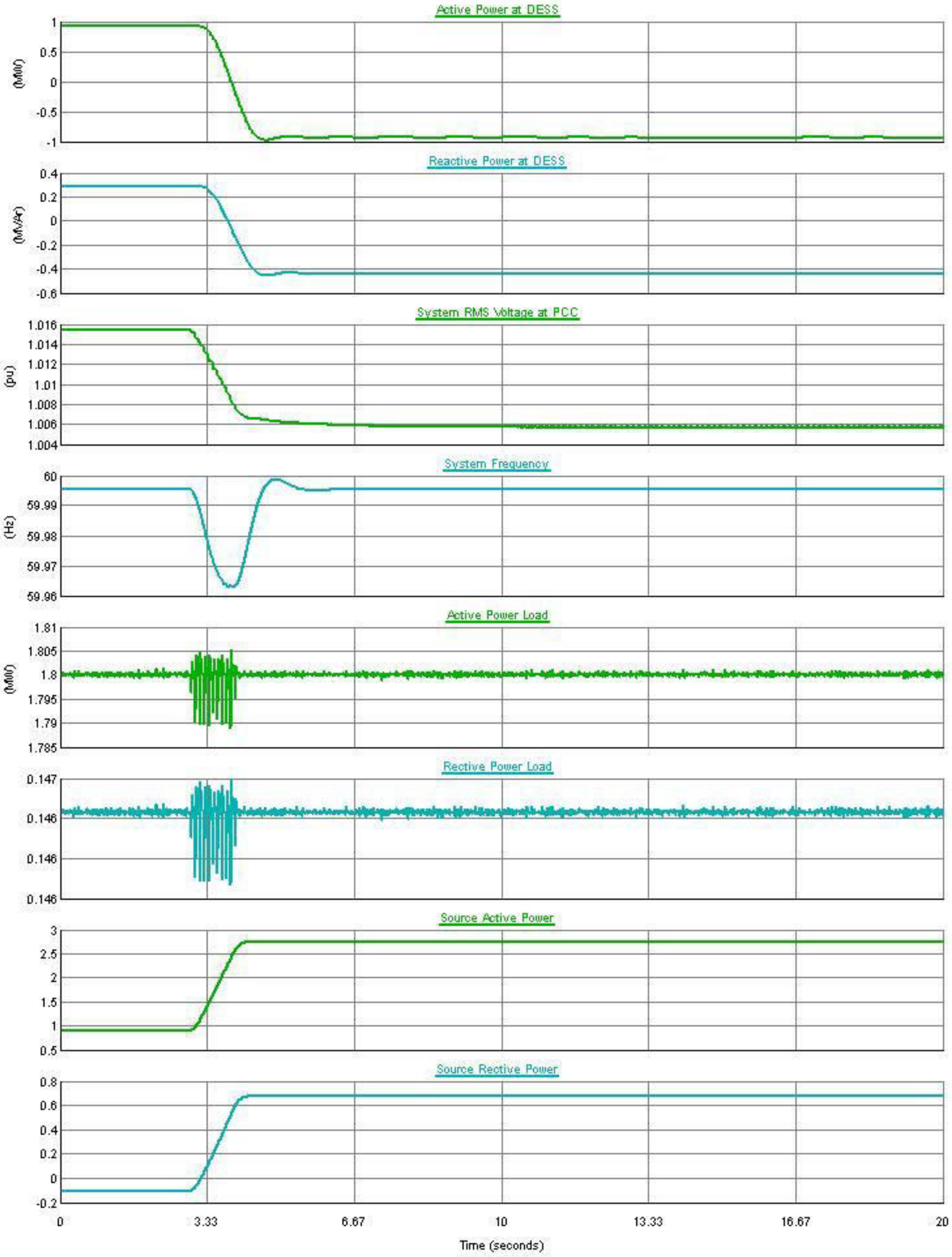

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Figure B.87: System Response for Test 2.1

Test 2.2: Changing the active power dispatch from -1MW to 0MW

On increasing the DER active power set point to 0MW from -1MW, the load reduced at the generator, because of which the voltage across the terminals of the generator increased. The system frequency remained unaffected by the transition.

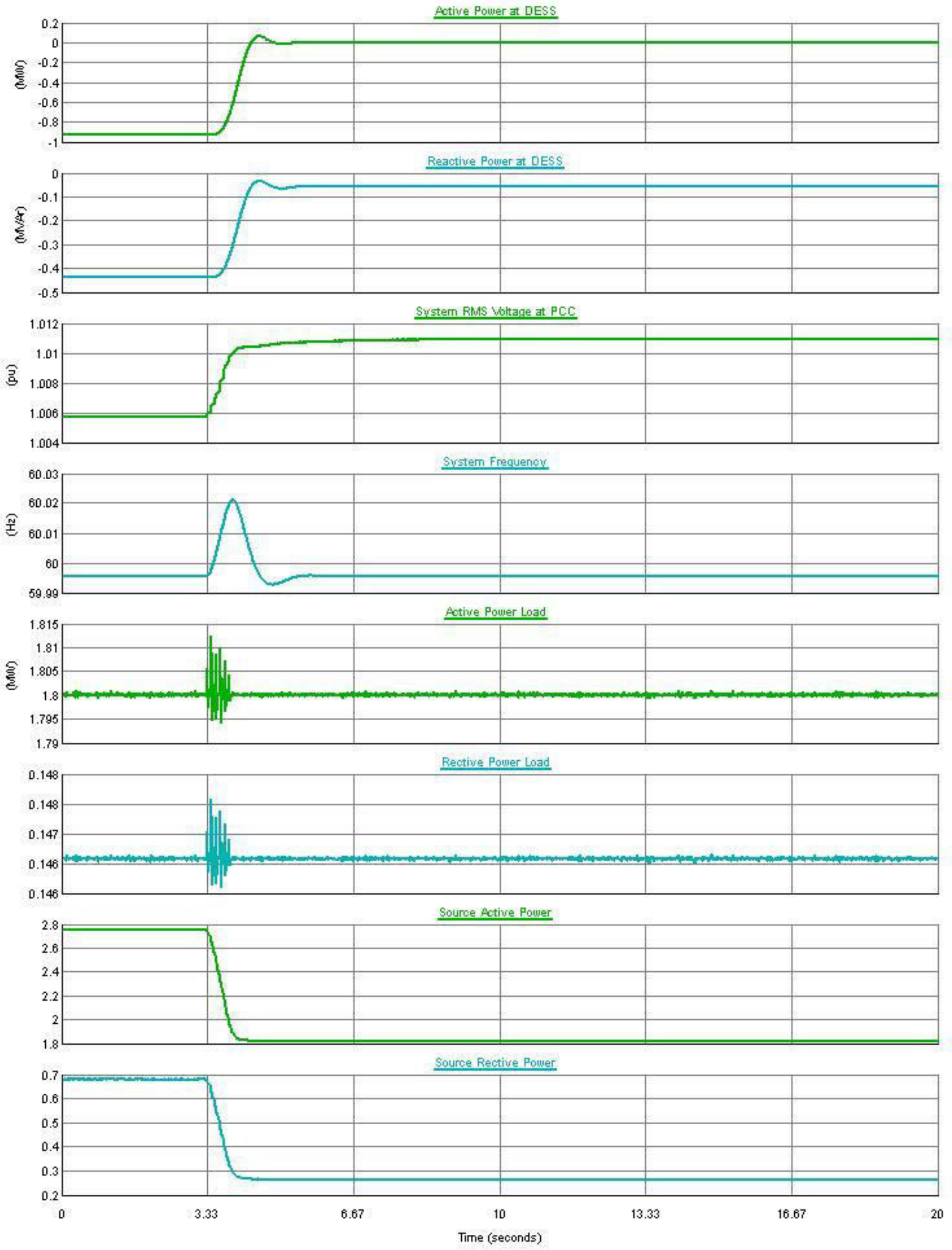

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Figure B.88: System Response for Test 2.2

TEST 2.3: INCREASING THE ACTIVE POWER LOAD BY 4MW

On increasing the connected active power load by 4MW, the DER stayed at the scheduled set point of 1MW while the additional load was supplied by the source.

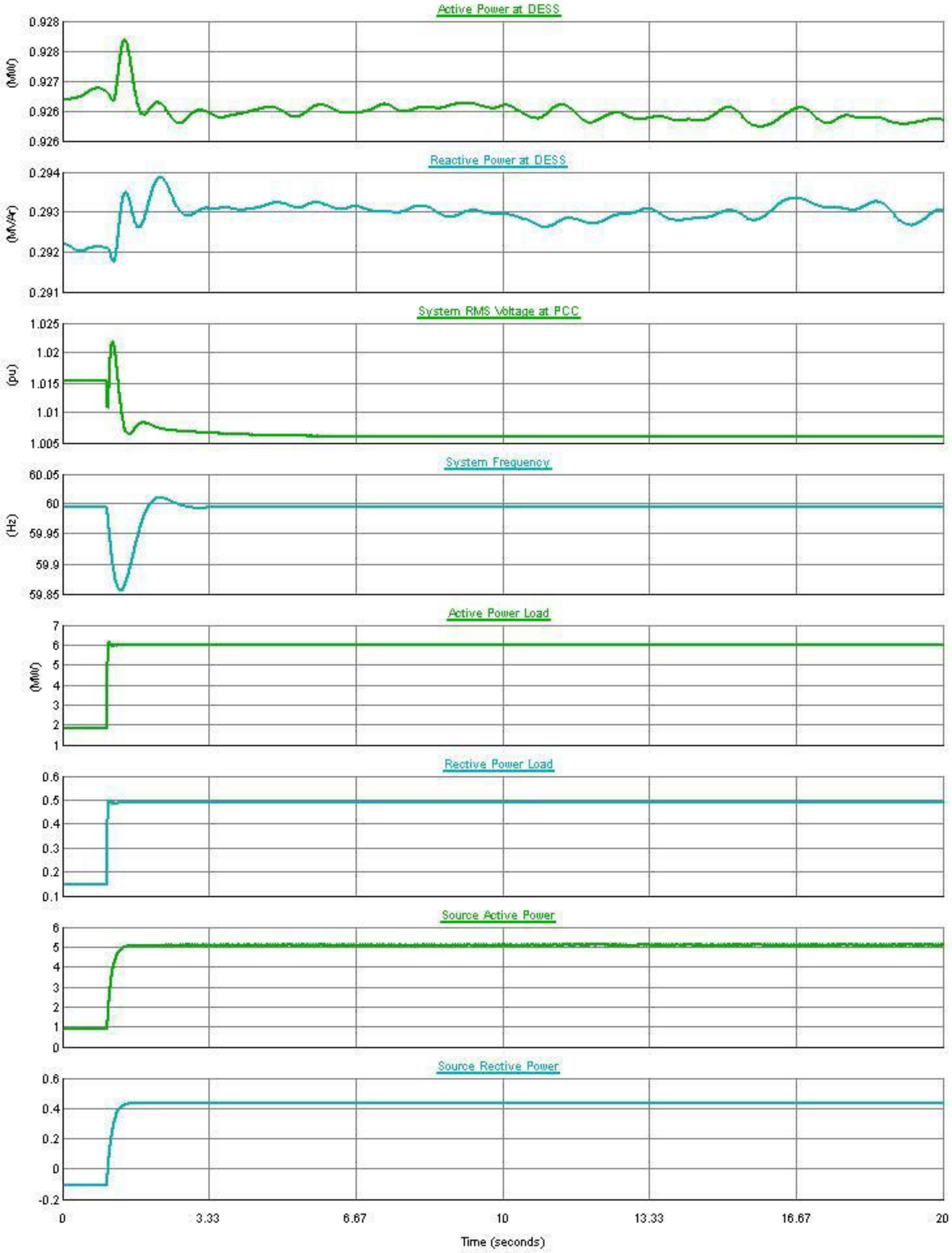

Figure B.89: System Response for Test 2.3

TEST 2.4: INCREASING THE REACTIVE POWER LOAD BY 800 KVAR

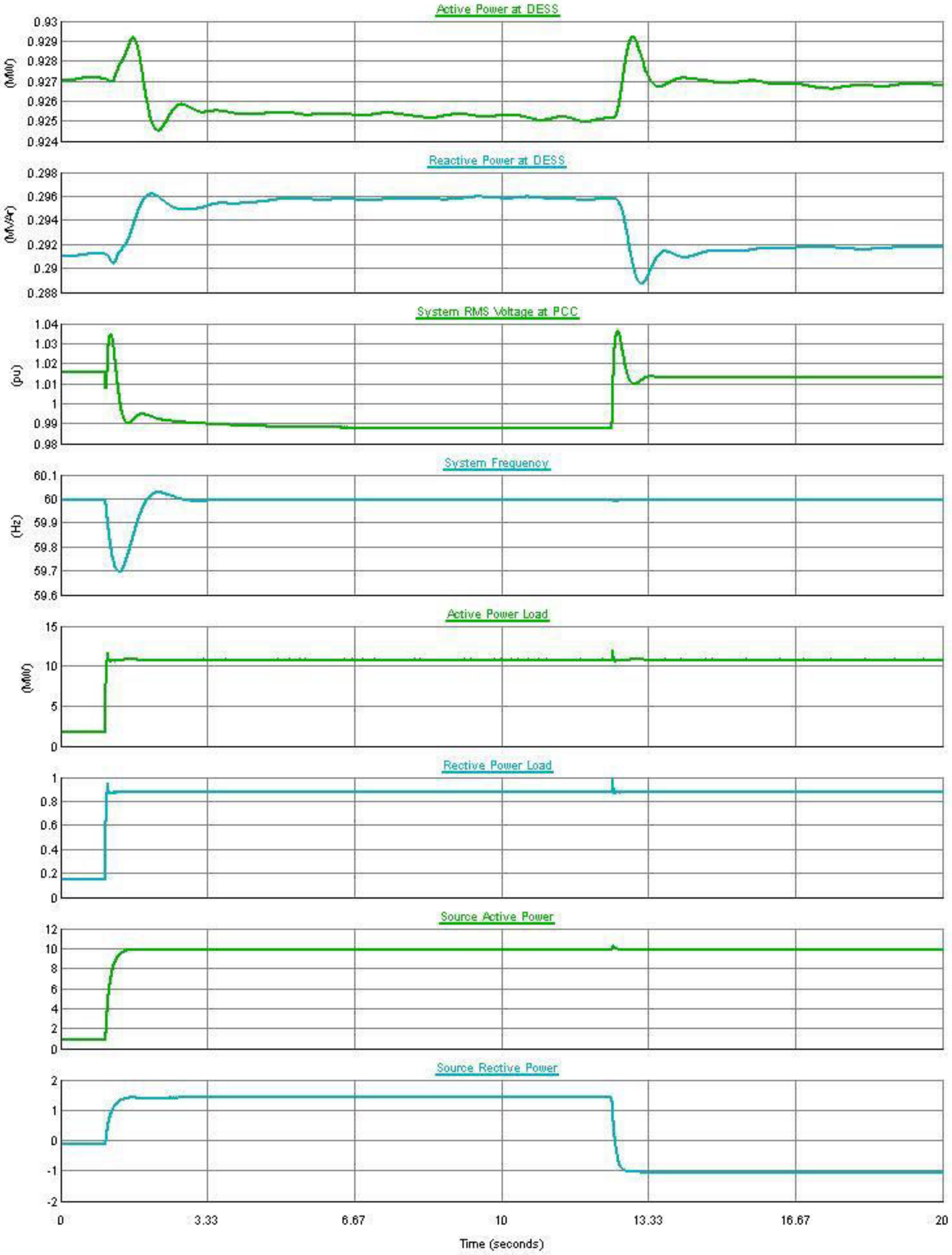

Figure B.90: System Response for Test 2.4

TEST 2.5: INCREASING THE REACTIVE AND ACTIVE POWER LOAD BY 9MW AND 700 KVAR RESPECTIVELY

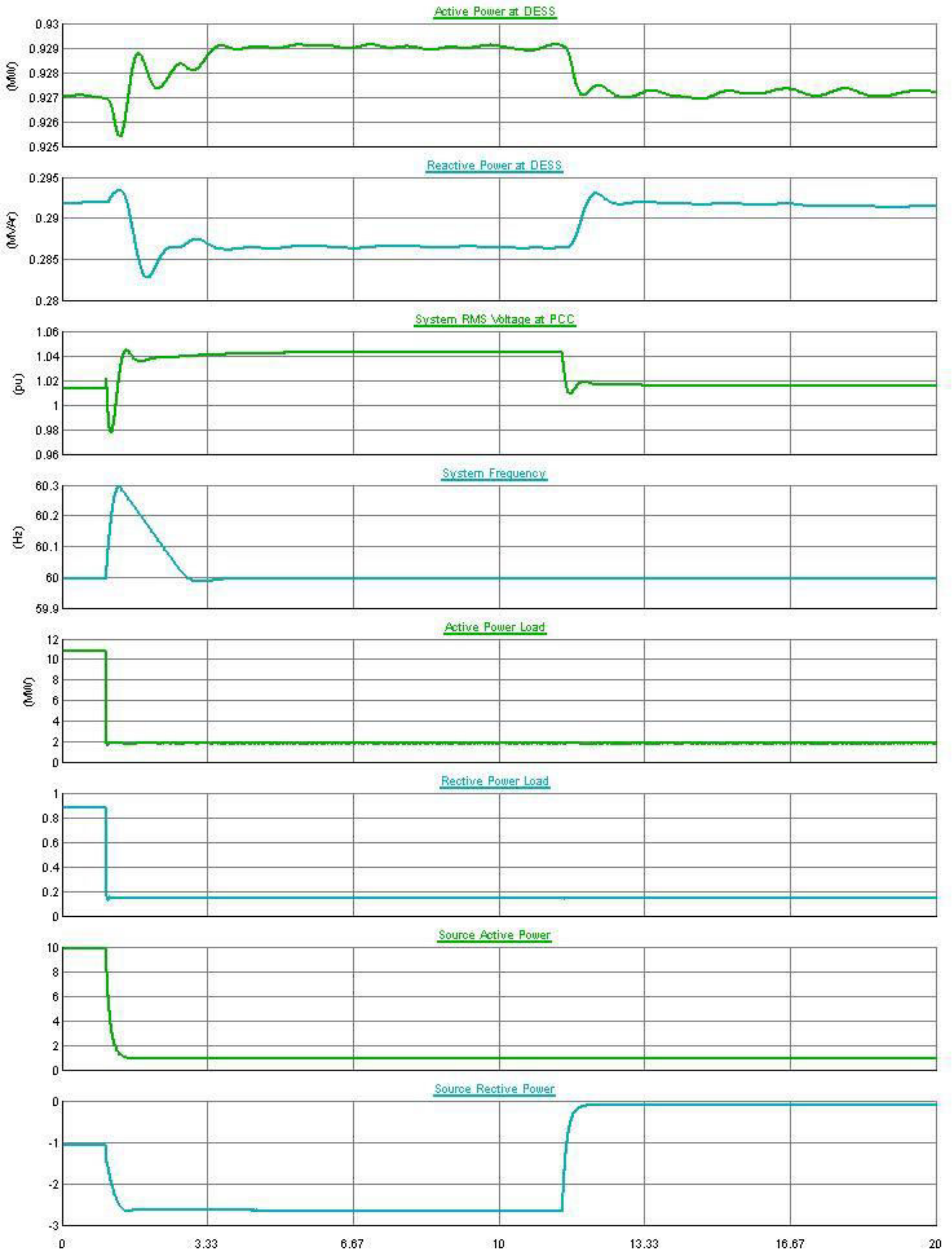

Figure B.91: System Response for Test 2.5

Test 4 – Volt-VAR

TEST 4.1A: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

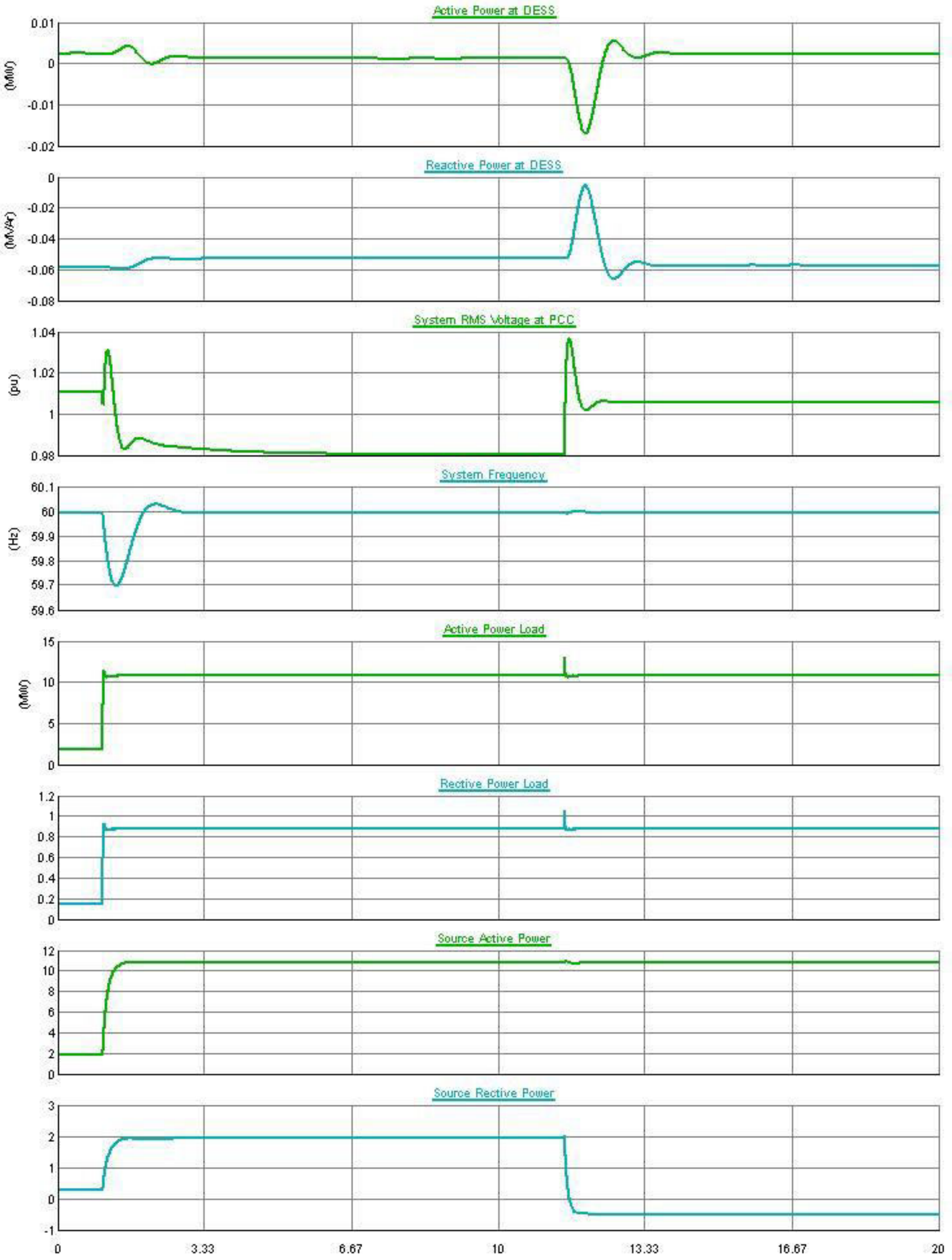

Figure B.92: System Response for Test 4.1a

TEST 4.1B: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

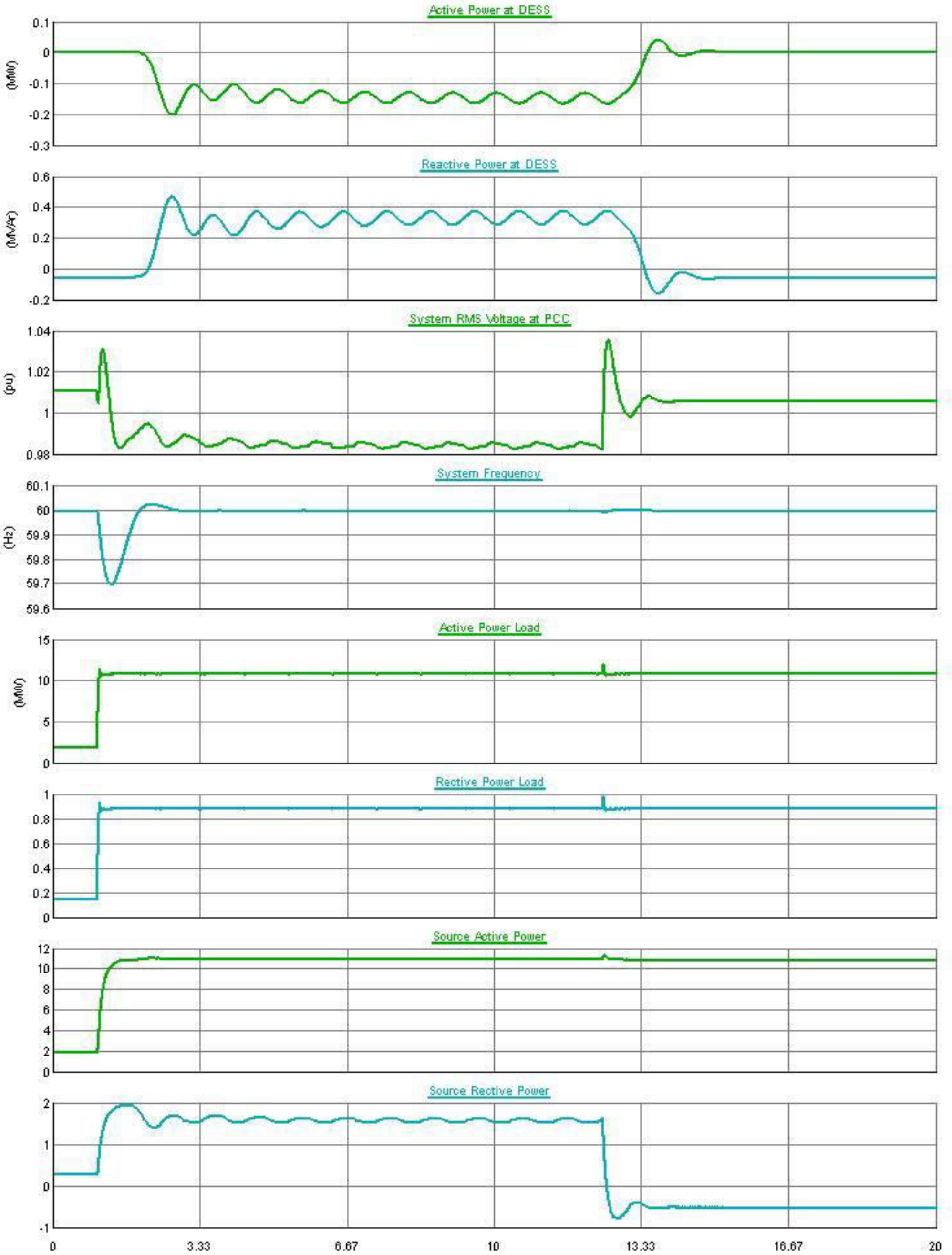

Figure B.93: System Response for Test 4.1b

TEST 4.2A: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

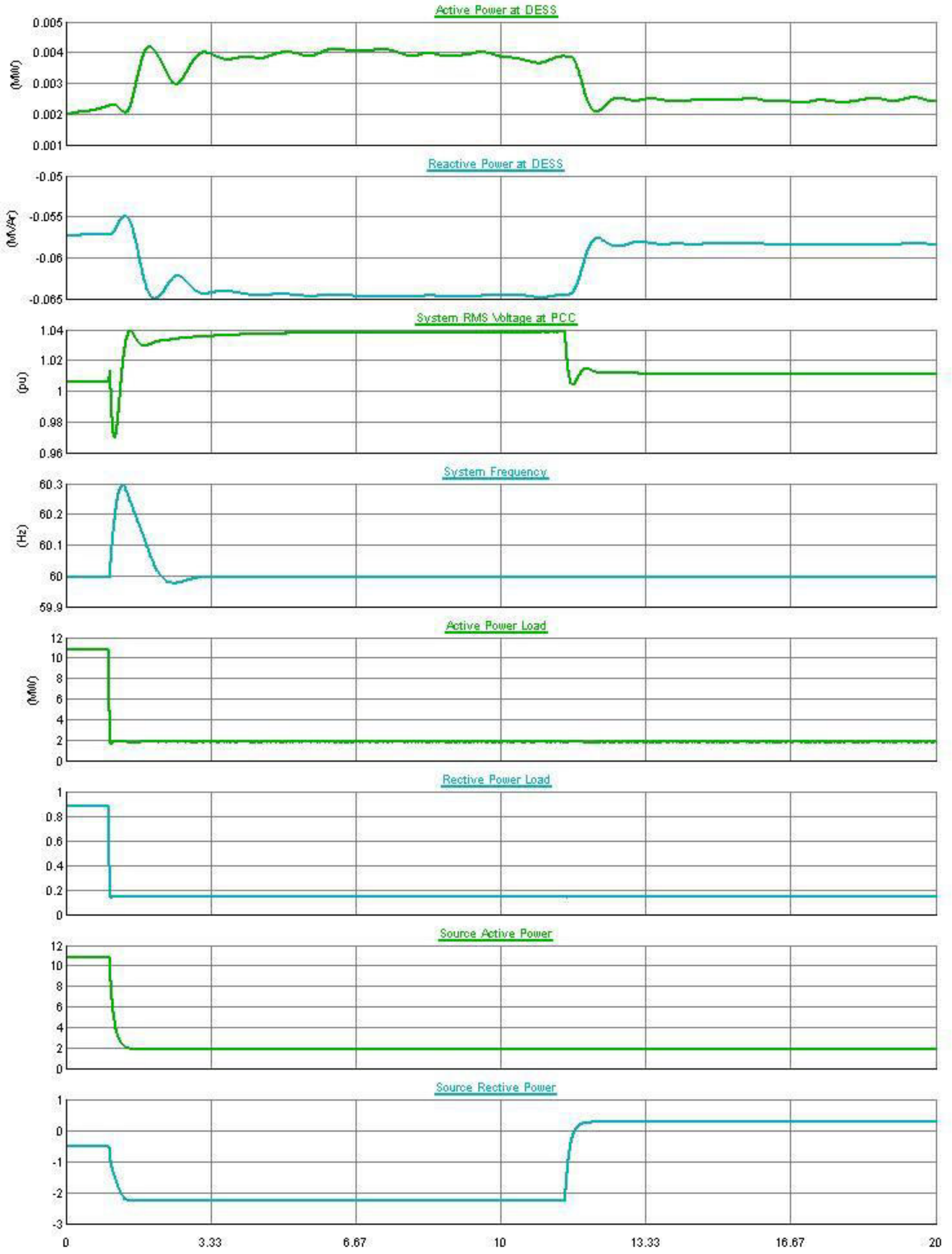

Figure B.94: System Response for Test 4.2a

TEST 4.2B: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

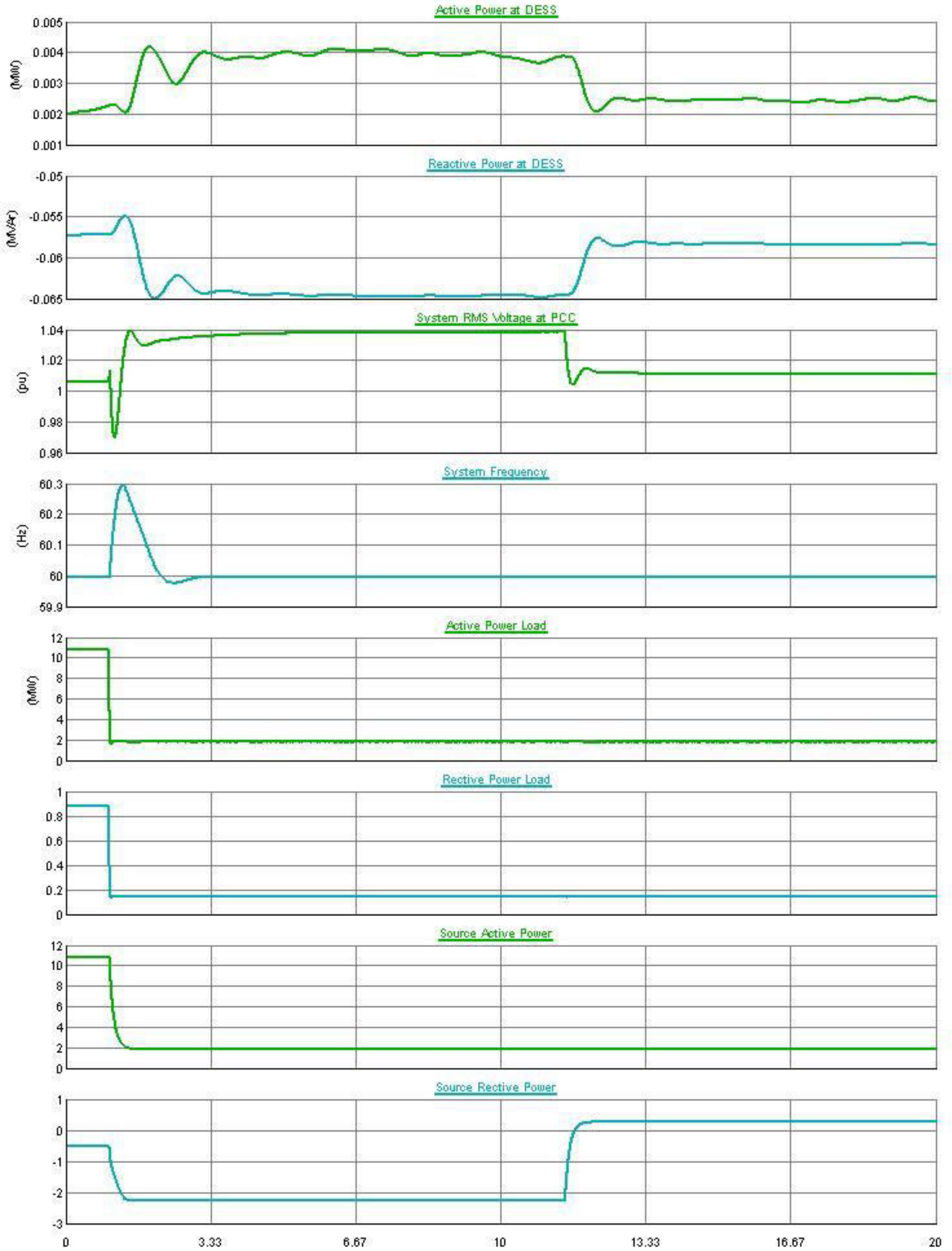

Figure B.95: System Response for Test 4.2b

Test 5 – Frequency-Watt

TEST 5.1A: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

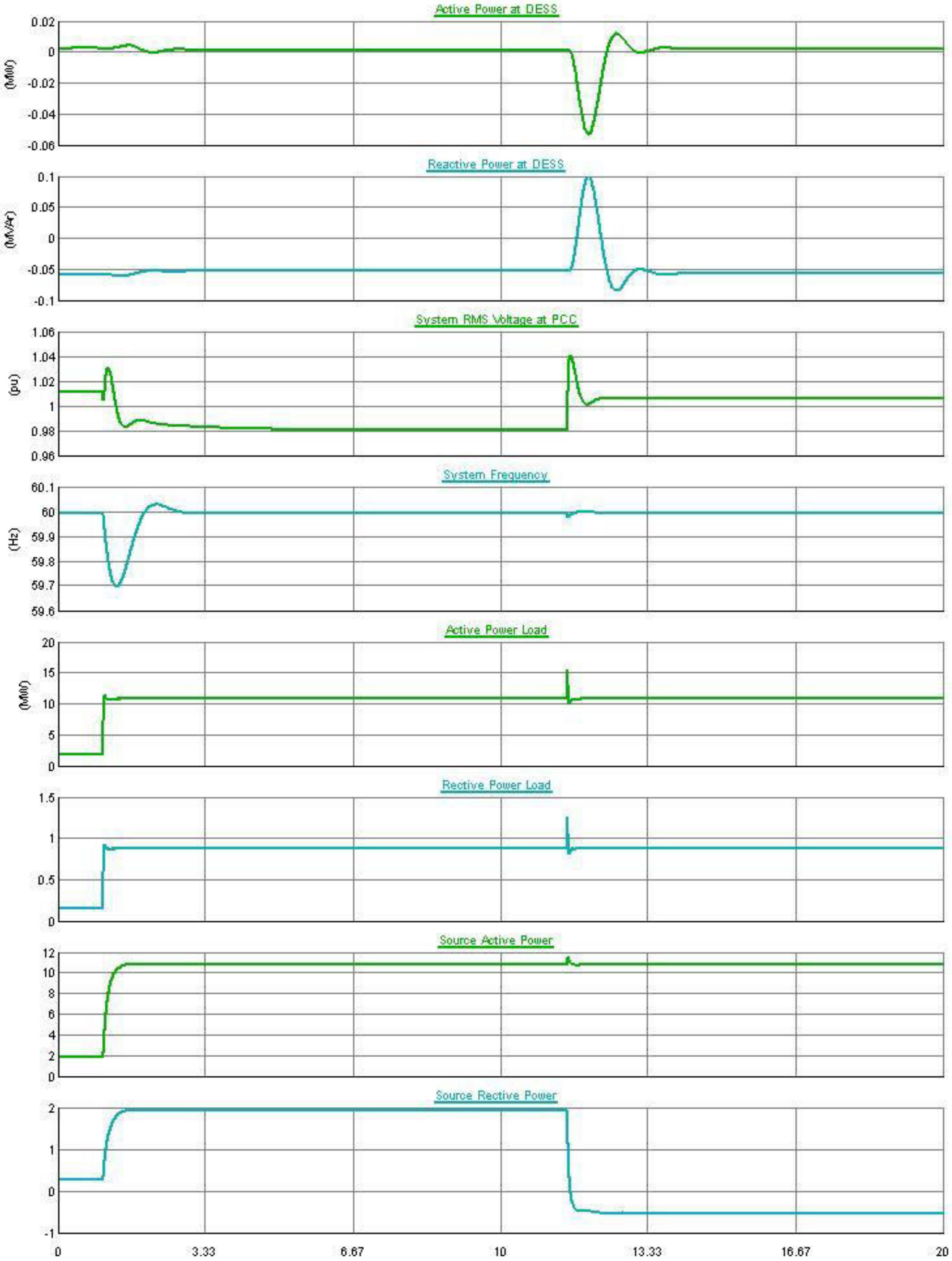

Figure B.96: System Response for Test 5.1a

TEST 5.1B: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

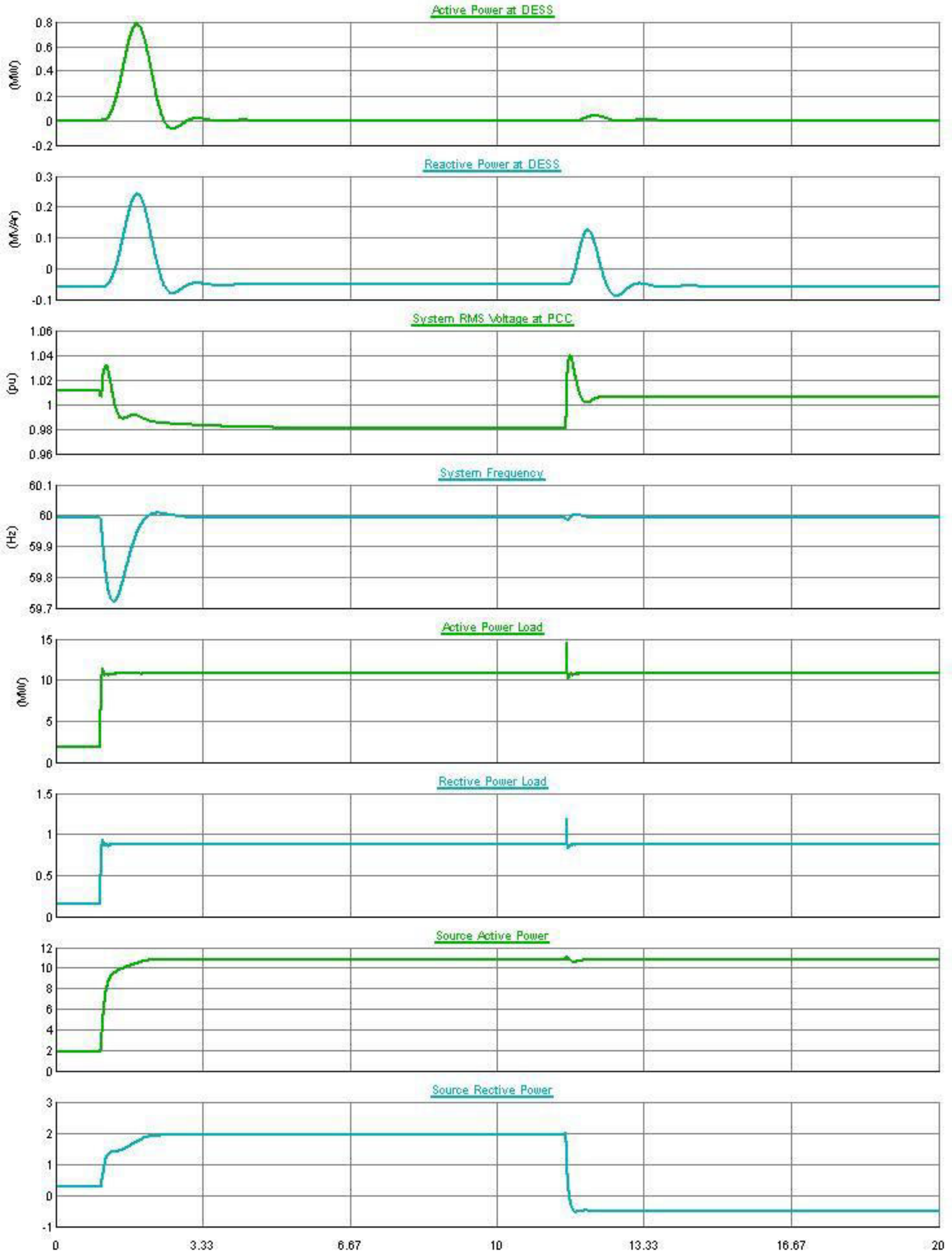

Figure B.97: System Response for Test 5.1b

TEST 5.2A: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

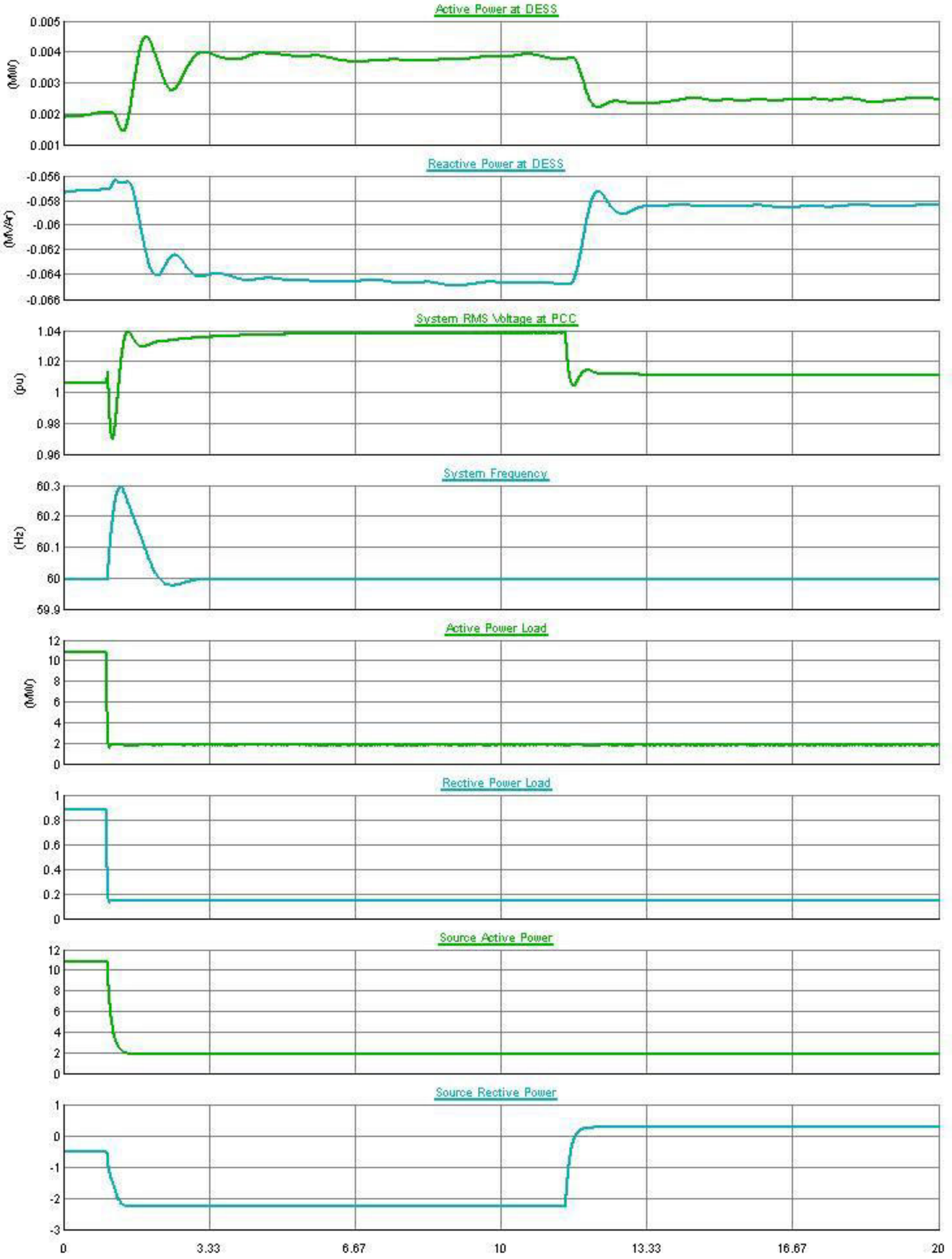

Figure B.98: System Response for Test 5.2a

TEST 5.2B: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

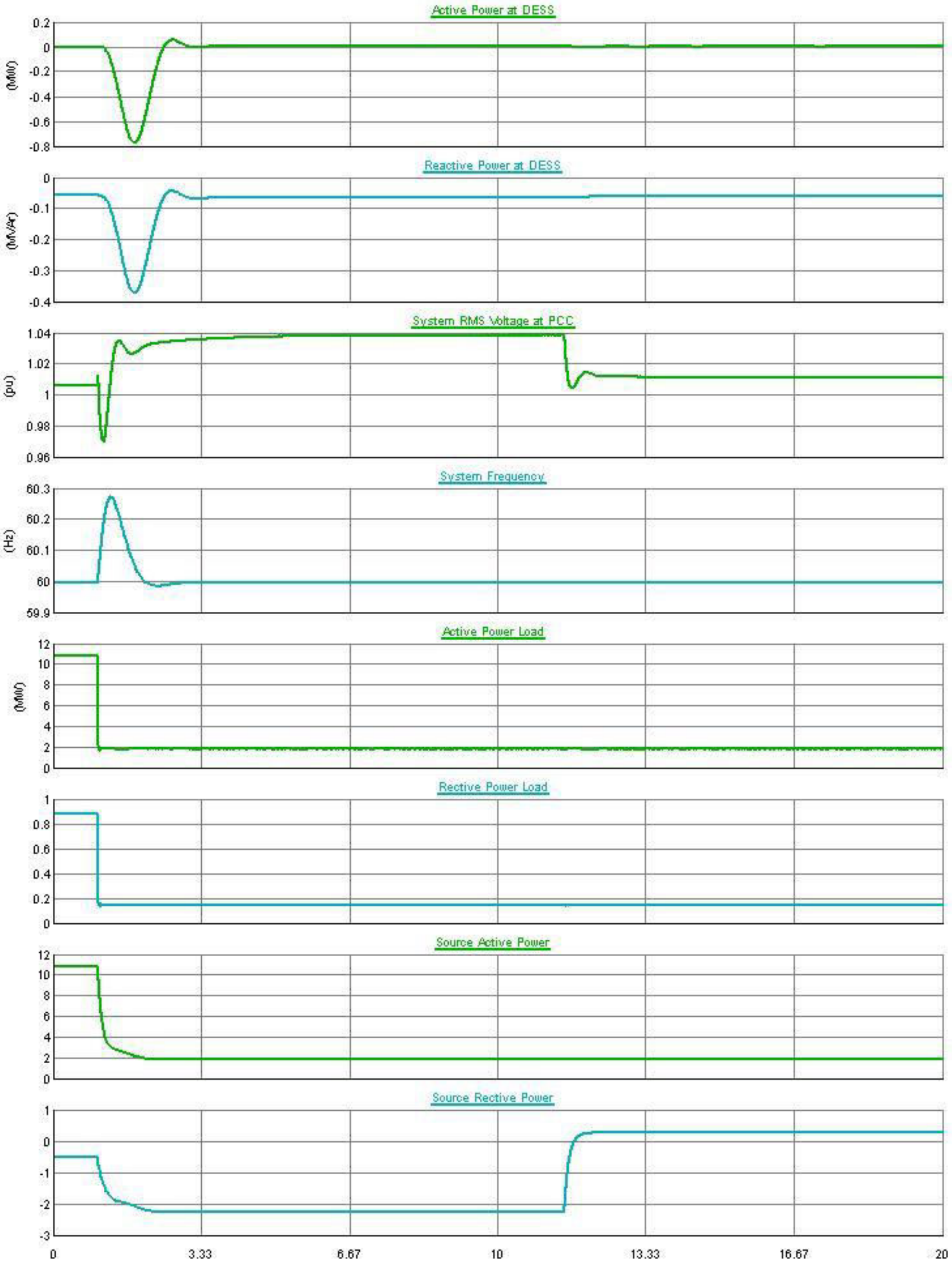

Figure B.99: System Response for Test 5.2b

Test 7 – Spinning Reserve

TEST 7.1A: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

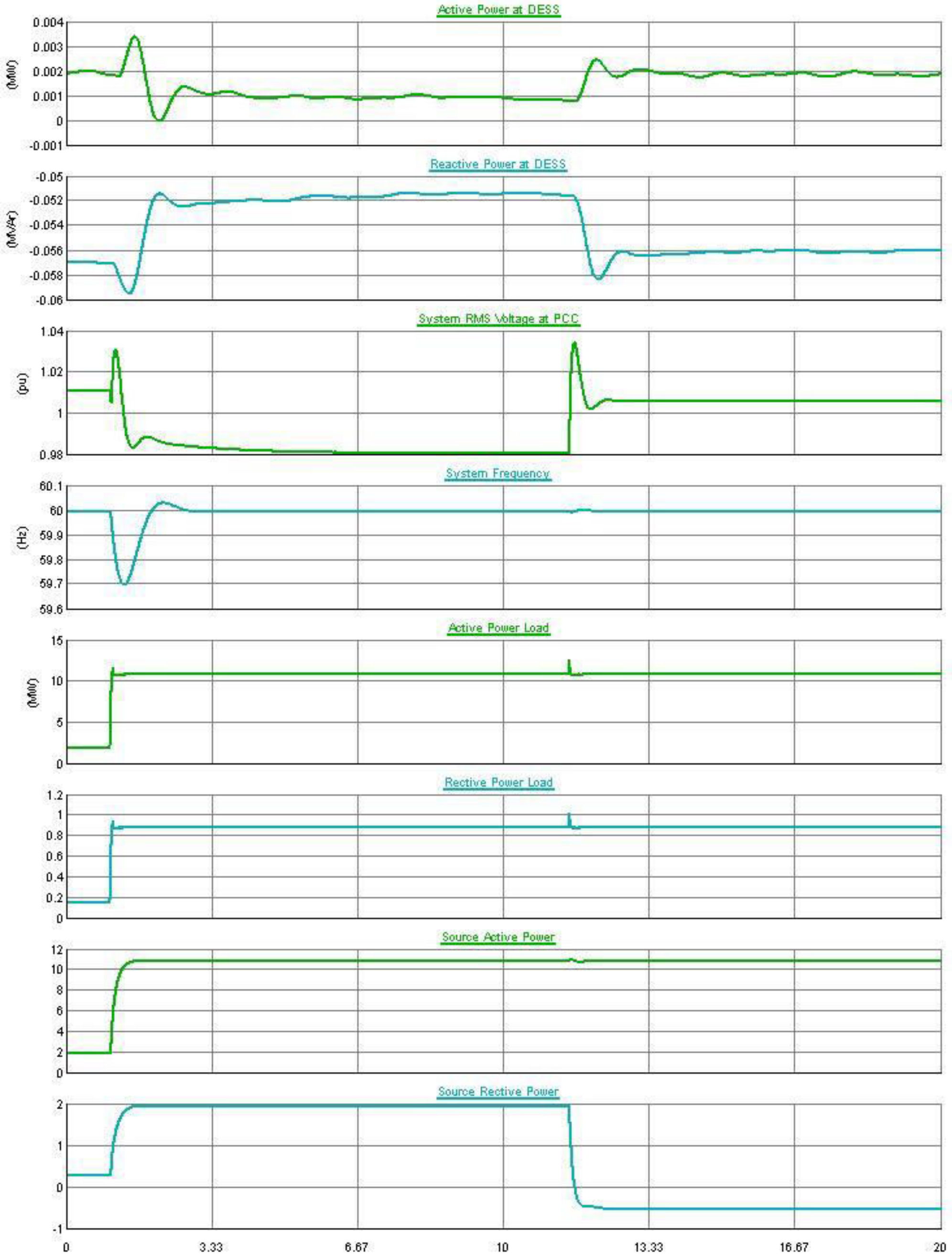

Figure B.100: System Response for Test 7.1a

TEST 7.1B: INCREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

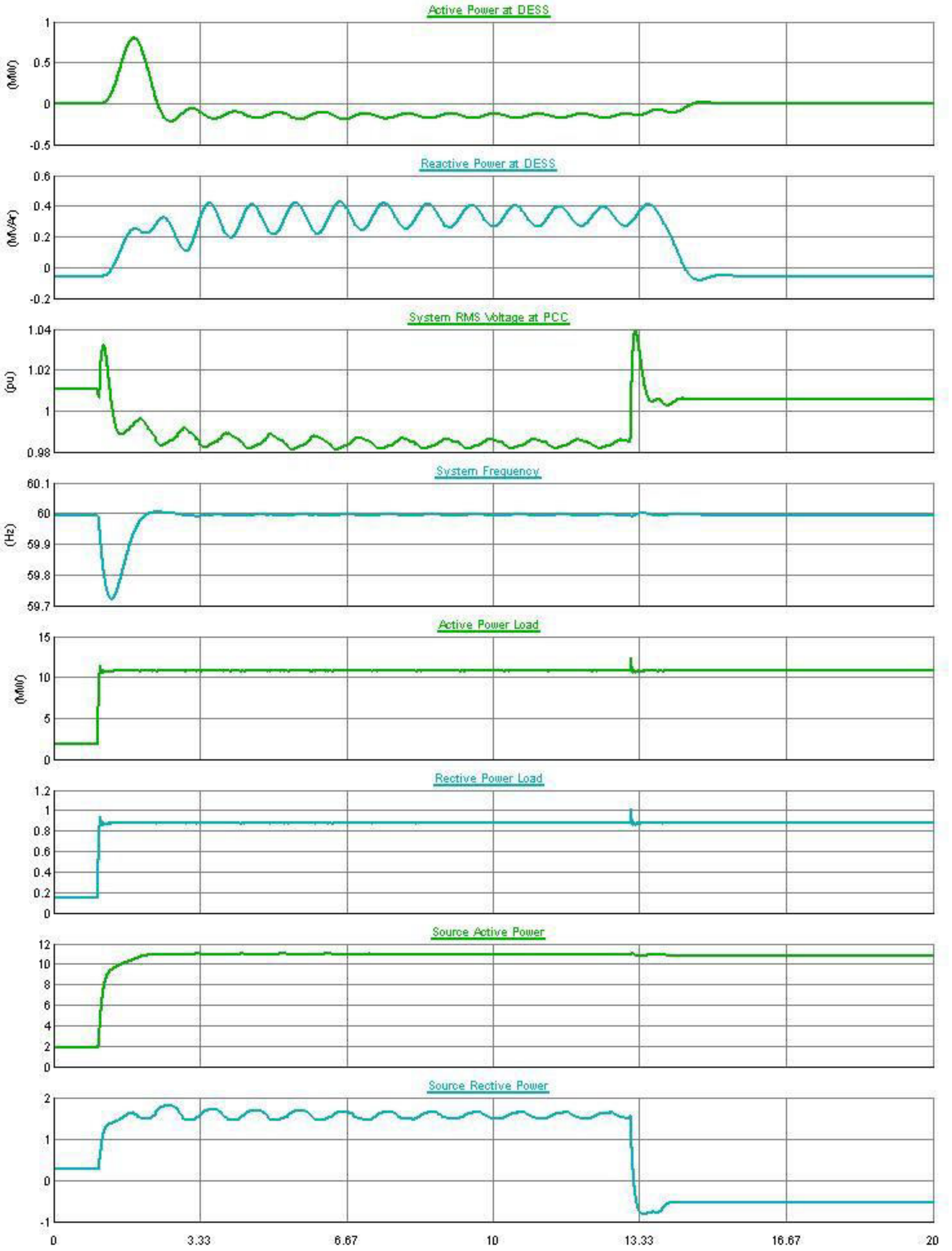

Figure B.101: System Response for Test 7.1b

TEST 7.2A: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR

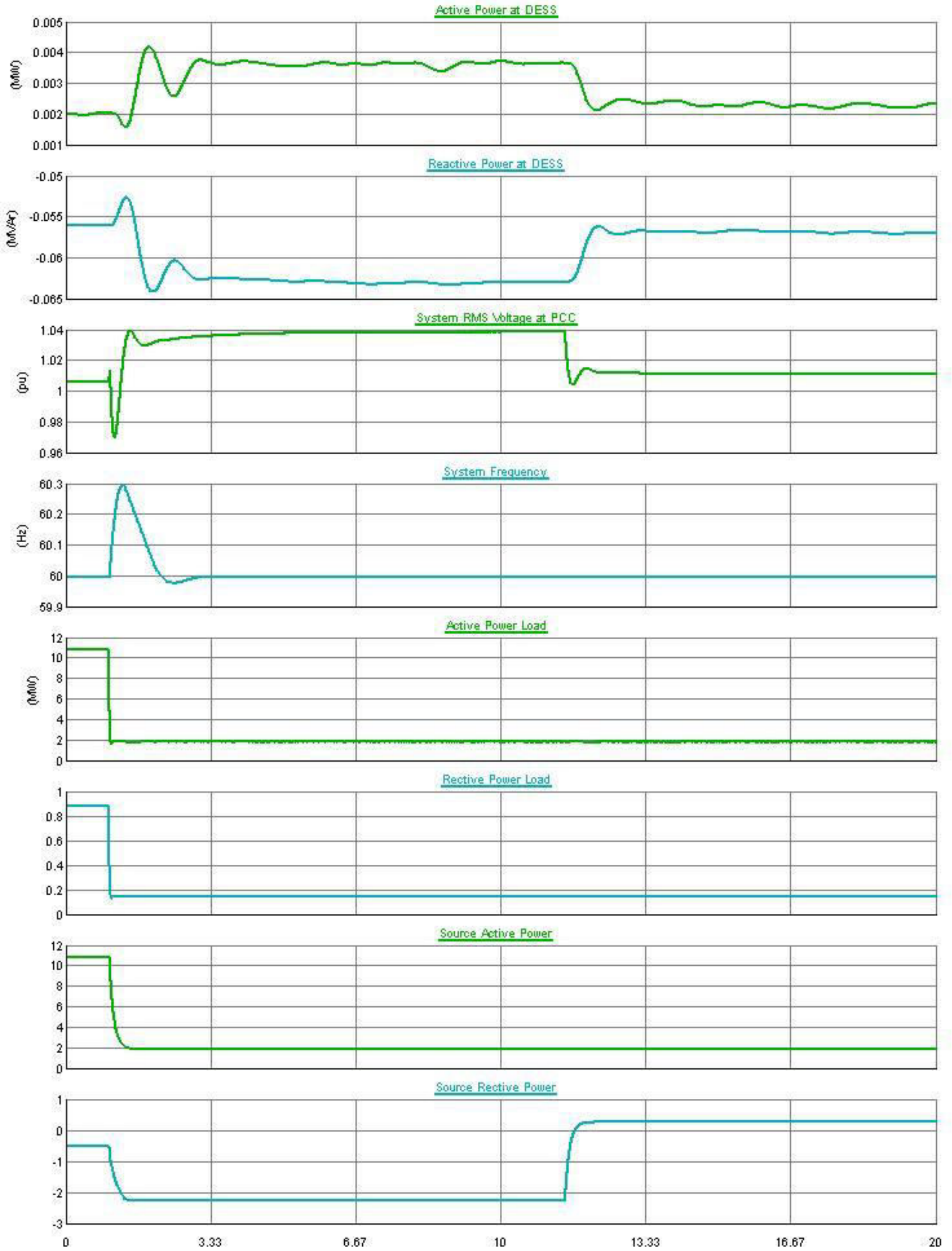

Figure B.102: System Response for Test 7.2a

TEST 7.2B: DECREASING THE ACTIVE AND REACTIVE POWER LOAD BY 9MW AND 700 KVAR RESPECTIVELY

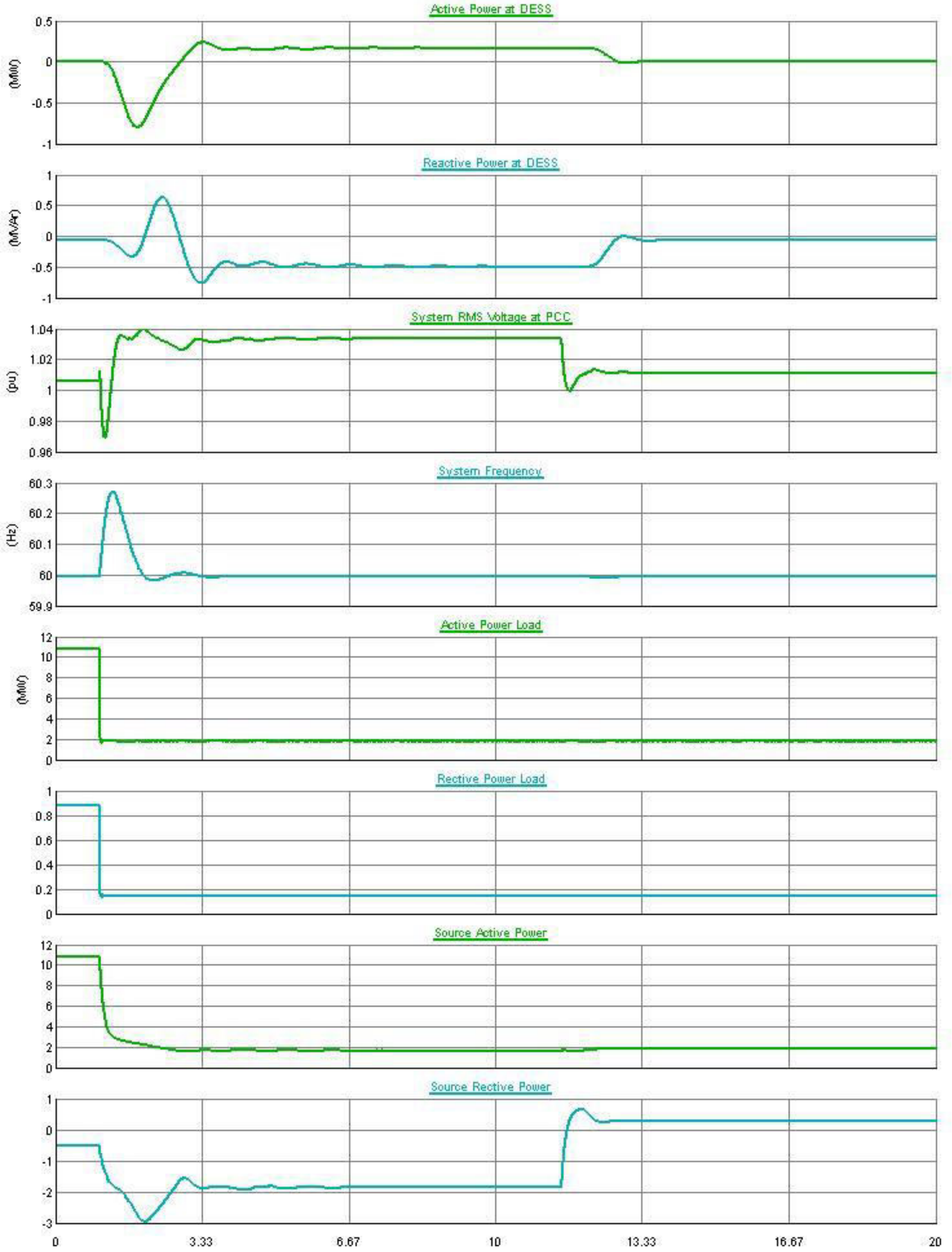

Figure B.103: System Response for Test 7.2b