Integrating Photovoltaic Systems into Remote Diesel Generator Powered Networks

A report submitted to the school of engineering and information technology at Murdoch University, in partial fulfillment of the requirements for a Bachelor of Engineering Degree.

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9/21/2016

Declaration of Originality of Research

I certify that the research described in this report has not already been submitted for any other degree.

I certify that to the best of my knowledge, all sources used and any help received in the preparation of this dissertation have been acknowledged.

Signed: ___________________________________

Word count: 13,867 words

Abstract

This thesis aims to research the effects of multiple ascending levels of photovoltaic (PV) power penetration on a prototype diesel generator powered network that has a PV power system integrated into it. First the effects of this additional photovoltaic penetration were documented then some ways to mitigate the effects of solar intermittency were investigated. This project relates to the Power and Water Corporation's (PWC) proposed roll out of 10 megawatt of solar throughout more than 30 of the remote communities they service in the Northern Territory. This thesis is concerned with instantaneous PV power penetration and studying the effects levels of instantaneous penetration higher than 30 per cent may have on an individual network.

To conduct this study, literature about solar irradiance data and previous trials in the Northern Territory was studied to make sensible simulation event estimates for a mock network. A network model was created and used in simulations to approximate the network's response to cloud shading during various levels of penetration. The simulations confirmed that photovoltaic penetration of 30 per cent and even 45 per cent could easily be implemented without the need for upgrading the existing infrastructure. Both 60 and 70 per cent penetration level simulations suggested that there would likely be a need to raise the nominal generated voltage and or apply shunt capacitor banks to the load buses. The significance of these results is that they confirm the Power and Water Corporations premise that 30 per cent penetration is a safe starting point and also suggest that higher levels of photovoltaic penetration can be achieved with little to no costly infrastructure upgrades, depending on the level of penetration implemented.

Acknowledgements

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Acronyms

AC	alternating current
ARENA	Australian Renewable Energy Agency
AVR	automatic voltage regulator
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC	direct current
DKASC	Solar Centre Desert Knowledge Australia
EMF	electromotive force
ESS	energy storage system
Hz	hertz
IES	Indigenous Essential Services
kW	kilowatt
kWh	kilowatt hour
kV	kilovolt
kVA	kilo-Volt-Ampere
kVar	kilo-Volt-Ampere-Reactive
NT	Northern Territory
p.f.	power factor
p.u.	per a unit

PV	photovoltaic
PWC	Power and Water Corporation
RIC	rotating internal combustion
SIL	surge impedance loading
THD	total harmonic distortion

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Glossary

Term	Meaning
Cloud event	A cloud event entails a cloud shadowing the solar panels from direct sunlight thereby changing the solar irradiance and causing intermittency in the system's output.
Controller	A controller in this context is a device which monitors and physically alters the operating condition of a dynamic system. This report focuses on two types of controllers, the speed governors, and the automatic voltage regulators of the diesel generators.
Diesel generator	When referred to in this text a diesel generator is the combination of reciprocating internal combustion engine coupled to an AC generator (often an alternator); accompanied by the appropriate mounting, drive bearings elements, and auxiliaries necessary for operation.
Dispatchable generation	Refers to sources of electricity where supply can be increased or decreased at the request of the power grid operator.
Distributed generation	Distributed generation is generation applied at the distribution level. Distributed generation can be defined as the utilisation of small, modular power generation technologies spread throughout a distribution network.
Hosting capacity	The maximum amount of PV that can be accommodated into the

system without having adverse impacts.

Intermittency — Intermittency refers to the sudden changes in the solar PV output usually due to environmental factors; most commonly cloud events.

Load — The aggregate power consumption of each community is being analysed as a single load. The loads are considered to be predominantly residential.

Minimum loading — Minimum loading is the minimum amount of load the online generators are allowed to service according to their minimum load factor.

Minimum load factor — The minimum load factor is the minimum allowable power output of the generator expressed as a percentage of the total rated power.

PowerFactory — PowerFactory is DIgSilent Pacific's electrical network analysis tool for generation, transmission, distribution, and industrial systems applications.

Power quality — The power quality determines the fitness of the electric power provided to the consumer.

PV penetration — PV penetration is best classified by both energy penetration and power penetration. Energy penetration is the fraction of total energy solar provides to the system. Power penetration (instantaneous

	penetration) is the fraction of total power that solar provides to the system at an instant in time. Both are often expressed as a percentage.
Ramp rates	Ramp rate in this context describes the change in PV solar output over a specified time period. A ramp up event usually occurs due to cloud shading of PV panels being removed, and a ramp down event occurs due to cloud shading of the panels.
Remote indigenous community	Remote indigenous communities are geographically distant to main towns and cities. Most residents of these communities are Aboriginal people.
Smoothing	The act of reducing the acuteness of intermittent solar output fluctuations that occur as a result of cloud events.
Solar irradiance	Solar irradiance is the power per unit area received from the sun in the form of electromagnetic radiation.
Spinning reserve	In this context spinning reserve is the amount of spare diesel generator capacity that is online and available to instantaneously service additional load.
Surge impedance loading	The surge impedance loading of a distribution line is the power loading of the line at which a natural reactive power balance occurs.

1 Background

The Power and Water Corporation (PWC) is currently managing the roll out of 10 megawatt of photovoltaic solar spread out through more than 30 remote communities in the Northern Territory (NT) through their not for profit subsidiary Indigenous Essential Services (IES). This 55 million dollar project is funded by the NT government and the Australian Renewable Energy Agency (ARENA). The implementation of the solar power will require the integration of a photovoltaic (PV) solar system into the existing remote diesel generator powered networks. This application of photovoltaic solar is not only aiming to mitigate environmental damage but also to stabilise the costs of dispatchable diesel generation in a volatile market, and reduce the costs of maintenance [1].

While integrating renewable sources comes with many benefits it also has some draw backs. For instance photovoltaic solar is not dispatchable, which means that solar generation cannot be increased to match an increase in load demand. Solar in particular can be intermittent due to unpreventable cloud cover events. It should also be noted in most scenarios peak load demand does not occur at the time of peak solar irradiance and therefore not at the time of peak solar power generation. In the NT peak demand tends to occur at the hottest time of the day. This is due to the air-conditioning load increasing as the day gets hotter so in these cases peak demand and peak solar generation may show some correlation, although it is important to remember the objective of PV solar input is to displace diesel fuel not diesel generation capacity. Providing enough diesel generation capacity to service the load without the PV system is important for providing power on overcast days and at night time, in the case that the inverter trips, and during the occurrence of sever solar intermittency. Several reasons why photovoltaic solar power can be hard to integrate into a diesel network are that doing so requires managing the spinning reserve requirements and adhering to power quality requirements.

This report assumes the mini-grid is located in the Northern Territory of Australia. The NT has many remote indigenous communities. At the time of the Solar/Diesel Mini-Grid Handbook's publication, the Power and Water Corporation (PWC) was responsible for supplying 72 nominated remote indigenous communities and 66 outstations in the NT utility-grade electricity services via the IES. This power was supplied by over 50 diesel mini-grid power stations between 300 kilowatt and 5 megawatt in capacity. In total, the installed diesel capacity was over 74 megawatt and was distributed through more than 1000 kilometres of power distribution lines. Of the mini-grid systems, eight were solar and diesel hybrid networks that supplied power to 11 communities. Some of the systems used various solar technologies such as concentrating photovoltaic dishes and flat plate photovoltaic solar systems. The total installed solar capacity was over 1.7 megawatt. In all these mini-grids, diesel is either the only or the primary source of generation [1]. This report aims not only to demonstrate the effect of high PV penetration but also to discuss some of the design implications associated with making it effective and reliable in the existing infrastructure.

2 Introduction

Operational experience has proved that with the addition of PV solar with the capacity to provide a 30 per cent system penetration, peak loads and diesel consumption can be substantially reduced without necessitating significant changes to the diesel power station [2]. This report aims to show the results of higher PV penetration in a simulated network, and to characterise the effects that varying levels of PV penetration may have on a remote system. A mock system has been modelled and the tests carried out via DIgSilent's simulation software 'PowerFactory'.

The PWC grids in remote communities often supply power to other small nearby communities as well. The network simulated in this report aims to mimic this arrangement by having two separate feeders of varying lengths distribute from the power station located near to one of two towns [2].

Achieving maximum effectiveness and harvesting the full potential of renewable energy in off grid power stations, requires demand-supply optimisation. The demand-supply relationship must be optimised to suit the characteristics of the renewable solar resource while at the same time providing a secure supply. Four key barriers to demand-supply optimisation in hybrid solar-diesel systems are [2]:

1. Behavioural influences on consumption
2. Technical influences on consumption
3. Power system stability
4. Solar irradiance variability

This report focuses on addressing the 3rd and 4th barriers listed. To do this, issues surrounding power quality, system stability, and spinning reserve as well as several solar intermittency mitigation methods are discussed in more detail throughout the report.

3 Network Model

A power system model was created in PowerFactory in order to simulate the effects of varying levels of PV penetration in remote communities. The network is powered by parallel diesel generators all on a central busbar. A PV system has been added to the central power station busbar. The busbar voltage is stepped up by two transformers each supplying a feeder. One feeder supplies community 1 and the other supplies community 2, both are modelled as overhead distribution lines. The feeder voltages are stepped down to a 415 line to line voltage before supplying both the remote community loads. The communities are both modelled as aggregate loads on separated terminals.

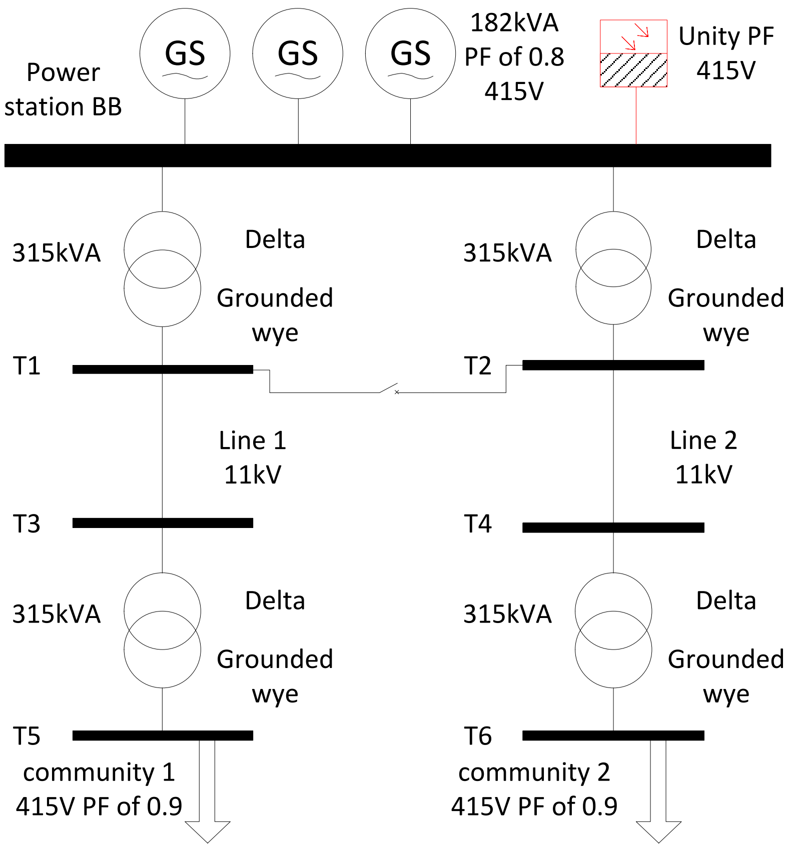

Figure 1 Experimental network that is used in simulations.

3.1 Generation

Generators are rotating machines that consist of two main parts known as the stator and the rotor. In the AC generator the stator carries the armature windings by which the electromotive force (EMF) is induced. DC excitation is used to create magnetisation in the main field system carried by the rotor. The generator's output is taken from the armature windings [3].

In this report a diesel generator or diesel generator set consists of a reciprocating internal combustion (RIC) engine coupled to an AC generator (often an alternator); accompanied by the appropriate mounting, drive bearings elements, and auxiliaries necessary for operation. In remote mini-grids, diesel engines are the most common electricity generation method used. Some of the advantages diesel engines have over other generation options are [1]:

- Widespread application and manufacturing results in low capital costs.
- Engine maintenance is predictable as it is based on run hours.
- Diesel engines are robust, proven, sturdy machines, and so are suited to harsh operating conditions such as those found in the NT, where they provide high reliability.
- Diesel engines can be started quickly, brought on line quickly if required, and require a minimal warm up time before being able to accept load.
- Good load following capabilities means that diesel engines are responsive to load fluctuations.
- High part load efficiency means that diesel engines are able to service loads well below their ideal loading (approximately 80 per cent) with reasonable efficiency.
- Diesel engine servicing skills are common and do not require highly specialised training.
- High energy density means that lower volumes of fuel need to be transported and stored to produce the same amount of power when compared to gasoline, and coal.
- Diesel engines are quick and easy to install compared to other alternatives such as gas, and steam turbines.

There are some disadvantages to relying primarily on diesel fuel for remote power generation. The high operational cost of diesel fuel, diesel fuel transportation costs, transportation difficulties during the wet season, large storage requirements, and the exposure to volatile fuel price increases are the main disadvantages experienced in the NT. PWC found diesel fuel to be the single largest expense for remote community service provision [1]. Another notable disadvantage to using diesel fuel is the ongoing maintenance requirements of diesel generators. This can be an issue as there are limited technical service proficiencies available locally in remote communities [1].

3.1.1 Parallel Operation

AC machines in parallel must operate in synchronism and at their synchronous speed as determined by the system frequency. For synchronous machines, division of active power is controlled only by the prime mover, whereas division of reactive power is controlled only by each generator's field excitation. It is worth noting that additional parallel generators are not bought online during these simulations as the timescale required to warm up and synchronise the generator is much greater than the time it takes for the system to stabilise [4].

3.1.2 Diesel Engine Sizing

Current PWC practice is to use multiple generator sets of different capacities depending on each mini-grid's load demand, and to allow for generator redundancy. This practice is a technique to ensure continuous supply. Multiple generator sets is a design decision implemented in order to allow for the wide load range that often occurs in remote indigenous communities, where substantial load variation occurs between seasonal and annual power consumption. The ratio of peak load demand to the minimum base load in the NTs remote communities can vary from 3:1 to 5:1. This large variation is mostly due to the high cooling loads in the summer (which is also the wet season in the NT) [1].

3.1.3 Generator Sets Configuration Characteristics

PWC's most common design uses generators of variable sizes in the same set. For instance, PWC generally uses three or four generators of ascending power ratings to service the expected wide load variation [1].

Some of PWCs guidelines for this particular configuration are [1]:

- The 70 per cent load point of a small generator preferably corresponds to the 40 per cent load point of the medium sized generator.
- The capacity of the small and the medium sized generator is usually 125 per cent of the largest generator in the set. This provides (N-1) redundancy in case the biggest generator fails.
- The generators are nominally operated between 60 per cent and 80 per cent of their prime power rating. On average they operate at 70 per cent capacity in order to achieve optimal performance and life span.
- The generators are called in turn when the loading approaches the capacity of the operating set. Likewise the generators change down when the load falls below the 'call-down' set point of the operating set. The change down occurs after a minimum runtime has been reached to prevent the generation plant from 'hunting' the load profile.

A benefit of having generators of different size in the same set is that normally only one generator is required at any time (over the whole load range). Operating one generator at a time opposed to two or more generators in parallel, reduces the accrual of engine run hours which helps to reduce maintenance costs. A disadvantage of this approach is that in the event that the smaller generator fails it is necessary to run a medium size generator in under loaded operation until the small generator is repaired [1].

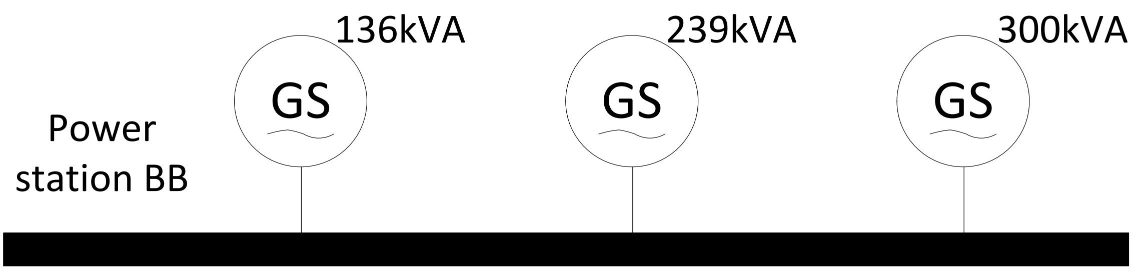

Figure 2 Arbitrary generator sizing example of variably rated machines.

An alternative generator sizing approach is to use multiple generators of equal size. Using this approach requires that multiple generators operate simultaneously to meet the load demand. This design approach has been used in the simulation model tested for this report. Multiple equal sized generators operating in parallel have been used in the simulated network because this configuration is associated with much greater spinning reserve margins under standard operating conditions. Greater spinning reserve margins are preferable when attempting to increase the PV penetration into a system. Other benefits of using multiple generators of the same size of less concern to this report are optimised call-up scheduling to distribute run hours across similar set sizes, the ability to prioritise run hours of particular sets, additional generation set redundancy, reduced parts type count, and greater flexibility when scheduling maintenance [1].

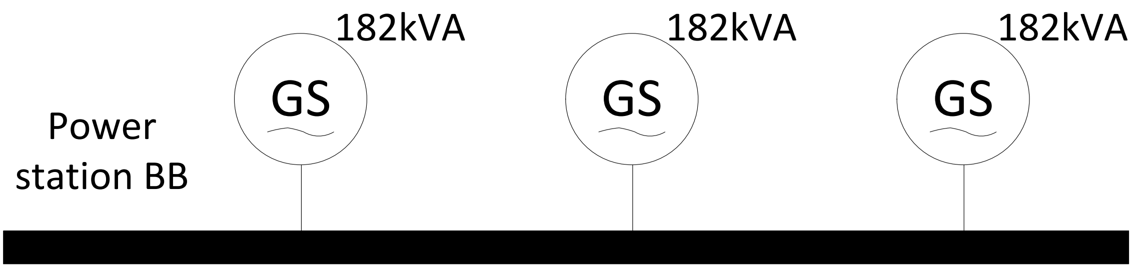

Figure 3 Generator sizing example of equally rated machines.

The major disadvantage to using multiple generators of equal size is the additional investment in capital for the generators, switchboards, controls, and ancillaries. Reduced average operating efficiency as a result of the matching between load demand and set sizes being more restricted is another economic disadvantage to this configuration [1]. As this report's analysis does not focus on capital investment, maintenance costs, and operating costs, the equal size design approach has been preferred. The generator model used in simulation was provided by a local utility. Each generator is rated at 182 kVA at a lagging power factor of 0.8. Using generator's rated at 182 kVA suited this network because it allowed three generators to cover the simulated load demand range. The generators' nominal voltage is 415 volts.

3.1.4 Photovoltaic Power Generation

Solar PV generation is designed to supply usable solar power via the use of photovoltaic cells. The major advantages of PV systems are [5]:

- Sustainability of solar energy as a fuel
- Minimal impact on the environment
- Significant reductions in customer's electricity bills
- Long functional lifetime of more than 30 years
- Low maintenance requirements
- Silent operation

PV systems are now being recognised by governments, environmental organisations, and commercial organisations as being a technology with the ability to supply a significant amount of the world's energy requirements in a sustainable and renewable manner. Due to recent improvements in inverter technologies and significant price reductions over the last few years, PV generation is now the preferred form of distributed energy resource for increase of local generation at a distribution class voltage level [5].

PV systems do still have several disadvantages. The main disadvantages of PV system generation are:

- they are not dispatchable, and so power output cannot be increased to meet the load demand [6]
- the intermittent nature of their output [1]
- high installation cost particularly in remote areas [5]
- low energy efficiency [5]

Related to the intermittent output of PV solar systems are ramp up and ramp down rates. Ramping down the solar output occurs as a result of cloud cover events and ramping up is a result of the clouds ceasing to cover the PV array. Ramp rates, particularly ramp down rates, will be further discussed in the next section.

3.1.4.1 Ramp rates

Ramp rate in this context describes the change in PV solar output power ('P' in equation 3.1 below) over a specified time period.

$$Ramp_{rate} = \frac{P(t + \Delta t) - P(t)}{\Delta t} \qquad (3.1)$$

Ramp down events often occur due to solar irradiance decreasing as a result of cloud cover and ramp up events often occurs due to clouds leaving after previously shading the panels (solar irradiance increase). High ramp up and ramp down rates can often occur as a result of inverters tripping or reactivating respectively [6].

This report aims to look at the worst case intermittency scenarios and will focus more on ramp down events. Originally the network was simulated with a maximum ramp down rate of approximately 52.4kW/s over the course of 5 seconds. Further readings showed the original ramp down rate was not a realistic estimate, and that rates within 15kW/s to 16kW/s are more realistic ramp rates. According to the CSIRO's analysis over a 10 month period by the Desert Knowledge Australia Solar Centre (DKASC), ramp rates of this size occurred several times within the 10 month period [6]. The events occurred over a 10 second period and resulted in a loss of solar output of between 150kW and 160kW. As the PV system used in this report is of a comparable capacity to the 196kW system used in the DKASC's study, and similar spatial distribution to the 196kW system has been assumed, the maximum ramp down rate was expected to be similar to that of the ramp down rates experienced in the DKASC's study. The network was simulated again with a ramp down rate of approximately 17kW/s as the worst case scenario. While this is more extreme than the scenarios recorded, it can help to account for very unusual wind speeds and or simultaneous load demand increases.

3.1.4.2 Var sharing

An important consideration when solar power is added to a diesel mini-grid is the practice of var sharing. A solar generator providing power with a unity power factor will cause the diesel generator power factor to reduce. This is because the diesel generator continues to supply the same reactive power but its share of the real power provided decreases. Var sharing means that the PV inverter outputs power at a lagging power factor so that the diesel generators' power factor is less affected. The network simulated in this report does not take into account var sharing for the following reasons [1]:

- Fixed lagging power factor of the solar inverter can cause the diesel generator to operate at a leading power factor in the case of the load power factor approaching unity. AVRs cannot regulate voltage with anything but a minimal leading power factor, so leading power factors risk system instability.
- Unity solar inverter power factor is recommended unless the risk of system instability can be negated.
- Many vendors are not yet offering the ability to control the solar inverter power factor in real time.
- Generators can usually operate at a poor power factor so long as they are not running at full load, and that power factor is lagging not leading.

Future works suggested for Potomac Electric Power Company (PEPCO) suggest that for smaller systems Non-dynamic var control of the PV inverters may be [6]:

- 0.99 power factor when PV at 0-50% output
- 0.98 power factor when PV at 50-75% output
- 0.97 power factor when PV at 75-100% output

So, in future trials, var sharing may be worth considering as vendors tend towards offering more inverter functionality.

3.2 Busbar and Terminals

The simulated network has used a single busbar and 6 terminals as shown in Figure 4. To best describe the system it will be broken down into the power station and the distribution network in the following sections.

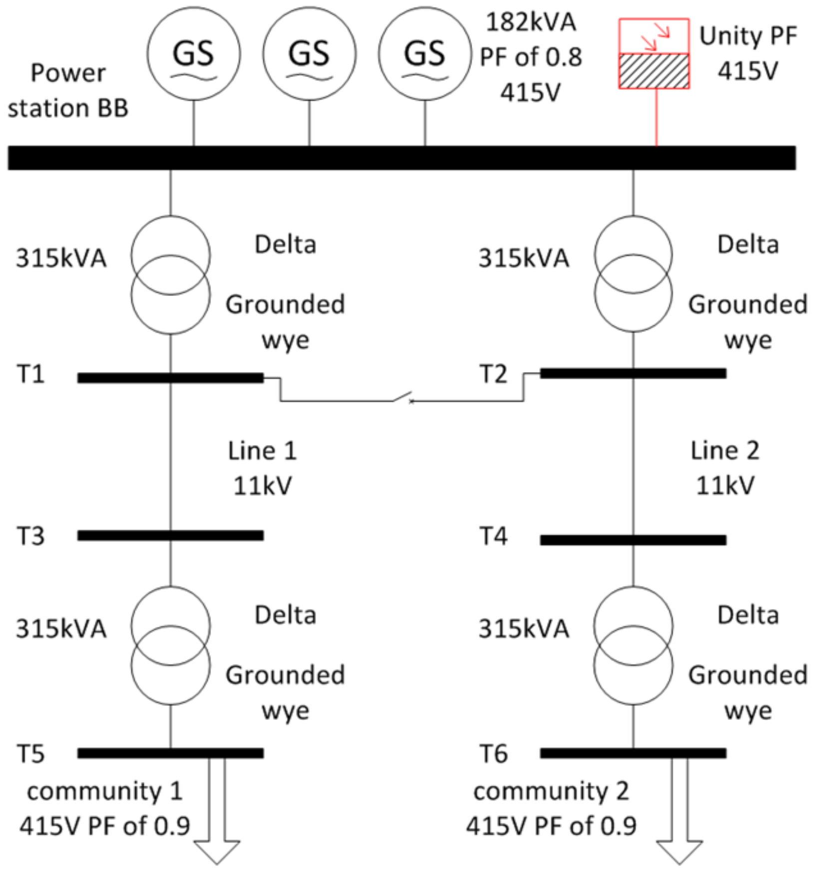

Figure 4 Original network single line diagram with the addition of the PV system.

3.2.1 The Power Station

The power station contains the 415 volt busbar which has 3 online generators, two transformers, and a solar PV system connected to it as shown in fFigure 5. The generators and the PV system are used to supply the power to the busbar which is then stepped up to 11 kilovolt for distribution along each of the feeders via the two transformers. Terminals ‘T1’ and ‘T2’ have been used to connect to the transformers grounded wye windings and the busbar supplies both transformers delta windings.

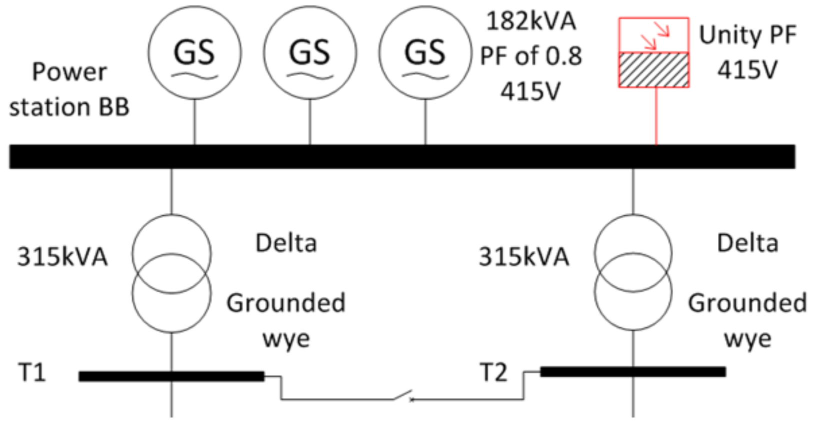

Figure 5 Power station

Both a static PV generator and a load have been connected to separate terminals of the busbar to create a rough model of a PV system that allows ramping events. The load is insignificantly small to begin with but mimics a cloud event by ramping up to a point at which the net power is zero when summed with the static PV generator.

3.2.2 Distribution Network

Terminals throughout the network have been used for joining the distribution lines, transformers, and customer loads together. Terminals 'T3' and 'T4' connect their respective distribution line feeders to delta windings of the transformers, that are stepping the line to line voltage down to the standard 415 volt as shown in Figure 6. Terminals 'T5' and 'T6' connect to their transformer's grounded wye windings to their respective community loads.

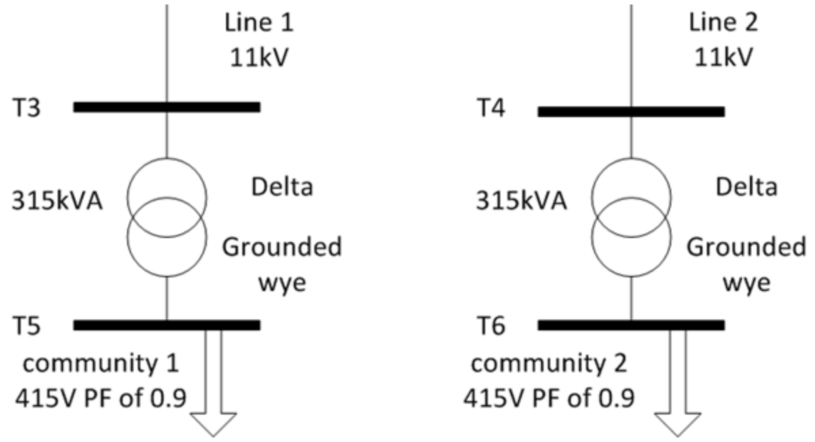

Figure 6 Distribution network

3.3 Distribution Transformers

The simulation network featured in this report uses four delta-grounded wye type transformers between the generation and the load side of the network. The generation busbar is connected to the delta windings of the two transformers each supplying separate feeders [7]. The load terminals are connected up to the step down transformers' grounded wye windings.

Many interesting features of the delta-grounded wye type transformers are related to its delta winding, which establishes a local grounding reference point on the delta side and prevents zero sequence currents from entering the primary windings. Some interesting points to note are [7]:

- The transformer can be supplied via a 3 wire or 4 wire system
- Service;
  - Supplies grounded-wye service , normally 415/240 V
  - Does not supply ungrounded service
- This configuration blocks zero sequence currents, so upstream ground relays are isolated from line to ground faults on the secondary side of the customer transformer.
- The delta winding serves to isolate the primary windings from the zero sequence harmonics created on the secondary windings. Third harmonics as well as other zero sequence harmonics are unable to get through to the primary windings as they circulate in the delta winding.
- For line to ground faults occurring on the delta windings, the grounded wye connection is unable to act as a grounding source (No primary ground source).
- This configuration of transformer provides a grounding source for the secondary side, regardless of the primary side's grounding arrangement.
- The delta connection guarantees that zero sequence flux will not flow in the transformer's core. This results in no tank heating so a three legged core transformer can safely be used.
- Delta-grounded wye transformers are highly susceptible to Ferro resonance.

When selecting appropriately sized distribution transformers, the loadings need to be considered. Distribution transformers are output rated. This means that they can generally provide their rated apparent power without exceeding their temperature rise limits if the following conditions are true:

- The secondary voltage does not surpass 105 per cent of the transformer's rating. This means a transformer behaves as a constant kVA device for a voltage between 100 and 105 per cent.
- The power factor of the load is ≥80%.
- System frequency is ≥95% of the rating.

It is also worth noting that the "Electric Power Distribution Handbook" by Tom Short, refers to ANSI/IEEE C57.91-1981 suggesting that generally over about 30 degrees Celsius the transformers loading capacity drops by about 1.5 per cent of the rated KVA for each degree above 30 degrees ambient temperature. Every degree below 30 degrees Celsius the loading capability increases by roughly 1 per cent of the rated KVA. While this should not be considered to be absolute, it is worth taking into account when selecting transformers of appropriate rating for the NT, where temperatures regularly and significantly exceed 30 degrees Celsius [7].

The network in this report has been designed keeping in mind that having a neutral line being fed along the feeder would better allow for expansion and network upgrades. The transformer model parameters were provided by a local utility that cannot be named for confidentiality reasons. The load side transformers are connected to the load bus via their grounded wye type windings and the delta winding are connected to the systems distribution line [7].

3.4 Distribution Lines

The overhead line selected was a global type from PowerFactory with minor adjustments to its rated current. It is worth noting that this cable selection has an excessive rating for this application but was the smallest allowable global type available. The line type used is rated for 190 amperes whereas in reality the line type should be rated for 20 amperes or less. Subsequently the system loading is too light for the distribution feeders. Light line loading implies a low line current ('I') which makes the capacitive qualities of the line dominant over the quantities of reactive power absorbed (‘Q’) over the fixed inductance (‘X’) [8].

$$Q = I_{rms}^2 X \quad (3.2)$$

Whether or not the line will be operating at a leading or lagging power factor can be determined by the amount of power being transmitted relative to the surge impedance loading (SIL). The SIL can be calculated if the lines characteristic impedance (Z_0) is known [8]. In equation 3.3 ‘R’, ‘G’, ‘j’, $'\omega'$, ‘L’, and ‘C’ represent the line’s total resistance, conductance, the imaginary unit, angular frequency, inductance, and capacitance respectively.

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (3.3)$$

If the amount of power being transmitted is below the SIL, the power factor is leading (capacitive) whereas when the amount of power being transmitted is higher than the SIL, the power factor is lagging (inductive) [9].The line to line voltage in equation 3.4 is denoted by $'V_{LL}^2'$.

$$SIL = \frac{V_{LL}^2}{Z_0} \quad (3.4)$$

In the simulated network the amount of power being transmitted is less than the SIL, this means that the lines inject reactive power. As a result, attempts to make one of the feeders longer, in order to mimic a more realistic geographical dispersion, makes the generator absorb rather deliver reactive power. This is not ideal as it threatens the stability of the power system [9].

While this rating is still too high, some excess in rating can be beneficial in accounting for the derating factor due to the high ambient air temperatures that overhead lines in Australia are likely to experience [7]. The line lengths 2.7km and 1km were arbitrarily chosen for community 1 and community 2’s respective distance from the power station. In reality line lengths can certainly be much longer.

3.5 Loads

Two balanced static loads were implemented in PowerFactory to represent the average loads of the remote community and the family outstation. Community 1 was arbitrarily chosen to be five elevenths of the total load and community 2 to be six elevenths. Both loads were considered to be residential, so were given a high power factor of 0.9 [1]. When simulating in practice, it was generally required to marginally scale up the loads that were calculated in order to receive the correct generator loading prior to the cloud event, because of voltage drop across the distribution network.

3.6 Controllers

Two kinds of controllers have been used in the simulation network to control the generators' speed and the operating voltage at the terminals within a prescribed limit. The generator is controlled by a speed governor to maintain a constant speed under all varying load conditions, and an automatic voltage regulator to maintain the nominal voltage regardless of changes to the generator's speed, loading, power factor, and temperature rise [3].

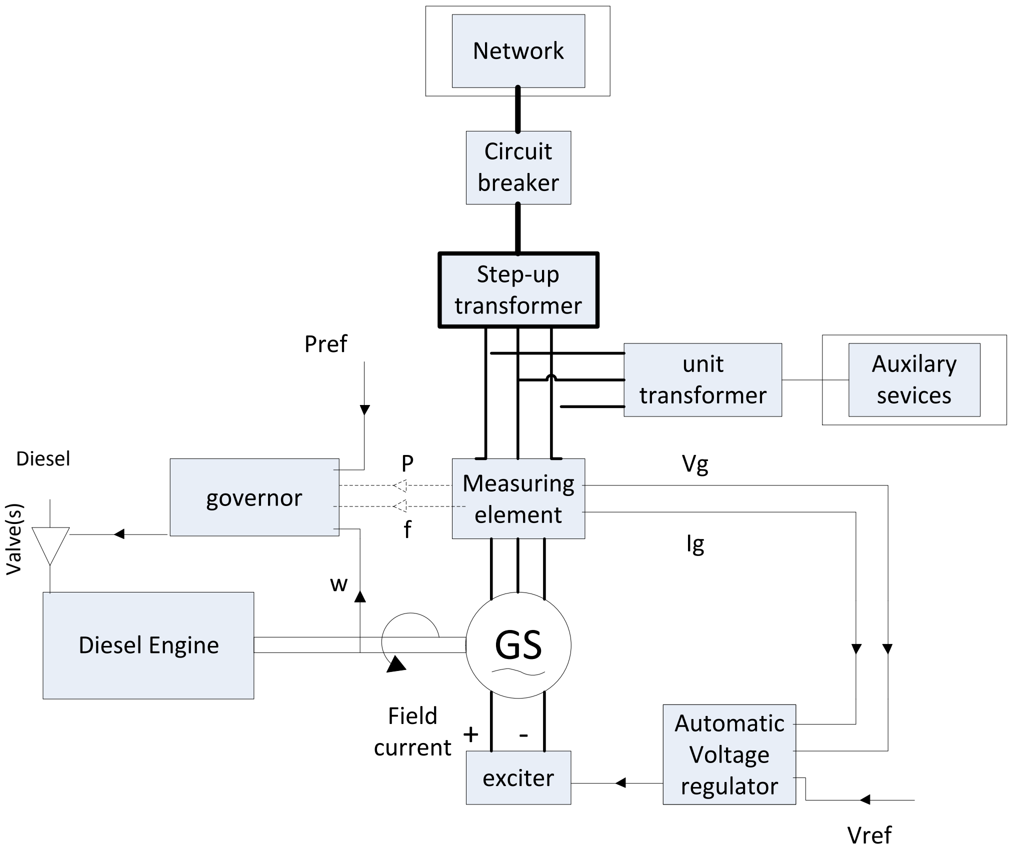

Figure 7 Power generation unit.

3.6.1 Speed Governor

A speed governor, in the context of synchronous generators, regulates the engine speed to a constant value under all load conditions. The governor does this by controlling the fuel consumption such that a rise in speed results in the actuator reducing the fuel consumption, and a fall in speed causes the actuator to decrease fuel consumption [3].

Any engine system is characteristically unstable. The instability occurs due to the time lag between adjustment of the fuel position and the subsequent new value of torque produced at the crankshaft. This results in an excursion from set speed causing the engine governor combination to oscillate continuously in an attempt to correct the offset. The continuous oscillation is a phenomenon known as 'hunting'. Due to hunting, a generator must include some compensating system additionally to the exact regulation of speed [3].

3.6.1.1 Isochronous Controllers

Isochronous speed governors maintain constant speed operation irrespective of the loading, so long as the loading is within the engine's rated capacity. This implies zero per cent speed regulation or zero permanent speed droop. To further improve the model used in this report, one of any of the three controllers should be an isochronous controller [3].

3.6.1.2 Droop Controllers

'Speed droop', commonly known as just 'droop', can be defined as the change in speed corresponding to the full range of the of the governor's output (i.e. from its full speed to its zero speed setting). Droop is a characteristic of governor operation that affords stability. Droop controllers are necessary when multiple engines controlled by speed sensing governors are operated in parallel with one another, in order for the engines to share load proportionately. To guarantee successful operation in parallel, all or all but one of the engine governors need to operate with a droop controller. This is because applying a load to two or more paralleled generators controlled by isochronous generators may cause one of the engines to take up the entire load within its capacity. The engine's droop may be temporary or permanent, unlike an engine's speed regulation. One of the global type governors provided in PowerFactory named 'gov_DEGOV1' has been used in the simulation model. The gov_DEGOV1 type governor does allow a permanent speed droop after the change in load. In the case of permanent speed droop, the governor's output actuator comes to rest in different positions for each speed. This permanent droop means that the engine's final speed in such a way that it is different for each load level. This compares with the case of temporary droop, where the governor's output shaft always comes to rest at the same speed, and as a result the rotor returns to the same steady state speed regardless of load. The temporary droop function is normally a feature of isochronous governors to provide stability in operation. Stability is referring to the governor's capacity to maintain the system speed steadiness within set limits, despite constant or varying loads, and without hunting [3].

3.6.1.2.1 Speed Regulation

'Speed regulation' is the increase in speed from full load to zero power output of the engine, without modifying the governor. Speed regulation is given as a percentage of the stated speed at the engine's rated power [3].

$$speed\ regulation = \frac{speed_{NL} - speed_{FL}}{speed_{rated,FL}} \times 100\% \qquad (3.5)$$

The speed regulation is dependent on not only the droop setting, but also on the percentage of the governor's output actuator which is required to move the fuel rack between its rated load and no load positions [3].

3.6.2 Automatic Voltage Regulator

The generator's excitation system comprises of an exciter and an automatic voltage regulator (AVR) and is required to provide the generator with DC field current [10] [11]. An AVR is a device that functions to keep operating voltage at the generator's terminals within prescribed limits despite changes in system speed, load, power factor, and temperature rise. AVRs are error-operated devices that are used in the closed-loop control principle [3]. The AVR controls the amount of current supplied to the generator field windings by the exciter .This means the speed of response is limited by the exciter's time constant [10]. Often AVRs are the only control component necessary for controlling small machines, but must include ancillary controls and protective features in order to be deployed on larger machines. Requirement for ancillary controls and protective features are particularly relevant to larger machines running in parallel with other generation sets. Where generators are required to operate in parallel with each other, their AVR's are configured to give terminal voltage droop with increased reactive power load [3].

The AVR subsystem includes limiters that function to protect the exciter, generator, and AVR from excessive voltages and currents. This is achieved by maintaining input and output signals within predefined limits. As a result, the amplifier is protected against overly high input signals, the exciter and generator are protected against excessive field current, and the generator from excessive power angle and armature current [11].

3.6.2.1 Voltage Regulation

A generator's regulation can be demarcated as the voltage change occurring due to a change in load. The voltage regulation characteristic is therefore the relationship between the generators loading and primary voltage under specified conditions. Voltage regulation is relevant to the end user and requirements may vary significantly. Generator performance measured by voltage fluctuation and recovery times when load is abruptly removed or applied under transient and steady state conditions is what impacts the end user's power quality [3].

3.7 Shunt Capacitor Banks

A later addition to the network is the shunt capacitor banks that can be seen on the load buses in Figure 8. The capacitor banks were implemented in PowerFactory as automatically switching shunt capacitor banks. The community 1 capacitor bank has 5 steps each of 10kvar and can provide a maximum of 50kvar. Community 2's capacitor bank has the same step size as community 1 but has 10 steps so is capable of providing up to 100kvar. Both capacitor banks have a controller time constant of half a second and a controller sensitivity of 0.1 per unit as these values were default in PowerFactory. The capacitor banks have been added to improve the network's power quality by raising the load bus voltages to within the allowable range of $\pm 6\%$ of the nominal voltage when required.

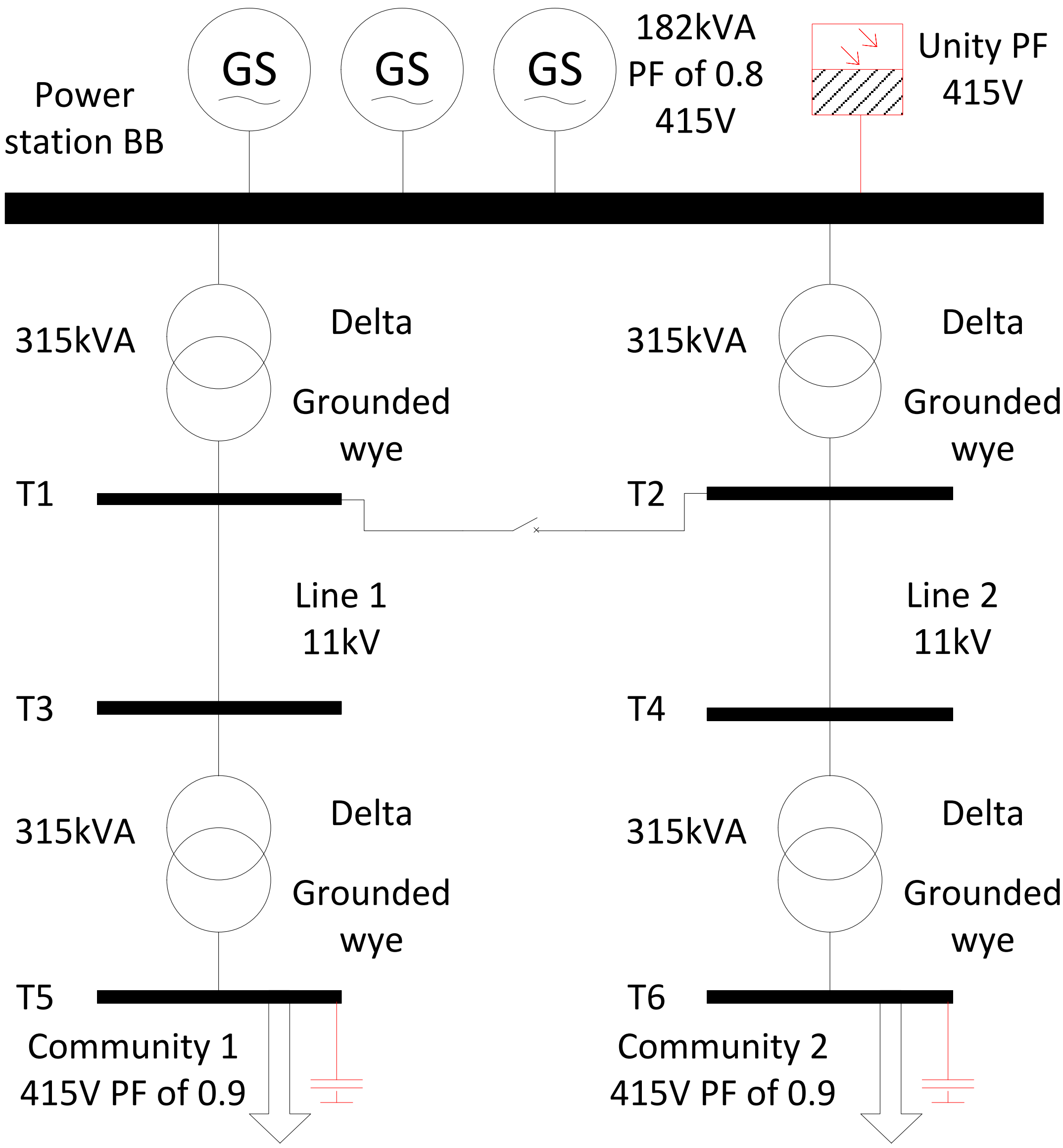

Figure 8 Network with the addition of capacitor banks on the load buses.

4 Stability in Power Systems

The three classes of stability are [12]:

1. Steady state stability is defined by the ability of a system to remain in synchronism during minor disturbances or slowly occurring system changes, such as increase in demand at varying times of the day (generally following the load profile).

2. Transient stability is defined by system behaviour immediately following an abrupt and often steep change in loading conditions. Some examples of when transient stability analysis is relevant are fault events, loss of generation, loss of an interconnecting line, and sudden connection of additional load. Transient periods have time duration in the order of a second. The way the system will behave in this interval is a crucial consideration when designing power systems.

3. Dynamic stability describes the system behaviour in the interval between the transient response and the time at which the system is considered to be restored to a steady state. Dynamic stability studies can be used for the behavioural analysis of turbine governors, steam flows, fuel flows, load shedding, and the recovery of motor loads, etc.

Power system stability can be divided up into several different categories for analysis purposes. Rotor angle stability, frequency stability, and voltage stability are the main categories of stability analysis. Both rotor angle stability and voltage stability can be broken up into 2 sub categories each. Rotor angle stability can be subdivided into small disturbance angle stability, and transient stability. Voltage stability can be subdivided into large disturbance voltage stability, and small disturbance voltage stability [11]. Frequency stability and large disturbance voltage stability analyses during the transient and dynamic periods are the most relevant to the simulations conducted in this report.

4.1 Transient Stability

Analysis of the transient period defines the ability of all the elements in a network to remain in synchronism immediately after a sudden change in the network operating conditions. The most arduous abrupt changes is a three-phase fault event, but rapidly increasing electrical system load, and network switching can also produce system instability. The imbalance of a source being disconnected is initially covered by the kinetic energy of rotating turbine rotors. In the network referenced in this report the simulations will demonstrate the system response following a sudden increase in the system's load through loss of power being supplied on the load buses by photovoltaic arrays. The generalised energy equation is as follows [12]:

$$\boldsymbol{Mechanical\ energy} = \boldsymbol{Electrical\ energy}\ \pm \boldsymbol{Kinetic\ energy} + \boldsymbol{Losses} \quad (4.1)$$

Under steady state conditions, when the power demands of the synchronous generators are changing slowly, the system's kinetic energy remains practically unchanged. In the case of sudden disturbances to the generators through abrupt load changes or line faults, the machine will not be able to supply the energy from its prime mover or absorb energy from the rest of the network instantaneously. The loaded spring analogy is often helpful for visualising the scenario. A good example is a motor that is suddenly asked to supply more mechanical load. The mechanical load in the motor will be supplied from the rotor's kinetic energy and as a result the rotor speed will decrease. The motor will slow excessively (undershoot) and thus will be followed by a speed increase so in this manner will approach the new load operating condition in an oscillatory manner as would a loaded spring. This concept is illustrated in Figure 9 where a loaded spring is attached to some stable reference point on one end and a suddenly changing load is applied on the other end. In the scenario that the spring of stiffness 'S' is gradually loaded with a mass 'M' it will extend by a distance of Δx up until the force of the spring's stiffness (SΔx) is equal to the weight of the mass. Notice that in this spring scenario the kinetic energy of the system has not been disturbed [12].

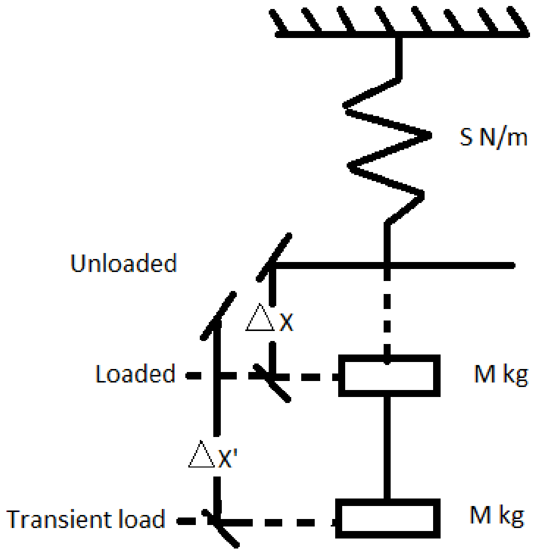

Figure 9 Loaded spring machine stability analogy – overshoot [12]

In this analogy, the spring can be considered to be the machine, the spring's stable reference point to the slack bus or an infinite busbar, and the extension of the spring (Δx) the machine's load angle (θ). Loading the spring past its elastic limit is analogous to steady state instability of a loaded synchronous generator. With a gradual load increase the spring is able to support a load such that if it were to be suddenly dropped on the spring it would cause the spring's elastic limit to be surpassed prior to the motion of the weight being stopped. Suddenly dropping a load on the spring that goes beyond its elastic limit is an analogy for transient instability in power systems. Equation 4.2 includes the applied mass multiplied by the acceleration or deceleration of mass relative to the extension, summed with the velocity damping and restoring force (the spring stiffness multiplied by the extension). To prove this analogy the simple equation for this spring is as follows [12]:

$$M\frac{d^2x}{dt^2} + K\frac{dx}{dt} + Sx = Force \quad (4.2)$$

This can be compared to the simple equation for the synchronous machine where θ is small [12]:

$$J\frac{d^2\theta}{dt^2} + K'\frac{d\theta}{dt} + T_e\theta = T_m \quad (4.3)$$

Where 'J' denotes the synchronous machines inertia, T_e represents the electric torque, and T_m represents the mechanical torque.

A fundamental consideration to be accounted for when designing a network that meets the quality of supply requirements is the inertia of the online diesel generators and the step load response capability of the diesel generators. Not only do generators need to carry adequate reserve to anticipate the worst scenario cloud events, they also need to be able to 'pick-up' the resulting extra load in a short time period. Suddenly applying a large load increase on a generator in small timeframe can decrease the generator's frequency before the generator overload steps in. If the generator does not have a sufficient step load capability then the generator may stall [1]. The electrical frequency and voltage collapse of a generator, due to a load step beyond its load step capability, is shown in Figure 10, and Figure 11 respectively.

To avoid generator stalling some control systems are designed to open a feeder if the step load is too large. This quickly reduces the loading on the generator. However this approach can cause a generator to shoot into over frequency [1].

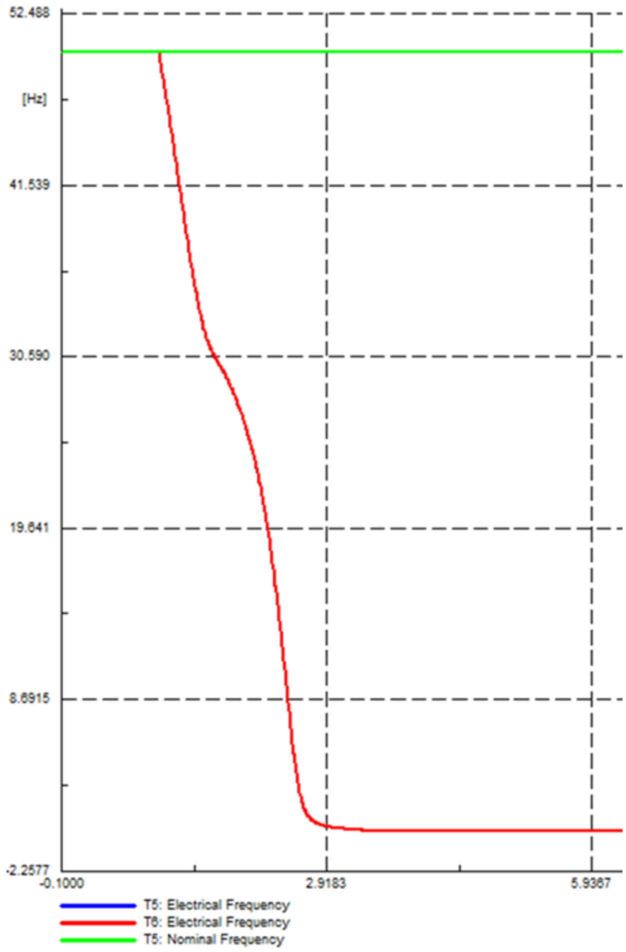

Figure 10 Grid frequency collapse resulting from an inverter trip (generator sees a sudden load increase).

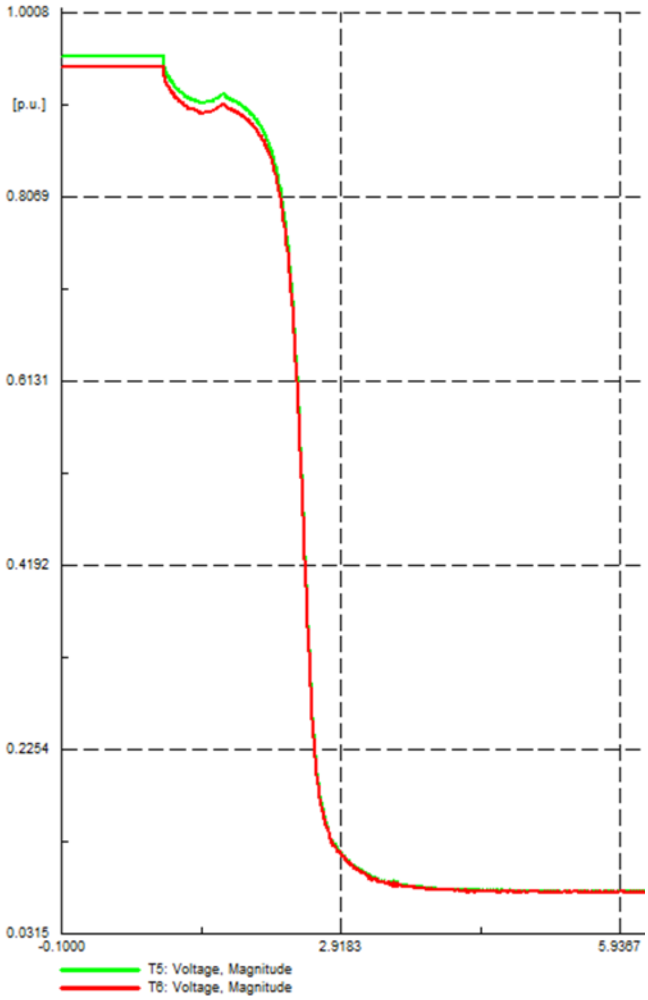

Figure 11 Voltage collapse resulting from an inverter trip (generator sees a sudden load increase).

Figure 10 and Figure 11 above show the resulting blackout that occurs if the generators are loaded up to quickly such as may occur in an inverter trip.

4.2 Dynamic Stability

Often a system may not lose synchronism in the transient interval immediately after a disturbance. The ability to adjust in the longer term to a significantly new set of operating conditions is the focus of dynamic stability studies. Many of the slower responding power systems components can be assumed to hold constant values during the transient time interval occurring immediately after a disturbance. This means the slow reacting power system components can be treated as having a negligible effect on the system's transient stability. Within the seconds and minutes following a disturbance the slow reacting components can become dominant. Therefore, in order to conduct a thorough analysis of network system stability from the end of the transient period to when the network is considered to have regained a steady state, consideration must be given to applicable effects such as [12]:

- Speed governor response
- The possibility of delayed tripping of interconnectors that may have become overloaded
- Load loss by frequency-sensitive load-shedding relays
- Motor loads automatically restarting

Usually dynamic stability studies are conducted for large interconnected systems to aid with the development of strategies for system control that responds to a number of types of disturbances. As opposed to large interconnected systems, in smaller industrial reticulation the preservation of stability within the transient period is normally considered to be the most important aspect for examination. The way in which the network adapts while in the dynamic period is largely up to the natural properties of the system and the control of the system (automatic or operator controlled). For example a control system can be used to restore the nominal frequency through adjustments to governors and improve the networks voltage profiles through capacitor bank switching and many other techniques [12]. In the simulated network the dynamic response will be affected by the speed governor, AVR, and automatically switching capacitor banks.

4.3 Steady State Stability

The hybrid solar/diesel network simulated in this report treats the PV solar output as a negative load. Over the course of the day the generators are not only responding to the more predictable change in the residential load profile but also to the change in the PV system output. The challenge for maintaining system stability in a network is related to the network's ability to generate sufficient restoration forces as a counter action to system disturbances. For minor system disturbances there is generally a mutual interchange of power between the machines in the network that acts to keep them synchronized and at the nominal system frequency. A state of equilibrium is retained between the total electrical power and total mechanical power. Total electrical power can be considered to be the output energy and total mechanical power considered to be the input energy. The equilibrium between the total electric power and the total mechanical power is retained through the natural adjustment of the common system frequency and the network voltage levels [12].

4.3.1 Automatic Voltage Regulators Effects on System Stability

In Figure 12 'E' represents the internally generated voltage, and 'X' represents the internal reactance of a synchronous generator. The internal voltage results from the induction in the stator by the rotating magnetic flux from the rotor. The magnitude of the internal voltage is determined by the excitation of the generators field windings. The reactance is there to represent the steady state synchronous reactance and the transient and sub transient reactance in events that suddenly change the operating conditions. The rest of the network beyond the generator representation is considered to be an infinite busbar.

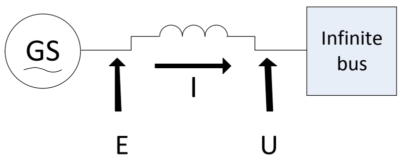

Figure 12 Generator connected to an infinite busbar [12].

An infinite busbar has the properties of constant frequency and voltage as well as infinite inertia which mean it can absorb any output supplied by the generator. It should be noted that an infinite busbar is strictly theoretical and can never be obtained in practice. Systems that are highly interconnected with multiple generators are relatively insensitive to change in the operating conditions of a single machine, so in some applications it is acceptable to approximate the rest of the network as an infinite bus. The synchronous generator is synchronised to the infinite busbar where the bus voltage 'U' remains unaffected by changes in the generator parameters 'E', and 'X'. The current supplied is denoted as 'I' and has a lagging phase shift 'Ø'. The network therefore has a lagging power factor (PF) of cosØ. Since 'U' is constant the electrical power output can be calculated as [12]:

$$P = UI * PF \qquad (4.4)$$

Also for the vector triangle shown in Figure 13 it is true that:

$$I = \frac{Esin\theta}{Xcos\emptyset} \qquad (4.5)$$

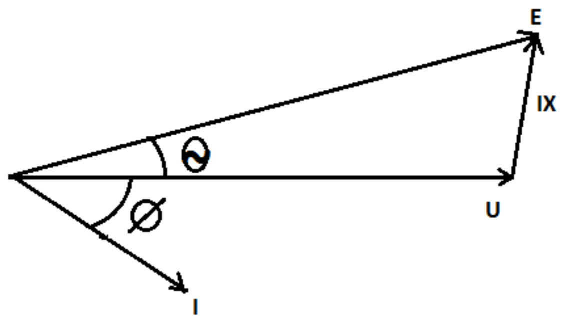

Figure 13 Example of a synchronous generator's vector diagram.

Substituting for 'I' gives:

$$P = \frac{Ucos\emptyset * Esin\theta}{Xcos\emptyset} = \frac{UEsin\theta}{X} \qquad (4.6)$$

If a prime mover power continues to increase a load angle of 90^o is eventually achieved. Beyond a load angle of 90^o further increases in mechanical input power will cause the electrical power output to decrease. The excess input power acts to further accelerate the machine and it is said to become unstable. As a consequence the synchronism with the rest of the system is almost inevitably lost. Modern automatic voltage regulators (AVRs) can now enable a machine to function at a load angle greater than 90^o, where the AVR can increase the internally generated voltage faster than the load angle increases as characterised in equation 5 below. [12].

$$\frac{dE}{dt} > \frac{d\emptyset}{dt} \qquad (4.7)$$

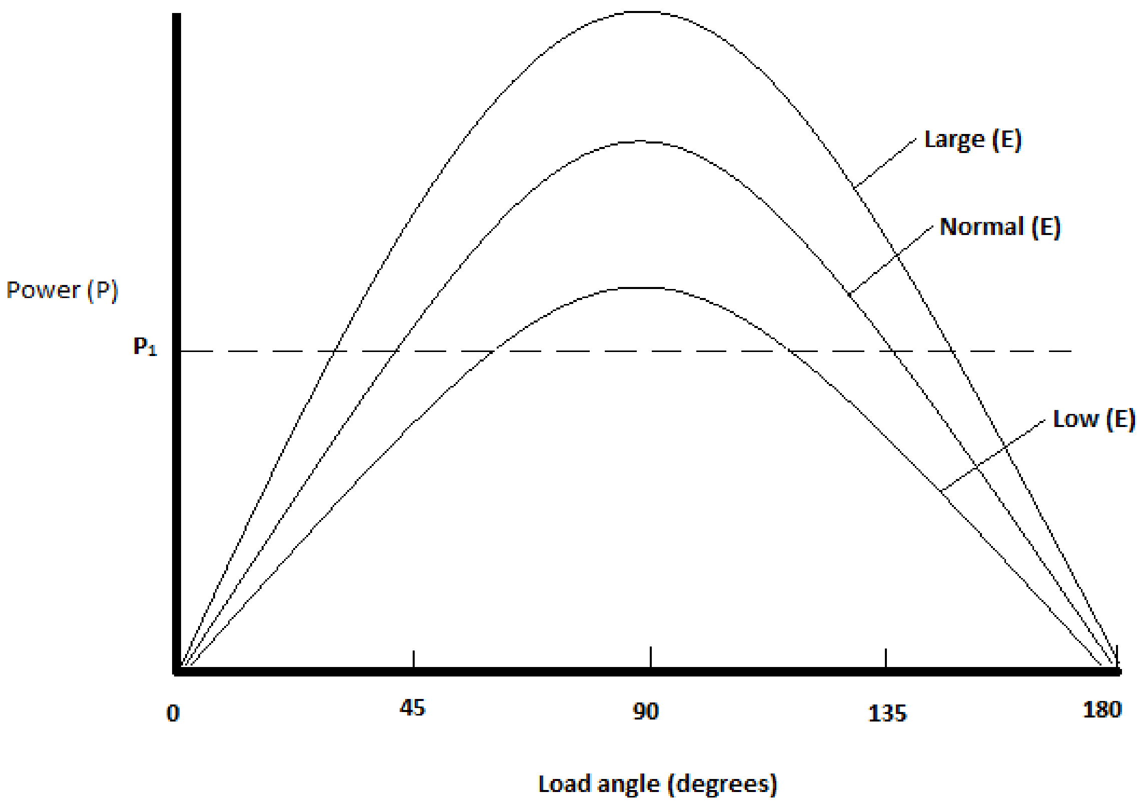

Figure 14 Power and load angle relationship. [12]

In this case stability can be maintained up to a theoretical maximum of roughly 130^{o}. It should be noted Figure 14 see above is only a simple representation and practical machine characteristics deviate slightly from the above behaviour. Loss of synchronism can be damaging because the machine may start alternating between behaving as a generator and behaving as a motor. This means power sometimes several times the machine's rating will surge in and out of the machine, putting the machine under massive electrical and mechanical stresses. Ultimately this can result in protection relays tripping and causing the whole network to collapse. This particular kind of stability issue arising from loss of synchronism will not be directly applicable to the network studied in this report. The reasons the network studied in this report is exempt from stability issues arising from generators alternating between their intended behaviour and behaving as a synchronous motor load, are that all the synchronous generators are supplying power in parallel on the load bus, they are all initialised to be in synchronization, all are identical, and all have the same controllers and values for their controller parameters [12].

The automatic voltage regulator's general objective is to maintain a constant generator terminal voltage under all conditions of electrical output. AVRs respond to terminal voltage variations by varying the excitation of the machine and as a result the internally generated voltage. Maintaining a constant terminal voltage aids not only to preserve power quality, but also in acting towards preserving steady state stability. It should be noted that in the network simulated in conjunction with this report the AVR is maintaining power quality and does not have an effect over system stability, as this network's loads are modelled with a lagging power factor. A lagging power factor was selected for the network because residential loads tend to have a lagging power factor. In networks where synchronous motor loads are present and or power factor compensation is used leading power factors can be possible.

5 Power Quality

Requirements for the quality of supply are a vital part of solar system design and configuration as stringent standards can have a substantial cost influence on control and spinning reserve practice. This is mainly due to the intermittent nature of solar power. An abrupt change in solar output can put at risk the stability of the power system as a whole and result in a total system outage. The rapid change in solar output can jeopardise the system stability if it is either beyond the power stations available spinning reserve or beyond the control system's response capability. Supply quality requirements aid in dictating the extent to which the diesel mini-grid system risks needs to be managed, and the ramifications of incorrect risk event management [1]. Table 1 below shows the PWC's guidelines for power quality.

Table 1PWC minimum supply requirements [1].

Nominal Voltages:	High Voltage (HV)	11KV,22KV
	Low Voltage (LV)	240V, 415V
LV variation range:	Steady state	Within +6%/-10%
Nominal frequency:	-	50Hz
Frequency variation range:	-	Within 5%; $\pm$ 2.5%

Horizon Power's guidelines are also similar and are presented in Table 2 below. Note that most system requirements for the prototype network that was simulated in this report have come from Horizon Power, as their requirements for load voltage are stricter than the PWC's requirements.

Table 2 Horizon Power Supply Requirements [13].

Parameter	Value
Three Phase Voltage	415V a.c. $\pm$ 6%
Frequency	50Hz $\pm$ 2.5%

Cloud events are the main reason PV generation experiences intermittency during the day. In such events it is common for PV generation to drop by 60 per cent in a matter of seconds. Solar system variability can be characterised as both temporal and spatial [6]. As spatial separation is increased the 'smoothing' effect will vary the impacts of variability on the electricity grid. The smoothing effect describes how the correlation between solar power intermittency and production is decreased as the spatial separation is increased [6]. While sunshine variability results in the intermittency in PV solar outputs, the changes are generally slow enough to mitigate voltage flicker [7].

5.1 AS/NZS 4777.2:2015 Inverter Requirements

When connecting PV systems to the grid via inverters there are specific Australian standards relating to the functionality of the inverter that must be adhered to. For this network, it is important to understand the protective functions, sustained operation voltage requirements, and the sustained operation frequency requirements. The anti-islanding protective functions summarised in Table 3 work on a short time scale and are more applicable to the system's response during transient and dynamic periods.

Table 3 Anti-islanding protective functions [14]

Protective function	Protective function limit	Trip delay time	Maximum disconnection time
Undervoltage (V<)	180V	1s	2s
Overvoltage 1 (V>)	260V	1s	2s
Overvoltage 2 (V>>)	265V	-	0.2s
Under-frequency (F<)	47Hz	1s	2s
Over-frequency (F>)	52Hz	-	0.2s

5.1.1 Sustained Operation Voltage

In Australia the maximum nominal voltage ($V_{nom\text{-}max}$) is usually 255 volts, which is approximately 1.0625 per unit of the default nominal voltage of 240 volt. A 10 minute grid voltage average is compared against $V_{nom\text{-}max}$ every 3 seconds to determine whether or not to disconnect the inverter [14].

5.1.2 Sustained Operation Frequency

The 'Australian/New Zealand Standard 4777.2:2015 Inverter requirements' states that an inverter should be capable of supplying its rated power anywhere between 47 hertz and 50.25 hertz. The inverter must reduce its output power linearly from frequencies between 50.25 hertz and the stop frequency (f_{stop}). When f_{stop} is reached the output from the inverter must be zero watts. The stop frequency is 52 hertz by default but can lie anywhere between 51 and 52 hertz [14].

The inverter's output power should stay at the lowest power level reached in its response to over-frequency events lying between 50.25 hertz and f_{stop} until the grid frequency has been held at 50.15 hertz or less for a minimum of 60 seconds. This methodology provides a kind of hysteresis control in the inverter. Even when the conditions for the power output to increase again are met it must not increase at a rate greater than the specified power rate limit. In unconstrained power operation the inverter may increase its output power immediately after 6 minutes of a frequency equal to or less than 50.15 hertz [14].

5.1.3 Quality

Total harmonic distortion levels (THD) are likely to increase due to increased penetration, especially in high impedance grids such as suburban and rural grids. This is unlikely to be caused by PV inverters as the Australian standard AS4777 limits for harmonic distortion are significantly less than are allowed for loads. The main cause for increase in THD is due to the PV array reducing the active power requirement, which means the fundamental frequency component decreases. The reduced fundamental frequency can result in an increase in the THD ratio to the fundamental frequency, though this is generally not a significant difference [6].

All generators have physical restrictions to the rapidity they can respond to load changes. This speed of response is known as the generator's 'ramp rate'. Consumer loads tend not to exceed the generator's ramp rate because their large scale effects are predictable, so extra generation can be scheduled for the appropriate times, and because of the slow moving nature of the large scale effects [6].

5.2 Power System Conditions That Affect Power Quality and Efficiency

A hybrid solar/diesel network's power quality can be affected by factors such as the allowable instantaneous PV penetration, how much spinning reserve is available, and solar intermittency. Power Quality may also be positively affected by PV output 'smoothing' techniques. Additionally the maximum

PV system penetration is limited by the minimum load requirements of the diesel generating units. The diesel generators minimum loading power and optimum loading range also relate to the power system's efficiency.

5.2.1 Instantaneous PV Penetration

Hybrid mini-grid systems generally class the system solar penetration by two numbers; energy penetration and power penetration. Energy penetration is the percentage of total energy that the PV solar system provides to the network. This is usually evaluated per annum and is a measure of the average penetration. If the power being provided by solar to the network needs to be known at any particular instant in time then the power penetration must be assessed. Power penetration is the percentage of power that solar provides instantaneously to the power system (KW/KW). For example, a solar system may reach 70 per cent power penetration at some points in time but provide 20 per cent annual energy penetration over the course of the year [1].

5.2.2 Spinning Reserve

Spinning reserve is the quantity of spare diesel generator capacity to provide power that is online and accessible to instantaneously service additional loads. A spinning reserve is maintained in order to manage normal community load fluctuations. Additional spinning reserve may be required in solar/diesel hybrid networks in order to supply any unmet load in the event of a reduction in solar output, as may occur during cloud events. The minimum value of spinning reserve that must be available at any given time is controlled by the spinning reserve set point. For PWC's mini-grids the spinning reserve is generally determined by the known highest load in the community that can be turned on at any given time [1].

5.2.3 Minimum Loading

The aim of hybrid solar/diesel networks is not to reduce the capacity of the diesel generators in any way. The main aim is to replace a portion of the power that would normally be produced from dispatchable diesel fuel with solar power. This means that the network's diesel generators should be fully capable of providing power to the whole network in the event that no power is being provided by the solar system. As cloud events are difficult to predict and can occur within a very short space of time the engines must be kept online at all times and must not run continuously beneath their minimum load factor [1].

Minimum loading makes reference to the lowest recommended load factor as a percentage of a diesel engine's name plate rating. A minimum loading is specified because a diesel generator can be damaged by operating below the minimum load factor for an extended period of time. Extended under loaded operation may cause problems such as 'blow by', 'wet stacking', and 'cylinder glazing'. Blow by occurs when fuel, air, and moisture in an engine's combustion chamber are forced past the piston rings into the engine's crankcase. Wet stacking is a disorder that occurs in diesel engines where some of the diesel is not burned and instead passes into the engine's exhaust system. Cylinder glazing is where the bore (cylinder walls) gets a surface coating derived from the chemicals present in the oil and fuel. Reduced engine performance and premature maintenance or engine rebuilding may be the result of prolonged operation below the minimum load factor. The minimum loading of the diesel generator is typically in the order of 40 per cent of the name plate rating, but is set as a manufacturer recommended specification. Typically, to avoid the above issues and to maximise thermal efficiency, generators operate between 50 and 90 per cent of their rated capacity [1].

As a result of minimum loading on generators the system has a limited ability to accept solar power input. Table 4 illustrates generator minimum loading being taken into account when deciding on safe solar penetration levels, assuming a system load of 200 kilowatt and a 40 per cent minimum load factor [1].

Table 4 Examples of calculating allowable solar penetration.

Generator	Rated Capacity	Minimum Loading	Net Load 'available' to be serviced by solar	Allowable solar power penetration
A	250KW	100KW	100KW (200KW – 100KW)	50%
B	375KW	150KW	50KW (200KW-150KW)	25%
C	500 KW	200KW	0KW (200KW-200KW)	0%

According to Cummins Power Generation website, it is recommended that their generator sets should not be run beneath a minimum loading of 30 per cent of their rated capacity [15]. In this report a load factor of 30 per cent has been assumed as it allows higher levels of instantaneous PV penetration to be trialled. But this figure should be checked with the manufacturers, as often other typical values for minimum loading lie between 40 to 60 per cent of the name plate rating. Operation below minimum loading for short periods of time may be acceptable so long as the generator set is also operated at high loading for sustained periods of time to reverse the effects of wet-stacking and other generator disorders [3].

5.2.4 Solar Intermittency

In systems that do not include energy storage, load increases due to intermittency of solar output (usually as a result of cloud events) must be covered by the online diesel generators. Although diesel generators are quick starting they cannot start and synchronise fast enough to pick up the additional load in the limited time available during such an event. This constraint limits the total power output of the solar system [1].

5.2.5 Smoothing

Smoothing in the context of solar powered mini-grids refers to the act of reducing the systems sensitivity to acute solar output fluctuations during intermittent cloud cover events. The smoothing function is usually provided by energy storage systems although can be implemented by increasing the geographical dispersion of the PV solar systems. [1].

6 Mitigation Techniques Considered

Various techniques for improving the network's power quality and stability have been investigated in the following sections. In the simulations switching shunt capacitor banks and increasing the generator sets nominal voltage was trialled in simulation.

6.1 Distributed Generation

Distributed generation, also known as embedded generation, is generation applied at the distribution level. Distributed generation can be defined as the utilisation of small, modular power generation technologies spread throughout a distribution network. In addition to reduced emissions when using renewable energy sources, some benefits are [7]:

- Reduced transmission and distribution loading (reduced load growth)
- Reduced system losses
- Improved power quality
- Improved reliability

Reduced system losses can be achieved when applying distributed generation closer to the load. Voltage drops can also be reduced, which improves power quality as a result of distributed generation [7].

One of the fundamental principles of distributed generation is the 'coincident' factor. The coincident factor can be related to solar output smoothing and is defined as the ratio of the peak load demand of the system as a whole to the sum of the individual peak load demands within that system. The whole system's peak demand is often referred to as the peak 'diversified' demand or the peak coincident demand. Individual peak demands are known as the 'noncoincident' demands. The coincident factor is always less than or equal to one. Generally the coincident factor is much less than one due to the individual loads not reaching their peak demand at the same time [7].

$$f_{diversity} = \frac{\sum_{i=1}^{n} Max(Load_i)}{\sum_{i=1}^{n} Load_i} \qquad (6.1)$$

The relevance of the coincident factor applies in this report in that the PV solar output is being treated as a negative load. This means that when the solar output decreases the generator set sees this as a load increase. If the solar systems are geographically separated then the cloud events will usually not occur at the same time, which means the coincident factor is reduced. This generally allows the generator set more time to respond to the load increases [7].

In the context of the Northern Territory, a single power station provides power to the mini-grid. In the case of hybrid solar and diesel systems, the solar power station is located next to the diesel power station. While some homes in the remote communities do have rooftop solar, their impact is small when compared to the scale of the centralised diesel power station. There is no communication between the rooftop solar and the central power station. This implies that the rooftop solar system behaves as a negative load [1].

Remote power systems are typically being monitored and managed on a continuous and automated basis. In most cases the solar-diesel system interface takes place in the power station and the solar feeder is connected to the main switchboard. Usually no loads are connected to the solar feeder between the solar system and the switchboard. It should be noted that distributed generation would likely require a more advanced supervisory control and data acquisition architecture than the current centralised control systems [1].

The Solar/Diesel Mini-Grids handbook explains that distributed generation (such as customer owned rooftop solar) in remote indigenous communities does not serve to mitigate or 'balance out' the intermittency of these systems. This is due to the insufficient geographical separation between these systems. It would be interesting to trial distributed generation in this network as the generation busbar supplies two separate feeders that can be considered to be in reasonably separated geographical locations, and while ultimately the network will require the same spinning reserve, this distributed configuration may increase the time it takes for the solar to ramp up or down its contribution [1].

6.2 Automatic Tap Changing Transformers

Long term voltage stability often requires the use of tap changing transformers. This may increase the study period to several minutes [16]. Tap changing transformers are used to regulate bus voltages as well as control the reactive power flow to the lines to which they are connected. They can be automatically regulated for fast voltage control [4], though generally they are used for 'slow' voltage variations [12]. In the model created for this report, shunt capacitor banks have been favoured over the use of automatic tap changing transformers because they can be tested in PowerFactory's RMS simulations.

6.3 Energy Storage

Energy storage in the context of hybrid solar and diesel networks refers to a way of keeping a reserve of energy for when it is required to enhance power quality, provide better system stability, and maximise the use of renewable energy sources. Normally energy storage is classified as being either 'long-term' or 'short-term'. An example of long-term energy storage is a solar and battery system providing power over night. Alternatively a short-term energy storage system may be used for short periods of time for applications such as smoothing solar intermittency in solar and diesel hybrid min-grids. A few types of energy storage technologies are batteries, pumped hydro, compressed air, super-capacitors, and fly wheels. These technology types are suited to different applications [1].

Solar and diesel hybrid systems allowing for high penetration often require energy storage to smooth the solar output in the event of solar intermittency. This can mean that it is no longer necessary for the online diesel generators to facilitate enough spinning reserve to account for loss of the entire solar output. The philosophy is that during a cloud event the energy storage system (ESS) delivers enough power for a long enough period to allow for an extra generator to be started and synchronised. Full integration between the solar and the diesel control systems is required for high penetration solar and diesel hybrid systems to run efficiently [1].

Solar/diesel mini-grids can include energy storage systems to provide various different functions. The most common functions are listed below as [1]:

- Short term energy storage – To control power quality (voltage, reactive power, and frequency).
- Short term energy storage – To smooth the ramp rate of the solar output during cloud events, allowing higher PV penetration.
- Long term energy storage – Load shifting to closer match solar resources with load demand, allowing higher energy penetration.

6.3.1 Improving Power Quality

Energy storage systems used to preserve power quality work to ensure stable operation of the mini-grid when the inconsistency of the PV system output fluctuations are too much for the diesel generators to instantaneously compensate for. This type of energy storage system generally has to be capable of providing a substantial quantity of power for time periods in the range of seconds to minutes. Due to the short timescale, this type of energy storage provides a relatively small amount of energy. This is applied to achieve decreased ramp rates on both solar and diesel generating equipment. Reducing the ramp rates serves to limit the frequency and voltage variations that can jeopardise system stability [1].

6.3.2 Ramp Rate Smoothing

Load following applications of energy storage systems are used to mitigate the effect of short time periods (in the range of minutes to hours) of decreased or increased solar energy provision. Energy storage systems of this magnitude can be considered to be a type of spinning reserve, and can serve to enable a network to operate with a smaller diesel generator in the case of generator sets with variable generator capacity, or less online generators in the case of generator sets where all generators are of equal capacity. Essentially this function smooths the solar output and assists in providing some form of short term certainty of available solar power [1].

6.3.3 Load Shifting

Load shifting applications of energy storage systems are implemented to match maximum output of the solar system with peak load demand. This helps to enable higher solar energy penetration as peak demand and peak load demand usually do not coincide. Theoretically, in high penetration systems long term energy storage can allow extended operation with smaller, or even no diesel generators [1]. Note that even with the addition of energy storage in solar and diesel hybrid systems to allow for high penetrations of solar, the minimum loading constraint of the existing diesel generators must be adhered to [1].

6.3.4 Battery Banks

Commonly available electrochemical ESS are lead acid batteries (flooded or valve regulated), Nickel-Cadmium, lithium ion, and lithium polymer batteries [1]. Batteries made up of a series of individual cells are used for electrical energy storage in the form of chemical energy and can be relied on to supply the necessary power for a specified period within set voltage limits [12] [4]. The most mature types of batteries are several types of 'advanced lead acid' battery which promise higher energy density, extended cycle life, and improved power levels [1]. Had the frequency fluctuations been more severe in the simulation network used for this report, battery banks would have been a viable solution. While battery banks have not been required in these simulations they may be required if the network is more accurately remodelled, and so are worth keeping in mind as a method for intermittent solar output smoothing (ramp rate smoothing) or possibly even load shifting.

6.3.5 Shunt Capacitor Banks

Shunt capacitor banks are extensively used in primary distribution to supply reactive power to loads. Capacitor banks can provide remarkable benefits to distribution system performance. This is due to capacitor banks' ability to reduce losses, free up capacity, and reduce voltage drop [7]. They serve to draw leading currents that offset the lagging component of currents in inductive loads. Shunt capacitors meet the reactive power requirements of the loads as well as distribution lines operating at a lagging power factor by providing an economical supply of reactive power [4]. Reducing voltage drops is especially relevant to the simulation network used as its load voltages fall beneath allowable levels at high levels of PV penetration. If not properly applied, capacitor banks can create losses and the risk of overvoltage under light loading. However this is not normally a problem with switchable banks such as used in this network [12].

It is important to note that while substantial use of shunt capacitors can contribute to the voltage stability problem, in some cases additional capacitor banks can also answer the problem by freeing 'spinning reactive reserve' in the generators. Some shunt capacitor banks are installed in a set of capacitor (reactor) blocks which can be switched in or out of the system automatically to improve voltage profiles [17] [12]. Automatically controlled switching has been used for the capacitor banks implemented in the simulation network.

6.3.5.1 Reducing Losses

Capacitor banks can be used to cancel the reactive power to loads with low power factors thereby reducing the line current. Reduced current frees up the generators capacity which allows the same network to serve a higher load. Significantly lower active power losses (I^2R) are also achieved by reducing the line current [12] [7].

6.3.5.2 Reducing Voltage Drop

Voltage can be boosted through the use of capacitor banks which serve to cancel out the voltage drop caused by system loads and system load increases. In the case of switched capacitor banks they can be used for voltage regulation [12] [7].

6.3.5.3 Load Management

Load management refers to the load being managed in order to optimise generator or network performance. In this report load management is referring to the direct control and interruption of loads in order to optimise power system operation. Optimising power system operation may be done in order to mitigate the effects of intermittent solar output on power station stability [1]. Load management techniques have not been further investigated in this report though may be an avenue for future research.

6.4 Adjusting the Generation Busbar Nominal Value

One of the options utilities have for mitigating voltage sags is raising the nominal voltage to the upper end of the allowable range. Increasing the nominal voltage can benefit the equipment such as computers, adjustable speed drives, and other equipment with capacitors or at least ensure that the voltage reaching the loads is not near the lower end of the range [7]. In this report the power station's nominal voltage was increased and proven to increase the load voltage back up to within its allowable limits. However the nominal voltage could not be raised by more than 1.5 per cent before it caused over frequency effects. This restriction is likely caused by the generators exporting more reactive power due to their field excitation being increased.

7 Simulation Method and Results

The main power quality and network stability concerns are related to the grid frequency and the voltages supplied at the load bus. In all simulations the PV system is ramped down from the required amount of power to achieve the desired penetration to zero output. Table 5 provides information about how much PV power must be provided to achieve 60 and 70 per cent power penetration in the network. Also provided in Table 5, is the duration of the ramp down events, and the generators' loading prior to and after the cloud events. The ramp down rate for each simulation was approximately 17 kW/s.

Table 5 Network conditions for each simulation.

penetration	Mitigation Method	PV (kW)	Total ramp time (s)	Initial Loading	Loading
60 %	none	262.1	15.40	45.0%	83.1%
60%	raised nominal voltage	262.1	15.40	47.4%	85.7%
60%	c-shunt	262.1	15.40	37.2%	79.7%
70%	none	305.7	17.96	39.8%	82.9%
70%	raised nominal voltage	305.7	17.96	42.0%	85.4%
70%	c-shunt	305.7	17.96	30.3%	79.4%

The simulation method used in PowerFactory, assuming the network has already been modelled, was as follows:

1. Ramp down event (load ramp up events) were created/selected with ramp times as shown in Table 5. For more information see sections 11.6 and 11.9 of the appendices.
2. Next switch events were made to open the PV system breakers (the negative load simulator and PV source breakers) once the net power from the PV system is zero.
3. The PV system power required for the penetration being simulated, as shown in Table 5, was then entered into the PV source.
4. Result variables were specified for PowerFactory to record during the simulation.
5. Plots of the system frequency, and the load terminal voltages were created from the recorded result variables. The plots were blank until the simulation was run.

6. In the ‘Change Toolbox’ drop down menu the ‘RMS/EMT Simulation’ option was selected.
7. Initial conditions of the network were then calculated.
8. The simulation was run and the plots automatically created.

Table 6 below shows the new steady state frequency (f_{new-ss}) that the network reaches after a solar ramp down event as well as the minimum frequency ($f_{min-peak}$) recorded during the transient and dynamic periods. The frequency has been recorded at ascending levels of penetration and trialled with and without raising the nominal generation voltage or the use of shunt capacitor banks. The recorded frequencies can be compared to their nominal value of 50 hertz.

Table 6 Frequency response to ramp up events at different levels of penetration.

Penetration (%)	Mitigation method	f_{new-ss} (Hz)	$f_{min-peak}$ (Hz)
45	none	49.3	48.3
60	none	48.8	47.8
60	raised nominal voltage	48.8	47.8
60	c-shunt	48.8	47.8
70	none	48.6	47.6
70	raised nominal voltage	48.6	47.6
70	c-shunt	48.6	47.5

The concerns related to the grid frequency are highlighted in red in Table 6 seen above. The concerns about frequency here relate back to the PWC and Horizon Power’s guidelines of keeping the operating frequency within plus or minus 2.5 per cent of the nominal 50 hertz (between 48.75 and 51.25 hertz). The highlighted values do fall short of the allowable limit, which could indicate the need for a battery bank system but quite likely implies the need for an isochronous controller.

Table 7 shown below lists the per unit voltage of the load buses at their initial values (V p.u.), the lowest point reached during the ramp down event ($V_{min\text{-}peak}$ p.u.), and also their new steady state operating voltage ($V_{new\text{-}ss}$ p.u.). This information is listed for the simulations of ascending levels of PV penetration and with or without mitigation techniques.

Table 7 Load voltage response to PV output ramp down events at different levels of penetration.

Penetration (%)	Mitigation method	Load terminal	V p.u.	$V_{new\text{-}ss}$ p.u.	$V_{min\text{-}peak}$ p.u.
45	None	community 1	0.969	0.961	0.96
45	None	community 2	0.96	0.952	0.951
60	None	community 1	0.955	0.939	0.939
60	None	community 2	0.944	0.929	0.928
60	raised nominal voltage	community 1	0.969	0.954	0.953
60	raised nominal voltage	community 2	0.958	0.943	0.942
60	c-shunt	community 1	0.961	0.944	0.943
60	c-shunt	community 2	0.956	0.941	0.939
70	None	community 1	0.955	0.938	0.937
70	None	community 2	0.944	0.927	0.926
70	raised nominal voltage	community 1	0.969	0.952	0.951
70	raised nominal voltage	community 2	0.958	0.941	0.94
70	c-shunt	community 1	0.961	0.942	0.942
70	c-shunt	community 2	0.956	0.941	0.939

Table 7 above includes an initial 45 per cent penetration level simulation to show that at lower levels of instantaneous power penetration no additional infrastructure or operating changes are required. In the 60 and 70 per cent penetration simulations it can be seen that while the operating voltage never falls low enough to trigger any trip functions, the new steady state voltages do fall below Horizon Power's grid requirements in the simulations containing no mitigation techniques. The result seen in Table 7 show that the new steady state voltage at the load buses can be improved to within the allowable 0.94 to 1.06 per unit value range through either using shunt switching capacitor banks or raising the nominal voltage at the generation busbar.

8 Conclusion and Future Work

In this thesis project, the effects of different PV penetration levels have been trialled in an ascending order. The effects the penetration has had on the mock network were tested in simulations and the results of these simulations documented. The results of the simulations conducted were then compared to the standards, the PWC, and Horizon Power's performance criteria. Where the criteria were not met, shunt capacitor banks, and raised power station nominal voltage were trialled to mitigate the effects of the simulated solar intermittency.

The simulations results suggest that levels of instantaneous PV power penetration higher than 30 per cent are feasible and that power quality issues tend to arise somewhere between the mark of 45 to 60 per cent instantaneous power penetration. The PWC consider 30 per cent penetration to not require significant upgrades to the existing infrastructure. Results from the 45 per cent penetration simulation suggest that even this level of penetration could safely be accommodated into the existing example network. Two more simulations of 60 and 70 per cent instantaneous penetration showed that the load bus voltages had fallen beneath Horizon Power's performance criteria. Both 60 and 70 per cent simulations were improved to within allowable voltage limits through the use of shunt capacitor banks, and increased nominal power station voltage.

Some limitations of this report are that the simulated PV system behaves simply as a negative load, the smallest cable type in PowerFactory's library was still oversized for its application as the distribution feeders' line type, and the ramp rates are based on limited information, and so require reassessment for plausibility. Due to limited time and control knowledge, the speed governor and AVR parameters have been left at PowerFactory's default values except for the controllers' primary gains, which have been experimentally adjusted.

Some recommendations for future work are:

1. Implementing an inverter model as part of the PV system to create a more realistic system model.
2. Creating a more realistic distribution line model (this may require contacting the PWC or Horizon Power for more information).
3. Further research into feasible ramp down rates and how they can be simulated in PowerFactory.
4. Research into ramp up rates.
5. Improving on the controller's parameters tuning and inputs.
6. Implementing an isochronous controller into one of the generators.
7. Trialling battery storage for intermittent solar output smoothing.

A more long term goal for future work is the inclusion of load profiles and solar irradiance profiles into the simulation model in order to be able to conduct time sweep simulations so that analysis on solar energy penetration can be performed.

A consideration for further modelling of the inverter and PV system is the use of tools such as MathWork's MATLAB, and the Simulink toolbox 'Sims cape Power Systems'. Models in 'm' files (the type used in MATLAB) can be called into PowerFactory. This may be easier than attempting extensive modelling in PowerFactory's programming environment [18].

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11 Appendices

The appendices show the relevant simulations' plotted results and provide a brief explanation as to the network model and cloud events.

11.1 Single-Line Diagram in PowerFactory

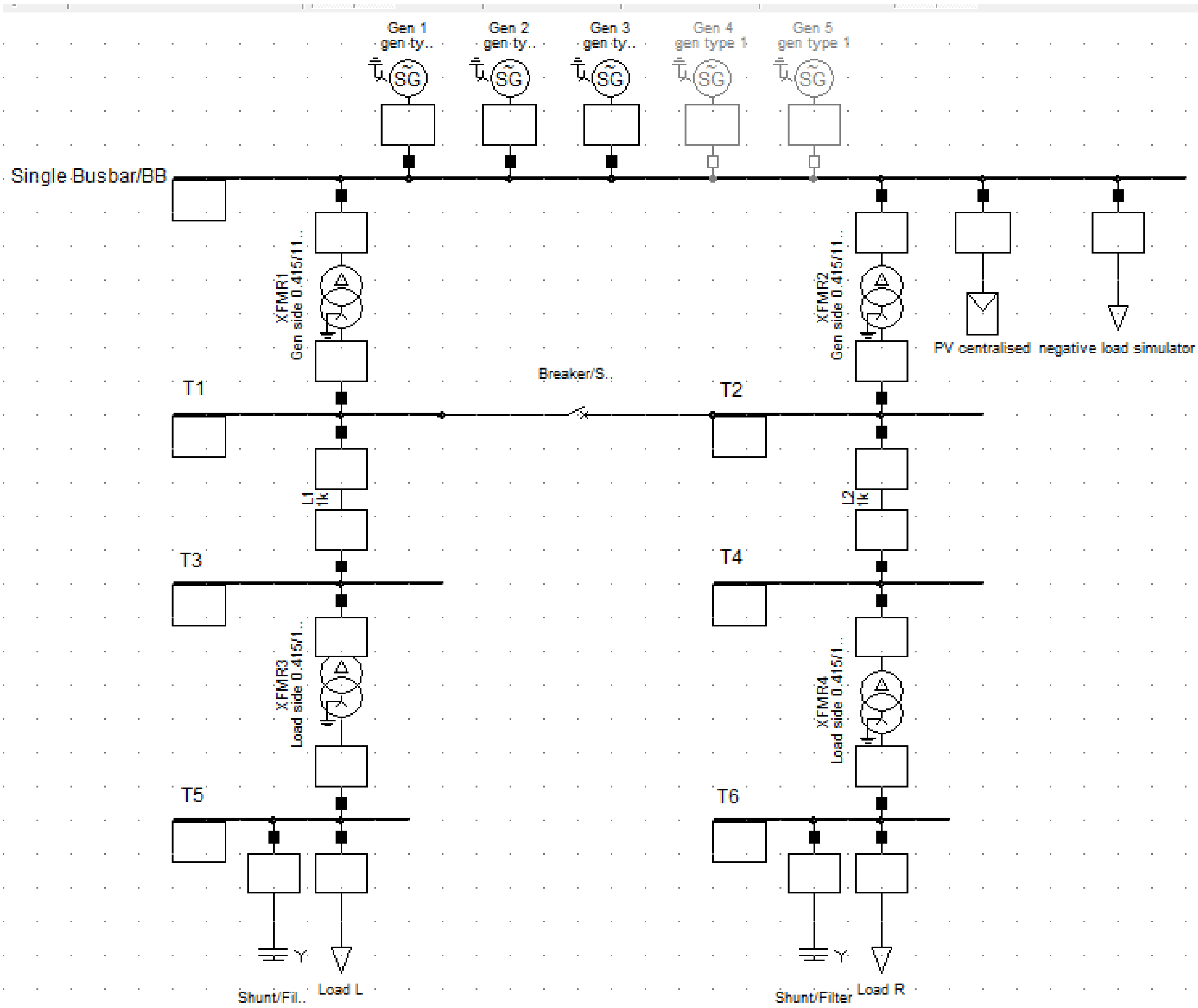

Figure 15 Single-Line Diagram in PowerFactory

11.2 Generators

The generator characteristics were entered into the 'Basic Data', 'Load Flow', and RMS Simulation' tabs. Entering data into the RMS simulation tab in addition to the load flow tab helps to more accurately characterise the generators transient and dynamic behaviour.

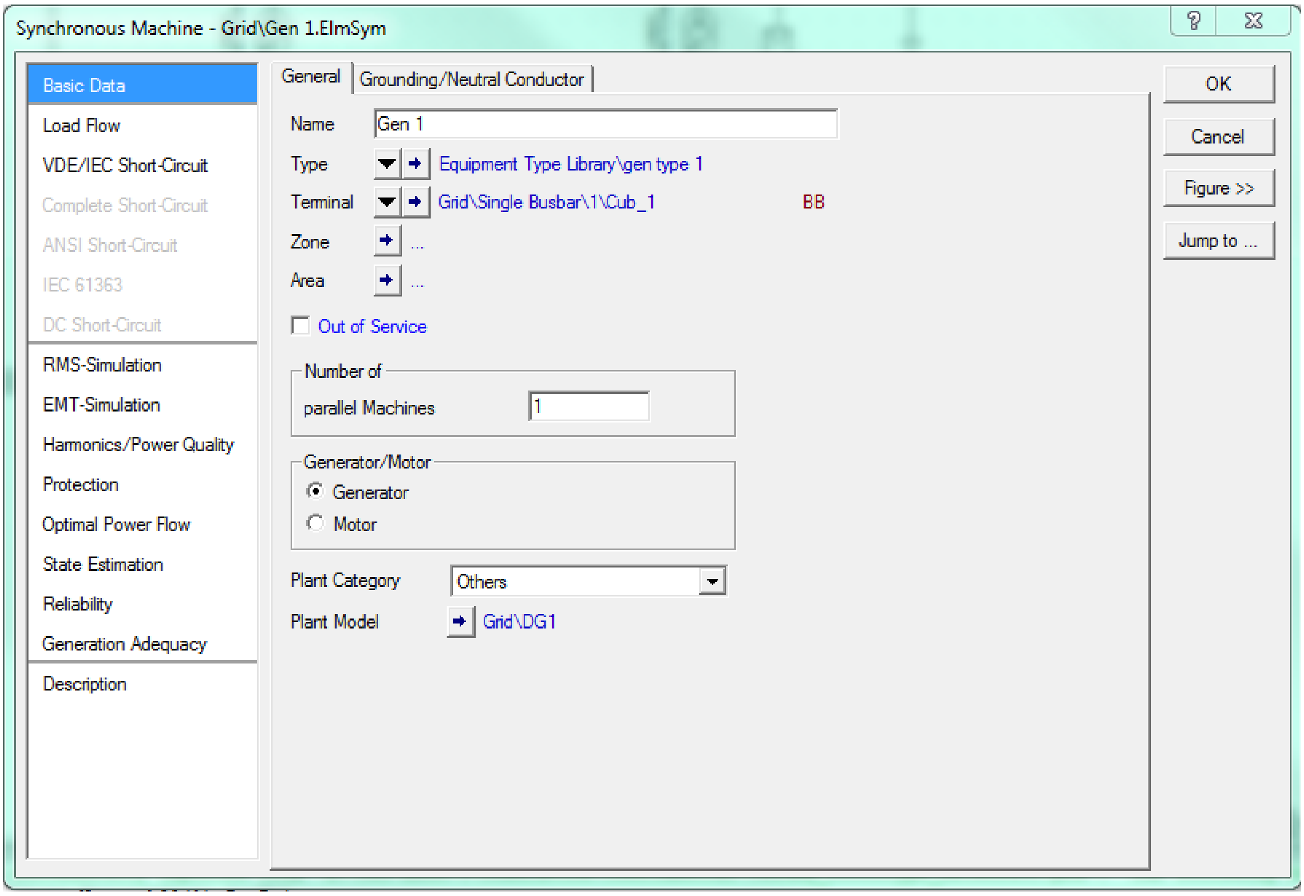

Figure 16 Generator 1 Basic Data tab.

By clicking on the drop down arrow next to the 'Type' parameter in the 'Basic Data' tab shown in Figure 16 the user is able to make a project type of diesel generator that can be reused within the project. The same generator type has also been used in generators 2 and 3. Clicking the side arrow next to 'Type' opens the diesel generator type created for viewing and editing. The parameters and model of the diesel generator can be seen below in Figure 17,Figure 18, and Figure 19.

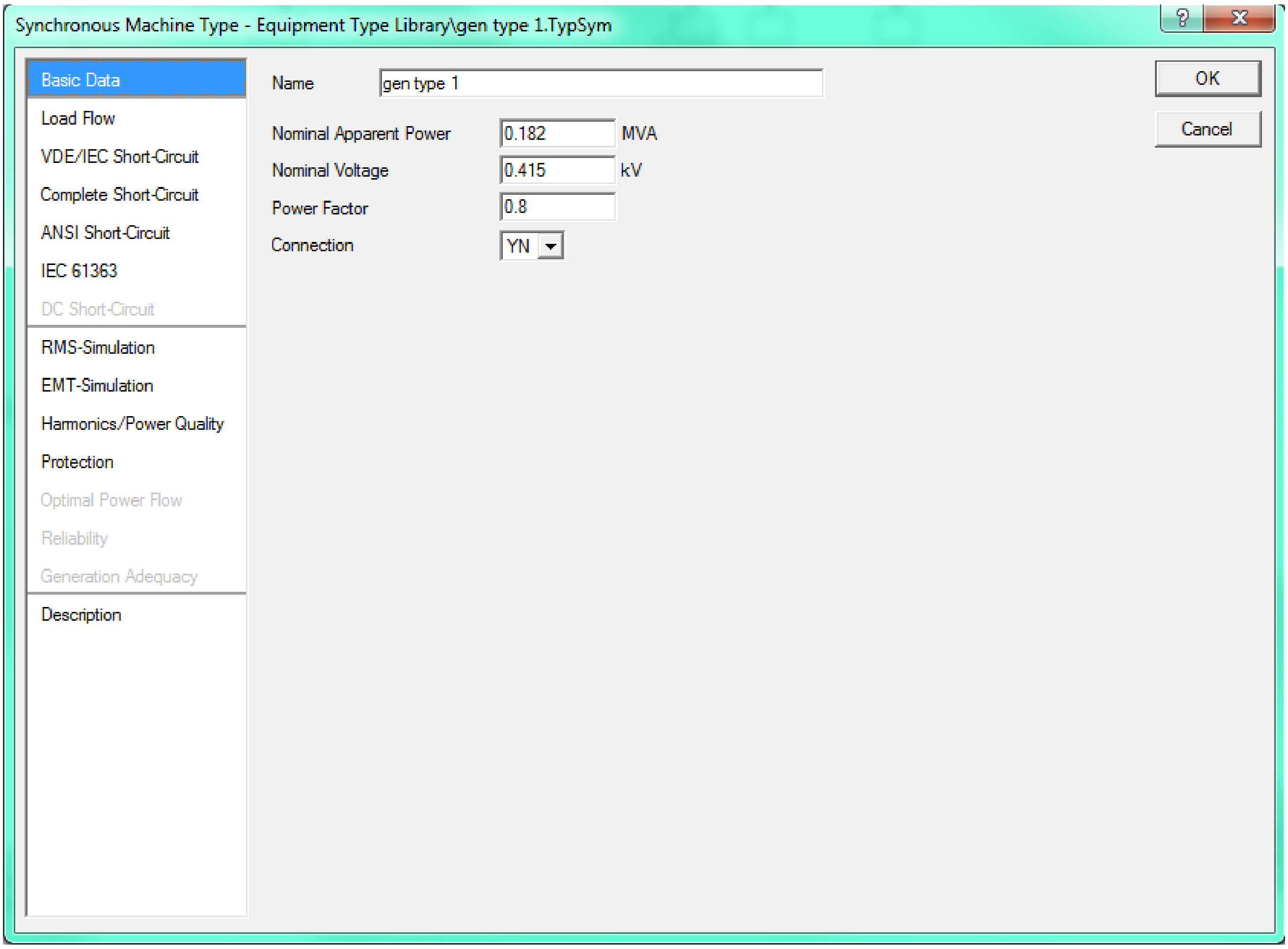

Figure 17 Diesel Generator Model Basic Data tab.

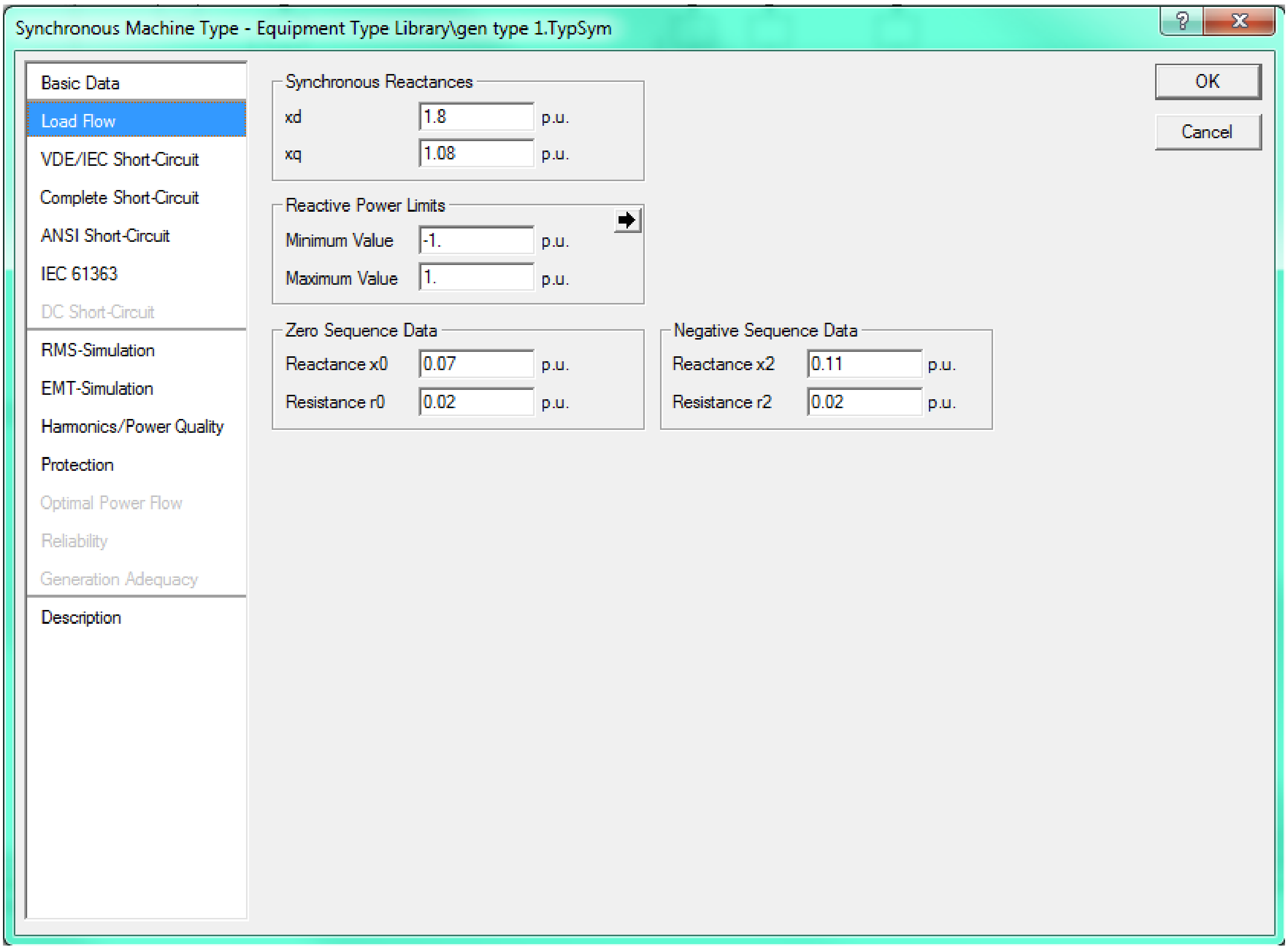

Figure 18 Diesel Generator Load Flow tab.

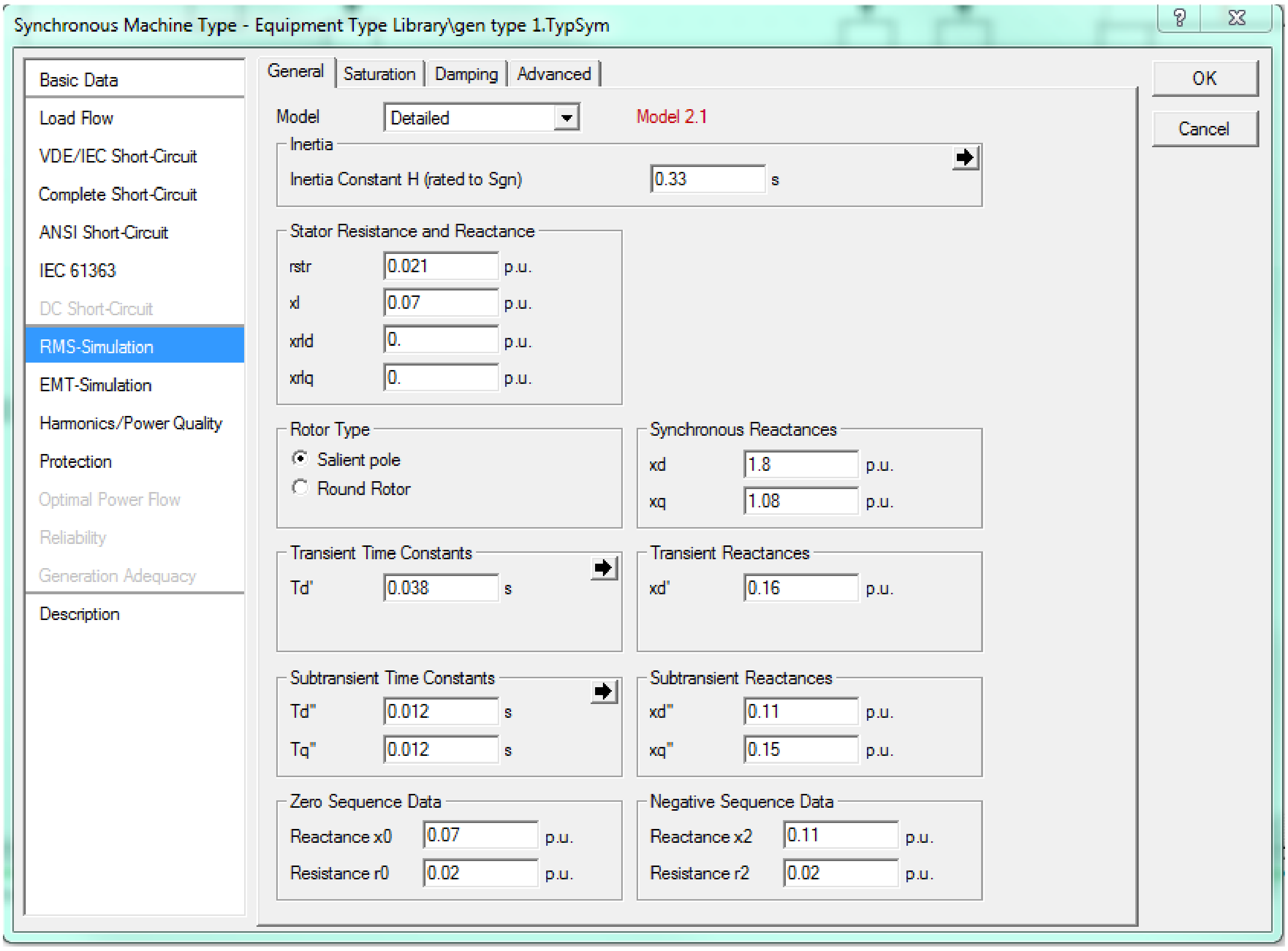

Figure 19 Diesel Generator RMS Simulation tab.

Figure 20, and Figure 21 show Generator 1's 'Load Flow and 'RMS Simulation' tabs. Generators 2 and 3 have the same values.

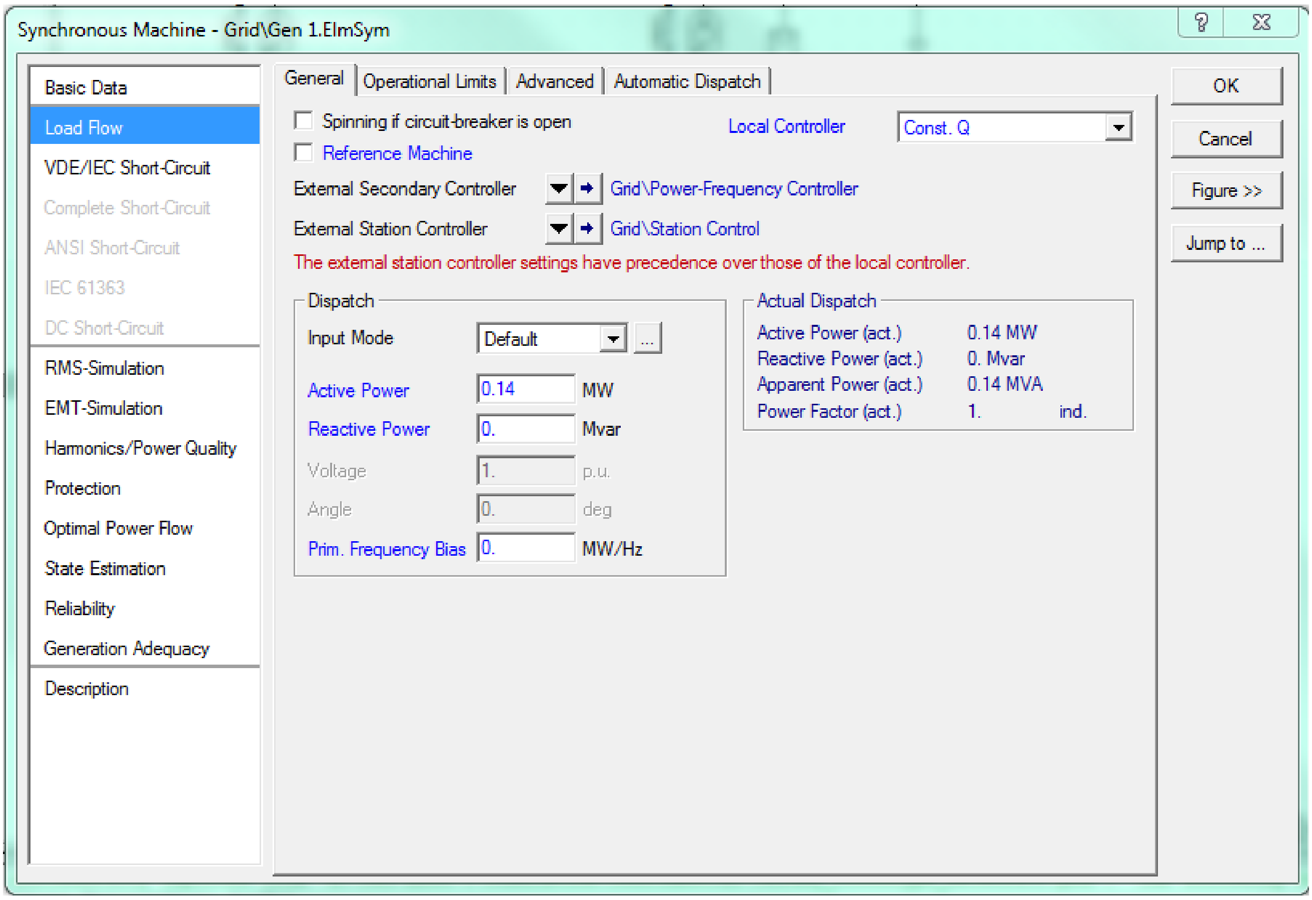

Figure 20 Generator 1 Load Flow simulation tab

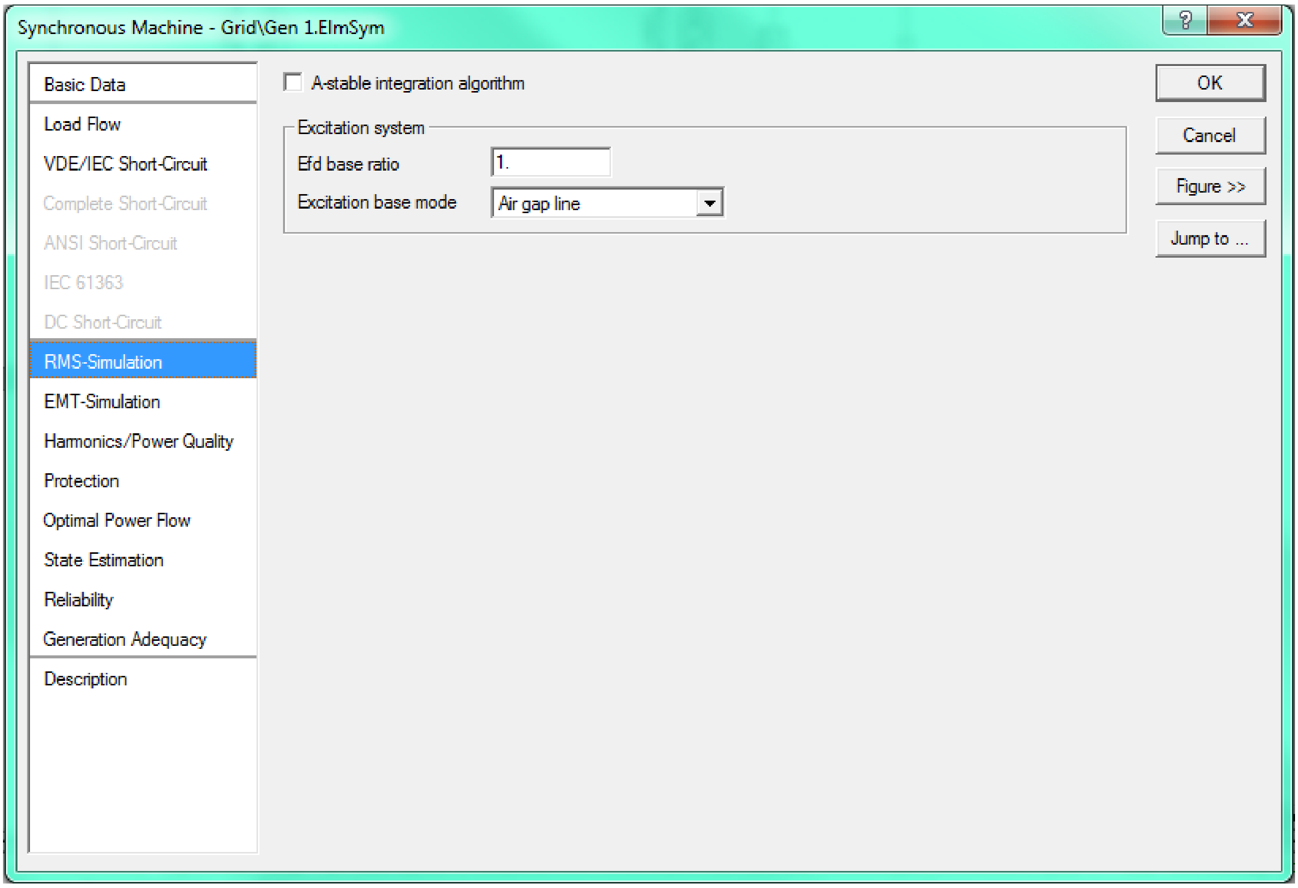

Figure 21 Generator 1 RMS Simulation tab.

11.3 Controllers

As shown in Figure 20 the generators have 'Power-Frequency Control' and 'Station Control' for their load flow analysis. Figure 22 below shows the configuration of the power frequency controllers.

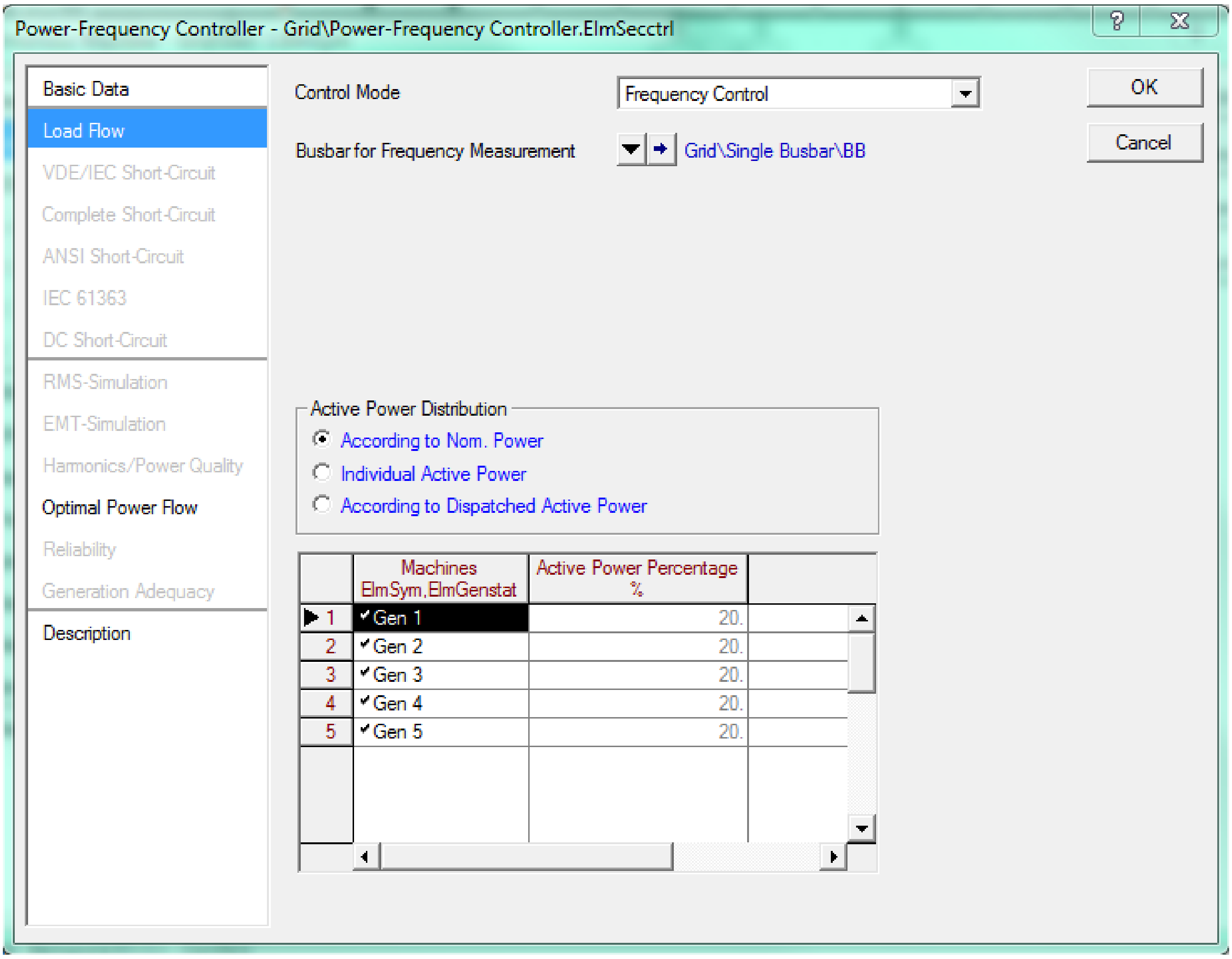

Figure 22 Power-frequency controller

Figure 23 shows how the station control has been set up to maintain the power station voltage.

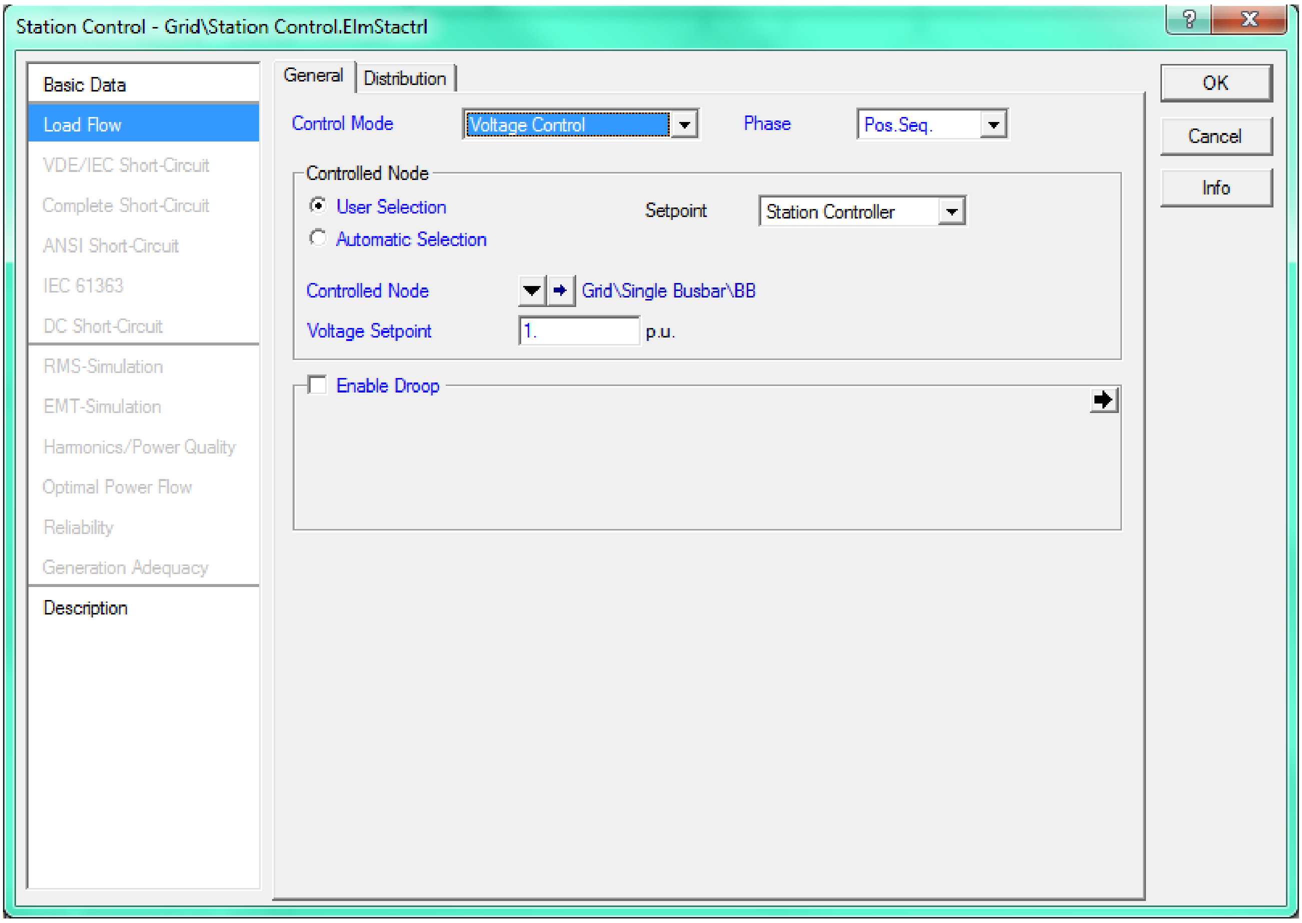

Figure 23 Station control (voltage control).

In Figure 24 can be seen the composite model for generator 1 (DG1). The composite model includes an automatic voltage regulator, and a speed governor.

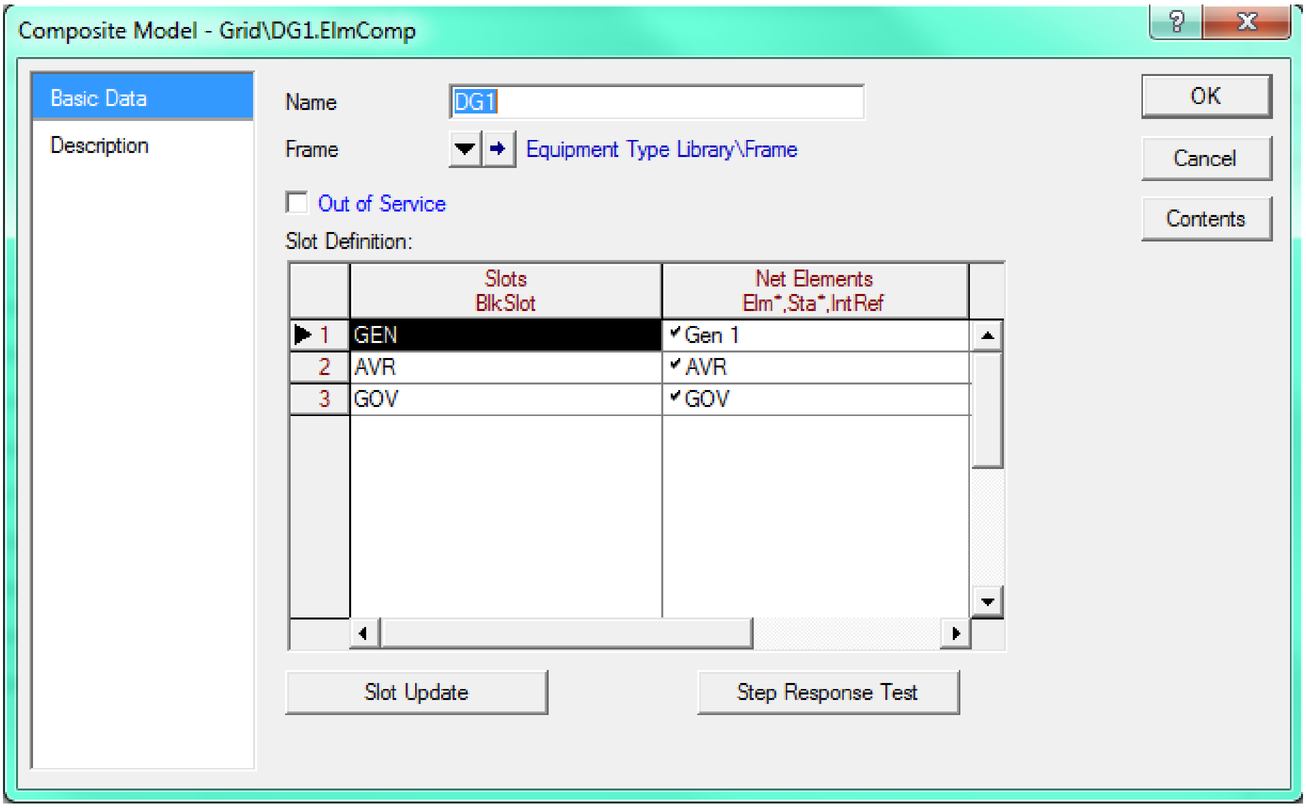

Figure 24 Generator 1 composite model.

Figure 25, and Figure 26 show the parameters entered for the automatic voltage regulator and the speed governor respectively. As time was limited only the controllers' gains were adjusted in both cases and all other parameters were left at their default values. Both the AVR and the governor are using Global type models available in PowerFactory.

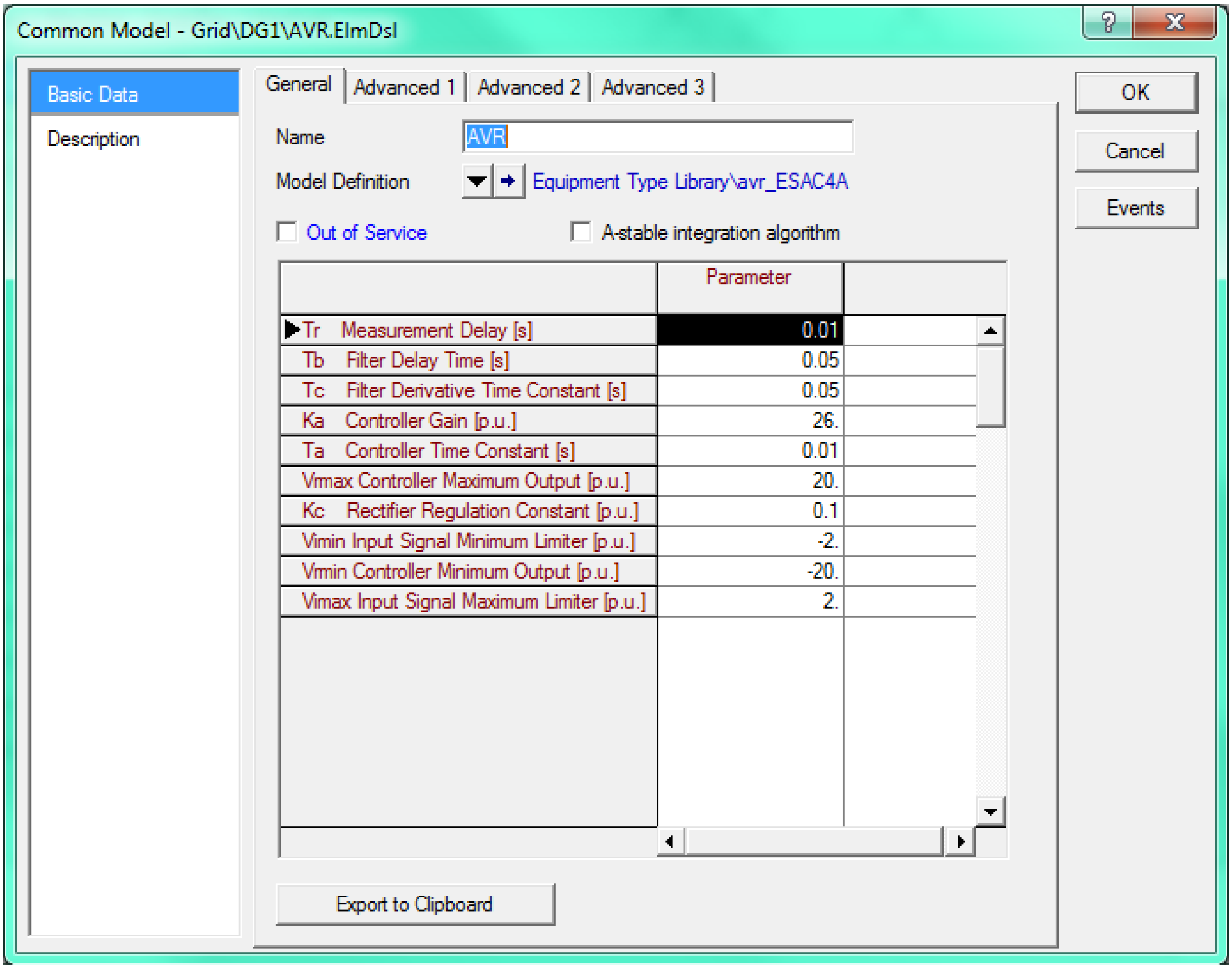

Figure 25 Diesel generator 1 automatic voltage regulator settings.

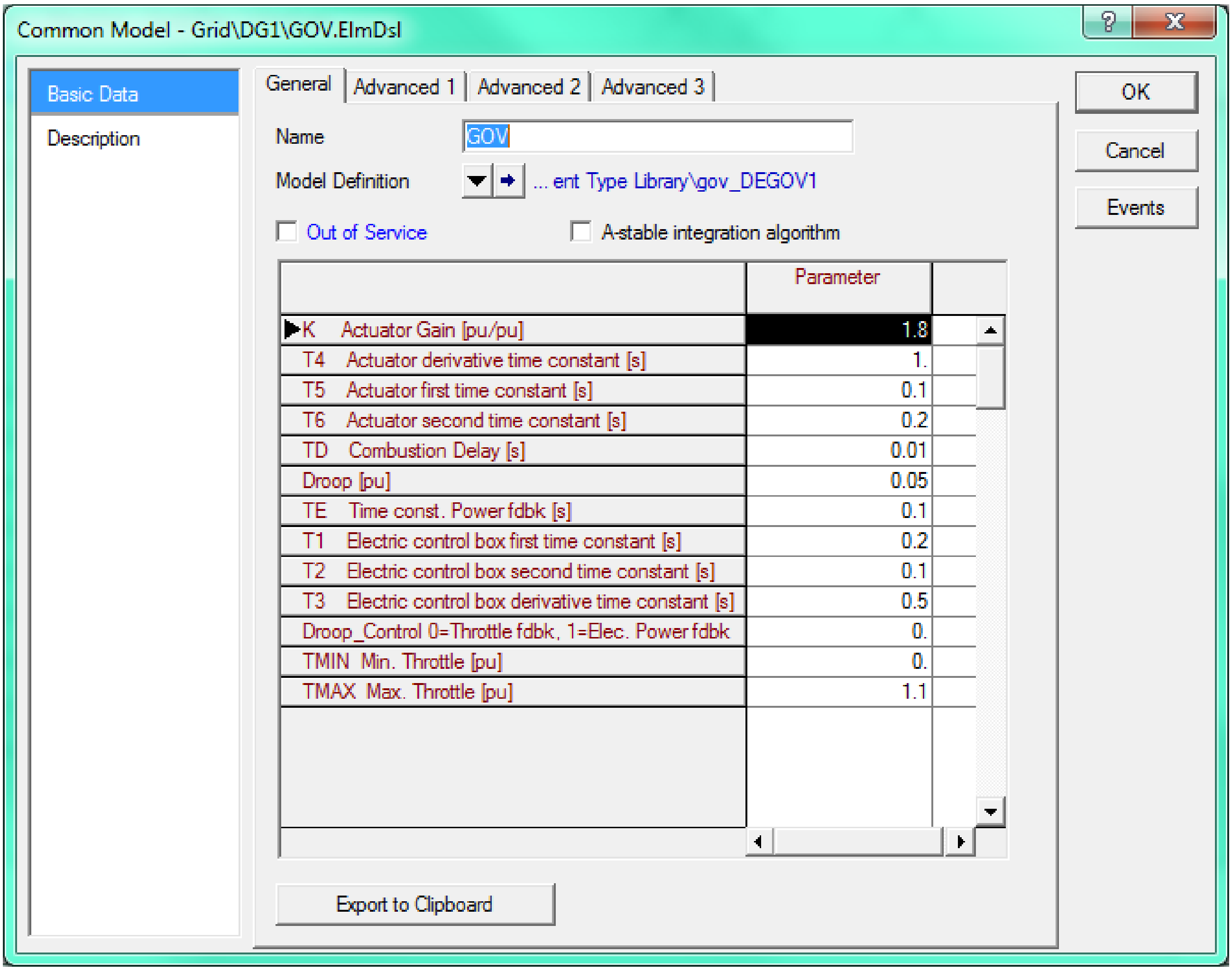

Figure 26 Diesel generator 1 governor settings.

11.4 Transformers

The transformers characteristics were entered into the 'Basic Data', 'Load Flow', and 'RMS Simulation' tabs to characterise the transformers' behaviour at steady state operation and in dynamic periods. The transformer model can be created by clicking the drop down box and edited by clicking the arrow next to 'Type' in the 'Basic Data' tab shown in Figure 27.

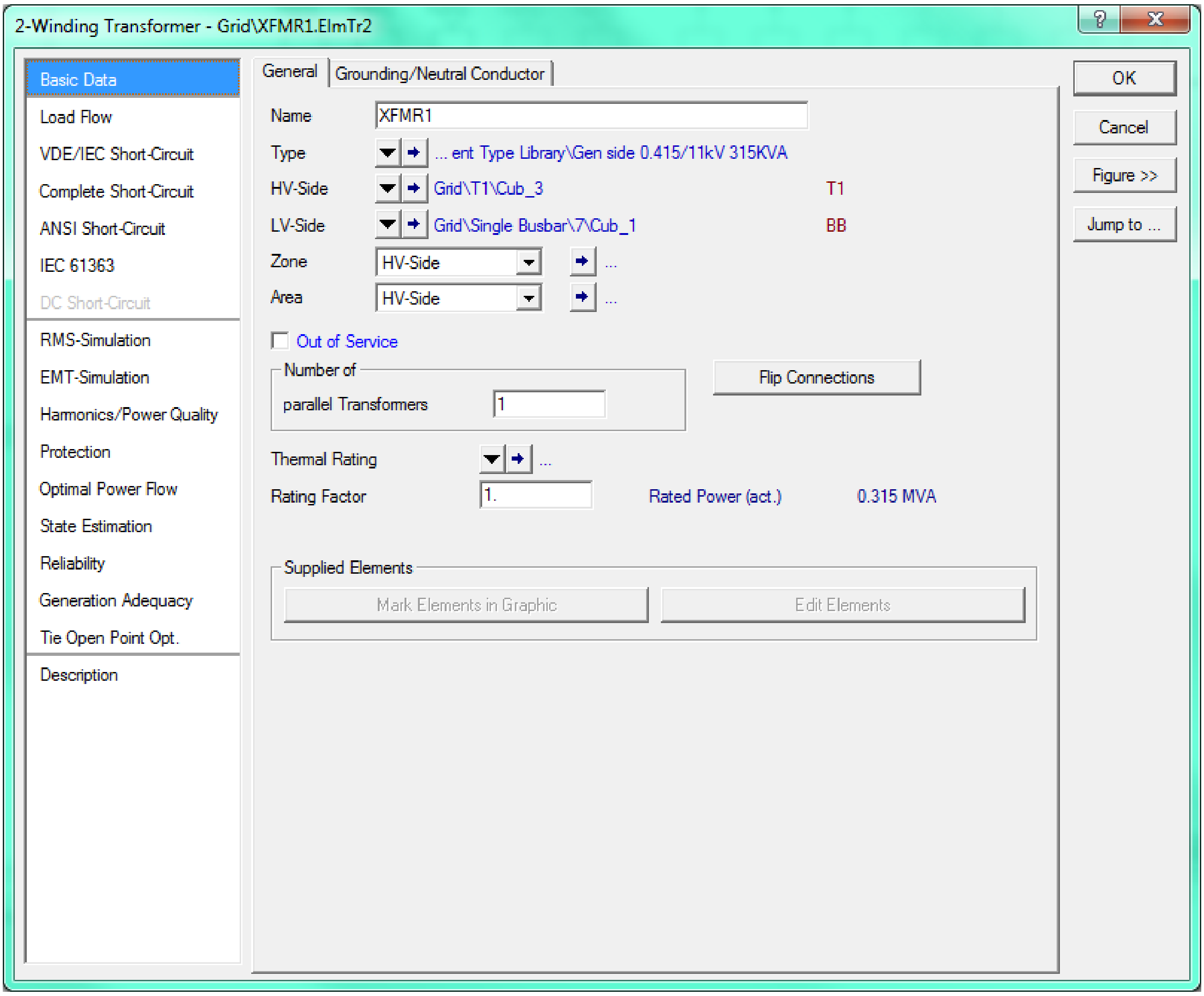

Figure 27 Transformer 1 Basic Data tab.

The transformers' model is shown in Figure 28, Figure 29, and Figure 30. The only variation between the power station side transformers and the load side transformers is whether the wye neutral or the delta configuration windings are operating at high voltage.

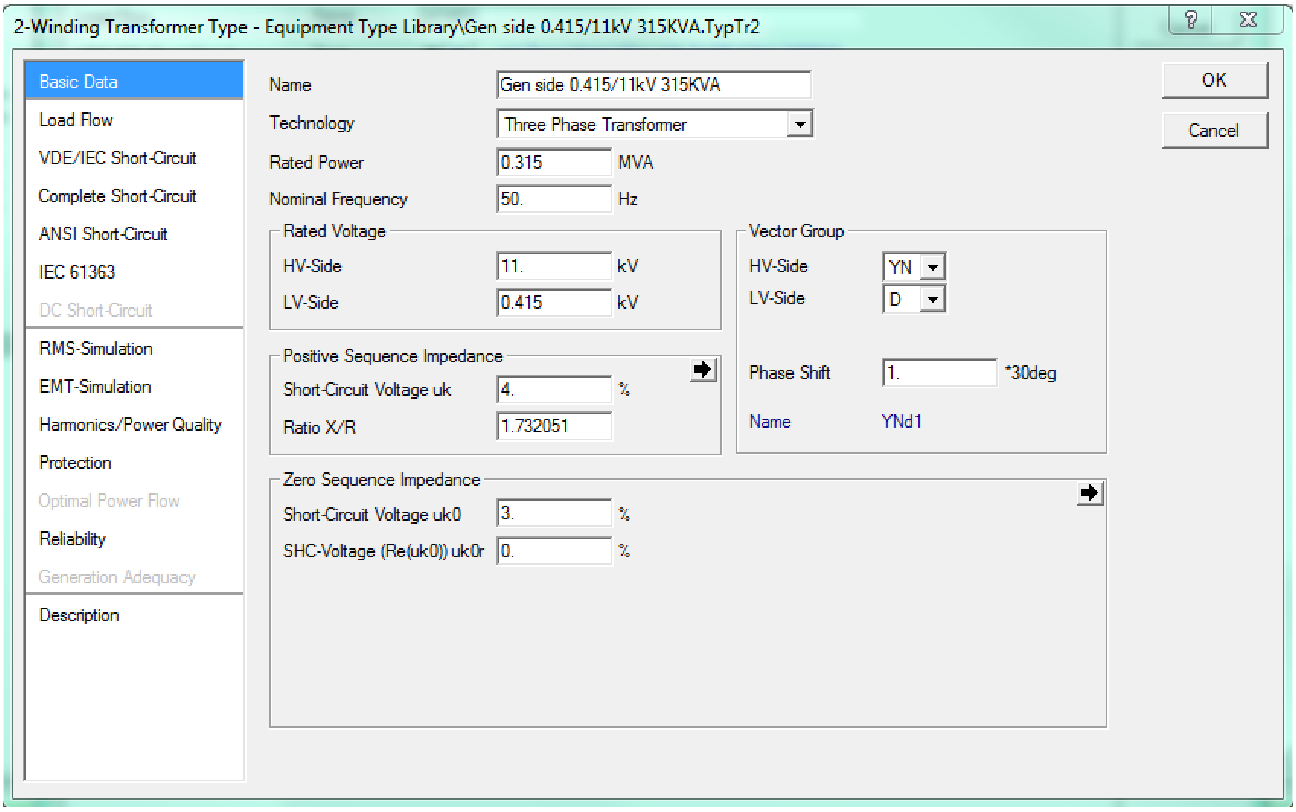

Figure 28 Transformer model Basic Data tab.

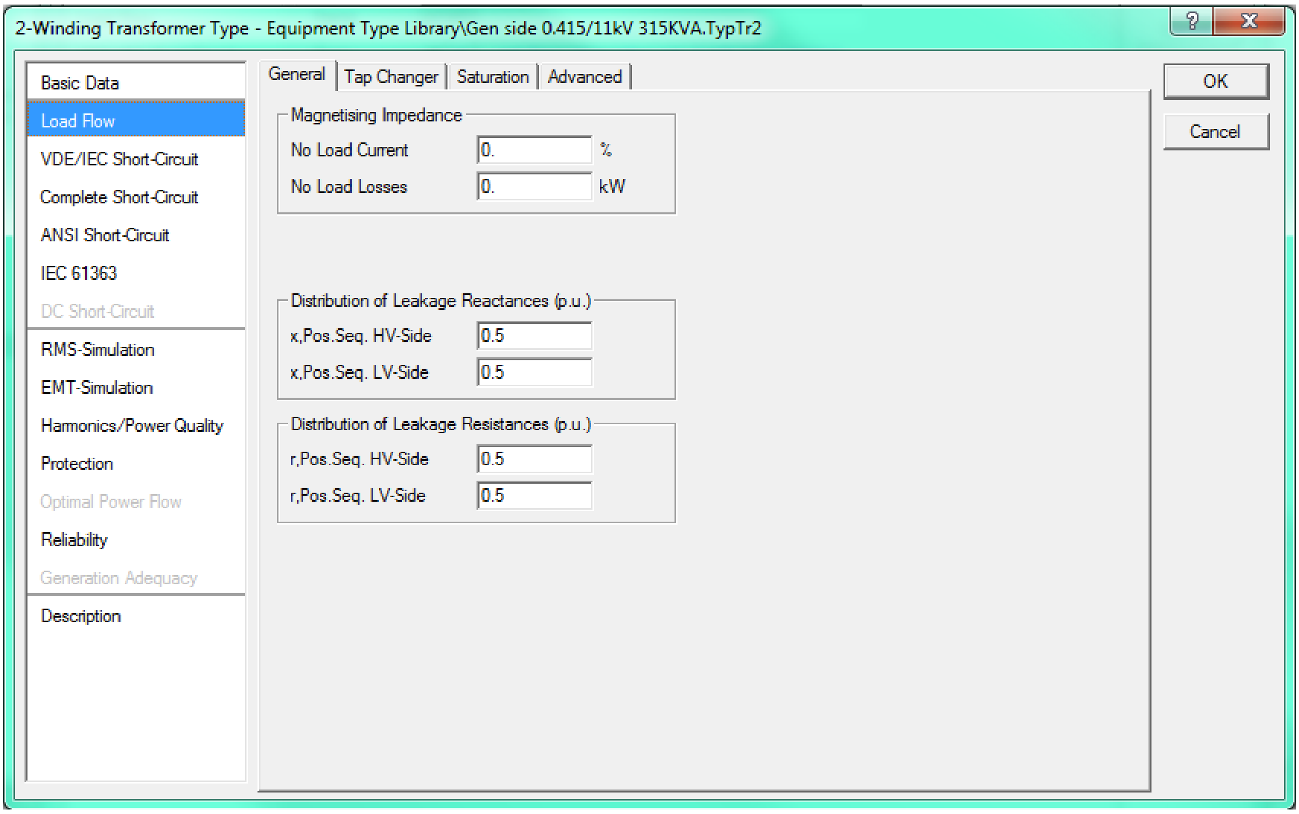

Figure 29 Transformer model Load Flow tab.

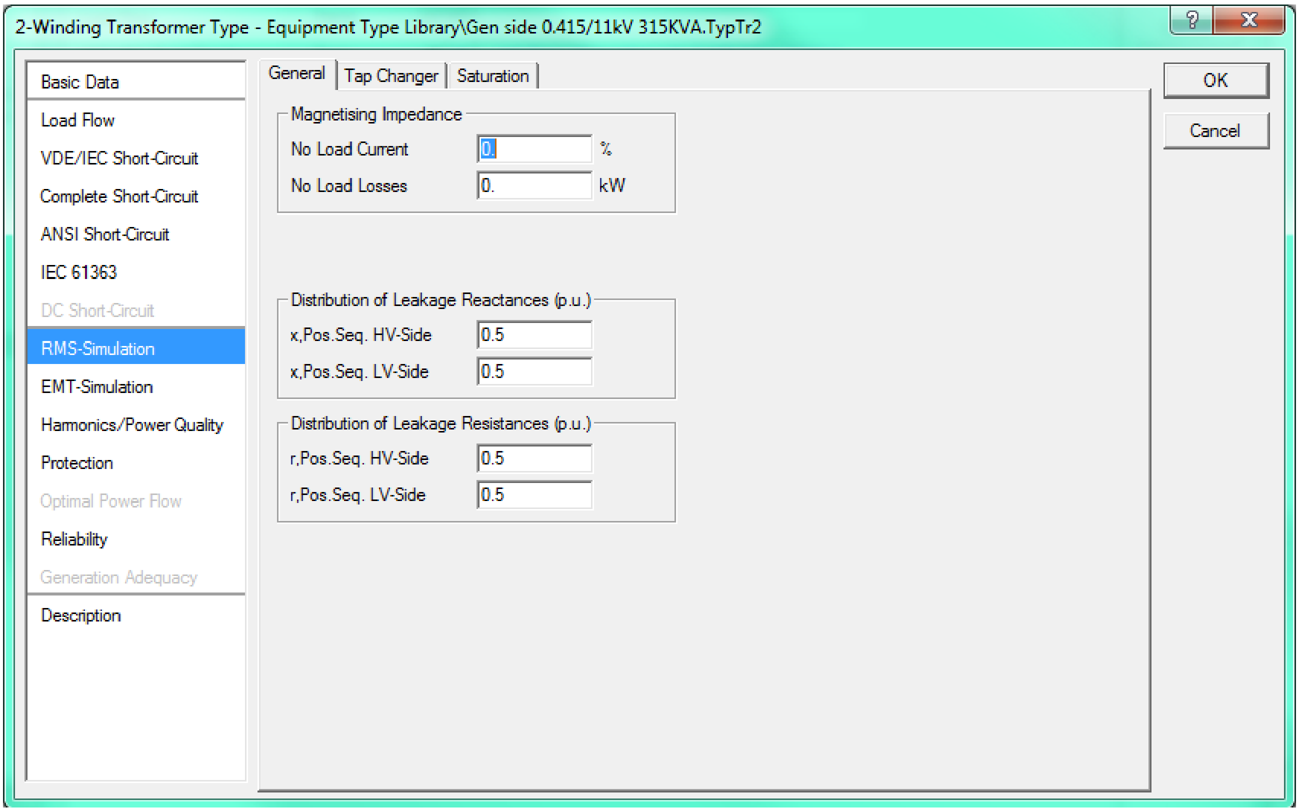

Figure 30 Transformer model RMS Simulation tab.

Line Model

The line type used is the NHKBA 3x50sm global type available in PowerFactory. This type can be found in the 15kV rated copper cable with paper insulation selection.

11.5 PV system

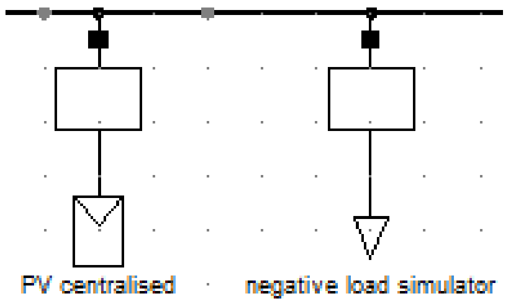

Figure 31 Static PV source and load used to model the PV system.

The PV source is held constant and the load is steadily increased in a ramp up function. The load is increased from a very small value up until the net power provided between the PV source and the load is approximately zero. When the net value is zero or very close to zero both breakers are opened effectively disconnecting both the PV source and the load. This essentially creates a solar output ramp down event that treats the PV system as a negative load. Power supplied by the PV system is different for each level of PV penetration tested. Similarly the 'negative load simulator's events also have to be adjusted to account for the varying levels of penetration.

Figure 32, Figure 33, and Figure 34 show the parameters entered into the PV array's 'Basic Data', 'Load Flow', and 'RMS Simulations' tabs. The active power parameter shown in the 'Load Flow' tab is specific to the 60% instantaneous PV penetrations simulations.

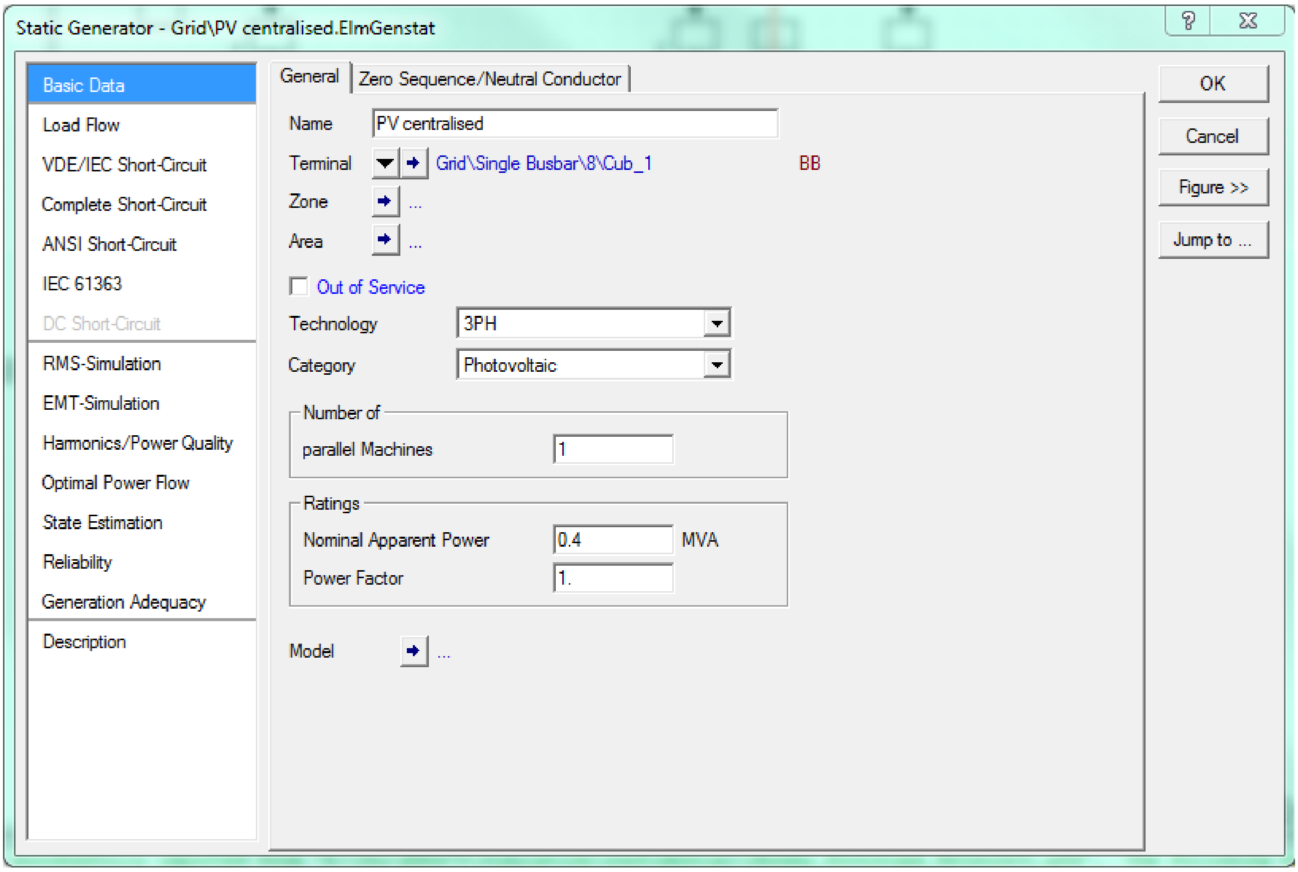

Figure 32 PV array (static generator) Basic Data tab.

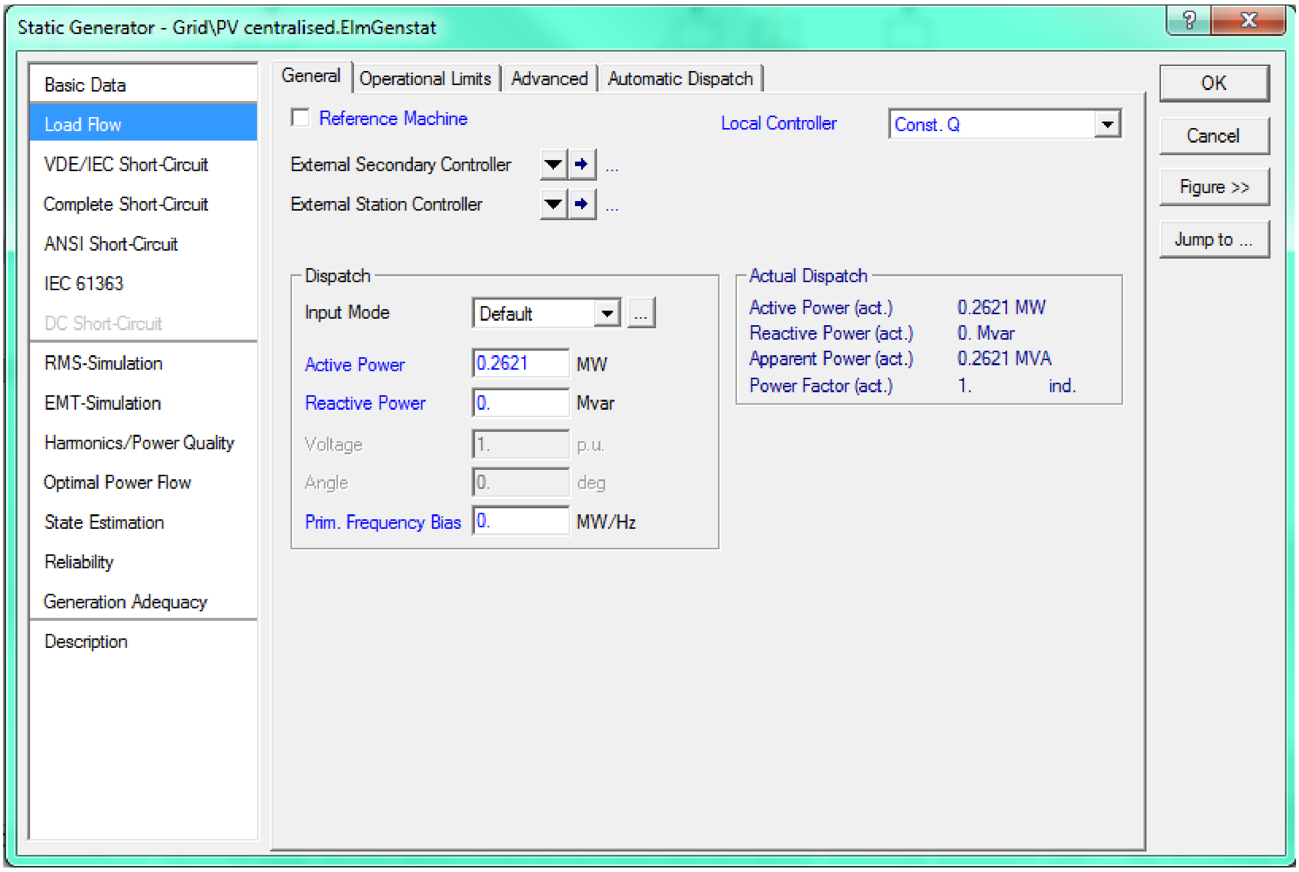

Figure 33 PV array (static generator) Load Flow tab.

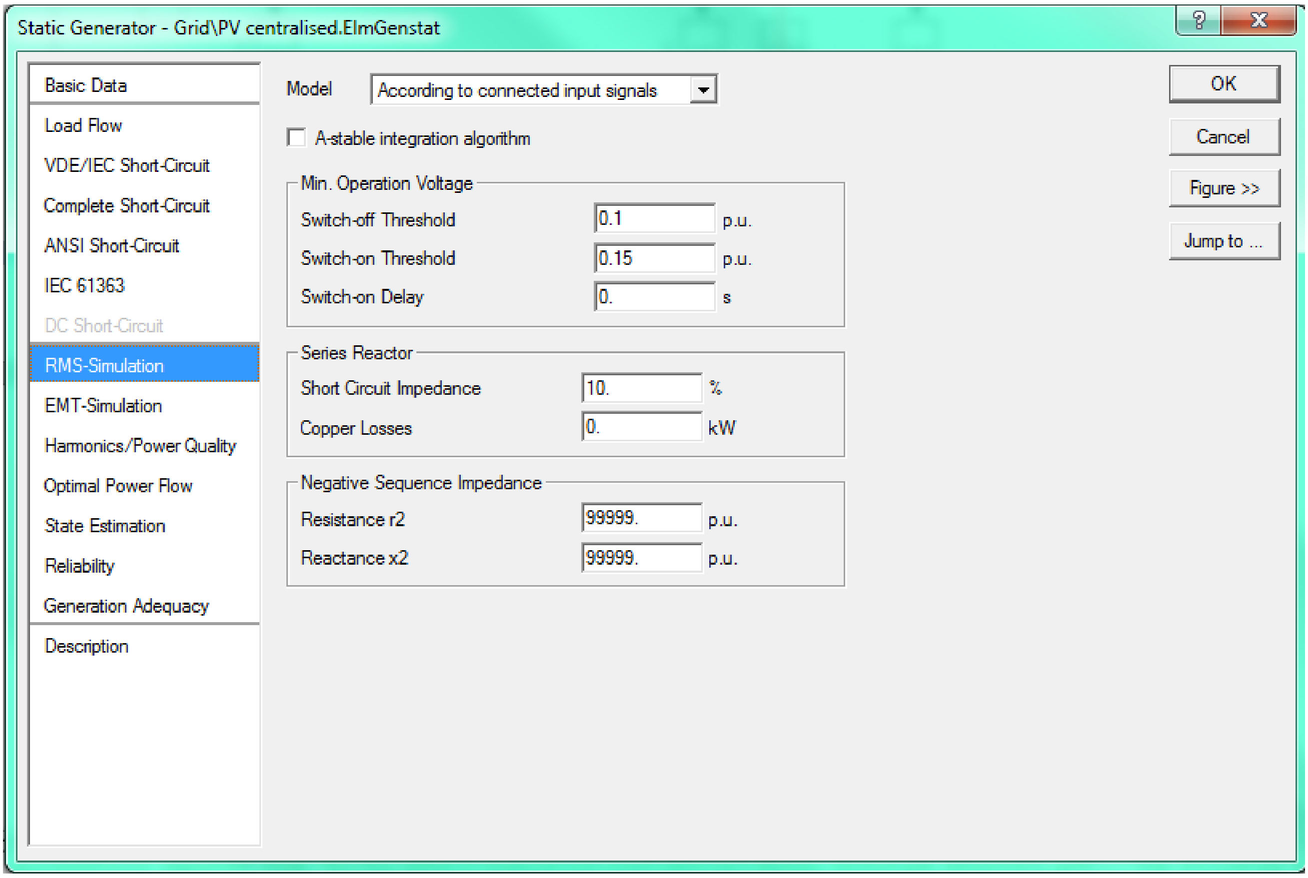

Figure 34 PV array (static generator) RMS Simulation tab.

The 'negative load simulator' load's initial parameters are shown in fFigure 35.

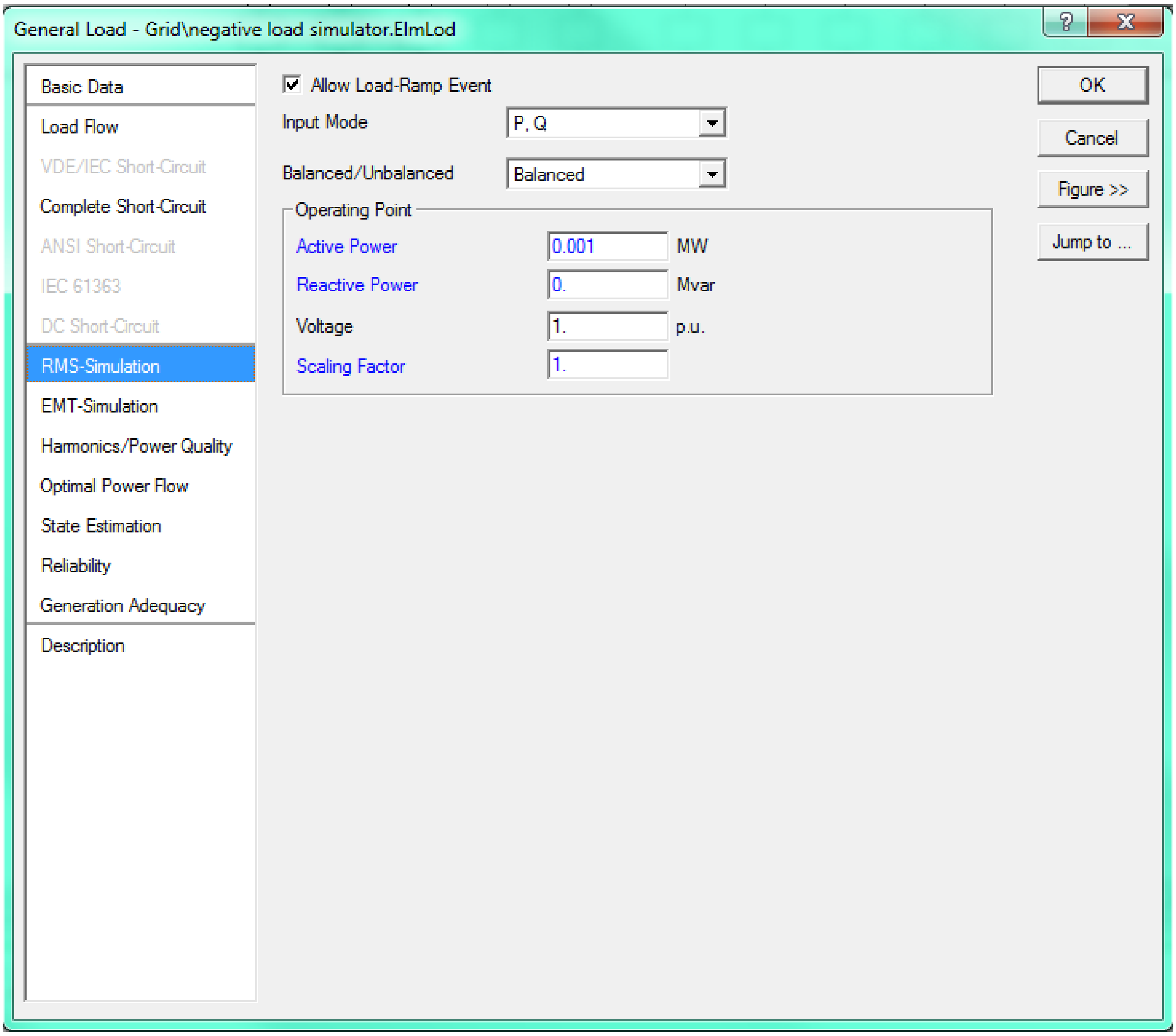

Figure 35 Negative Load (load used for simulating ramp down events).

11.6 Community Loads

Communities 1 and 2 loads' are shown in Figure 36, and Figure 37. The loads 'RMS Simulation' tabs have the same values as were entered into the 'Load Flow' tab.

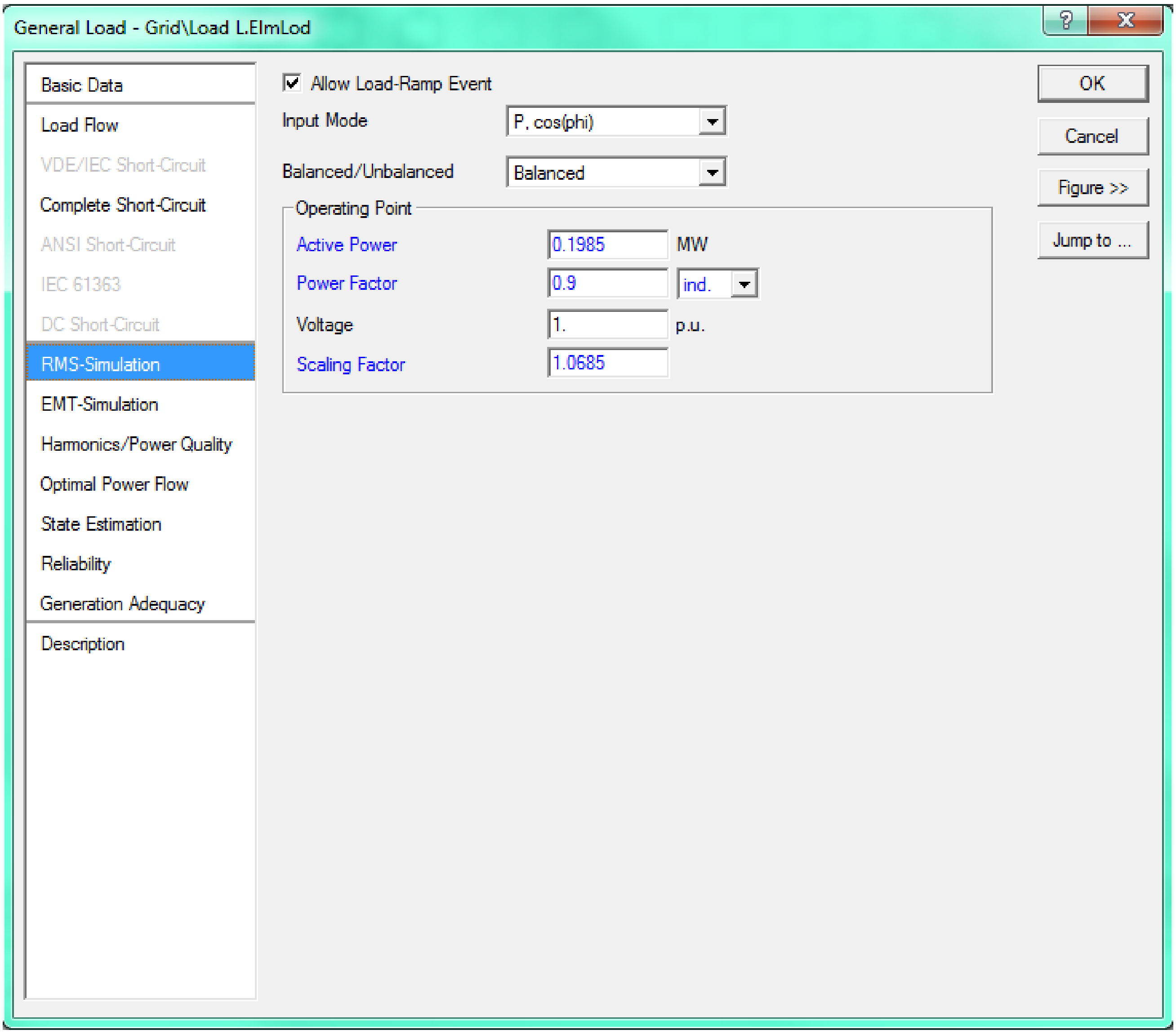

Figure 36 Community 1 load during 60% PV penetration simulation.

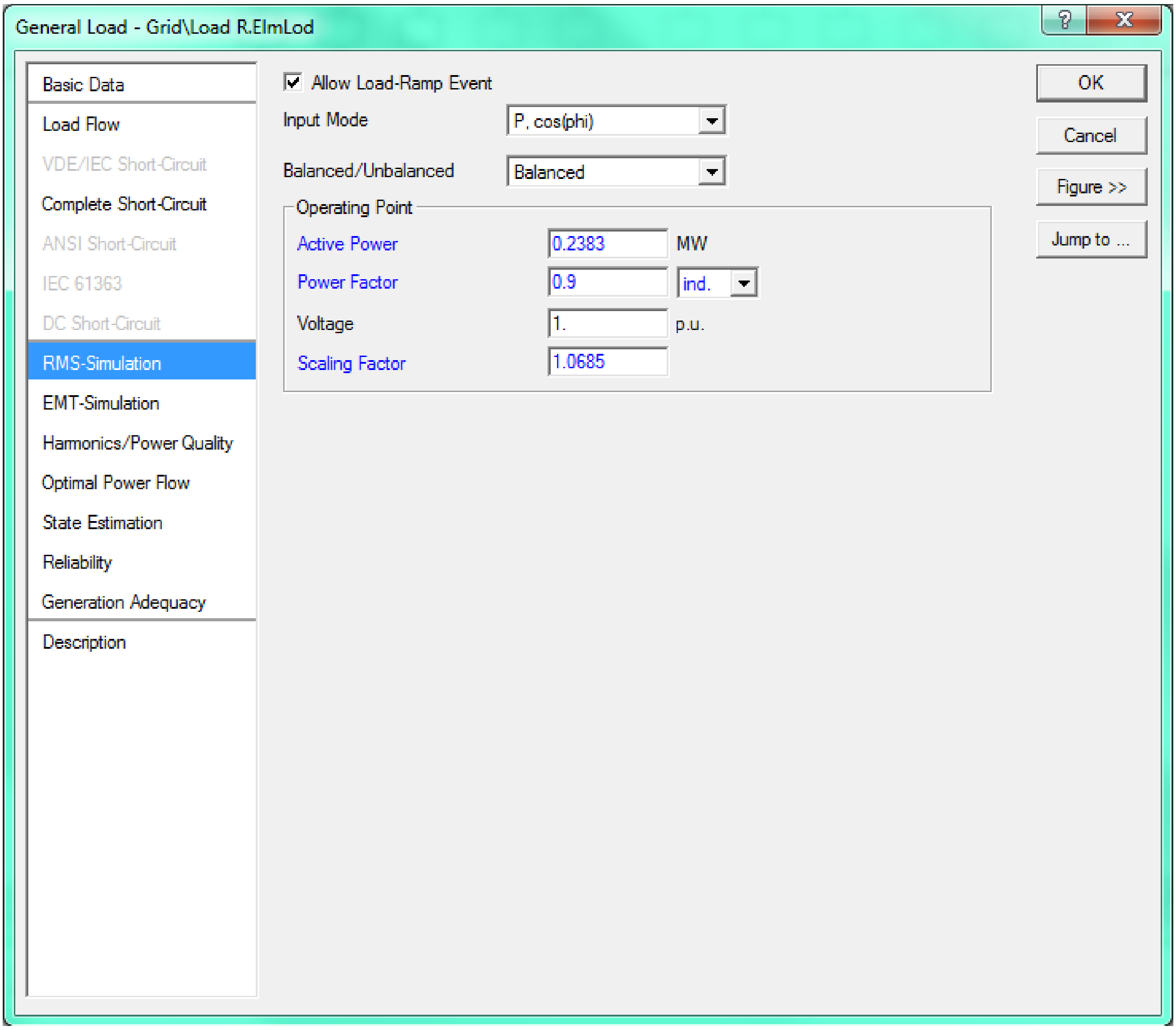

Figure 37 Community 2 load during 60% PV penetration simulation.

11.7 Switchable Shunt Capacitor Banks

Figure 38, Figure 39, and Figure 40 show the parameters for the automatically switching capacitor banks used to improve the power quality.

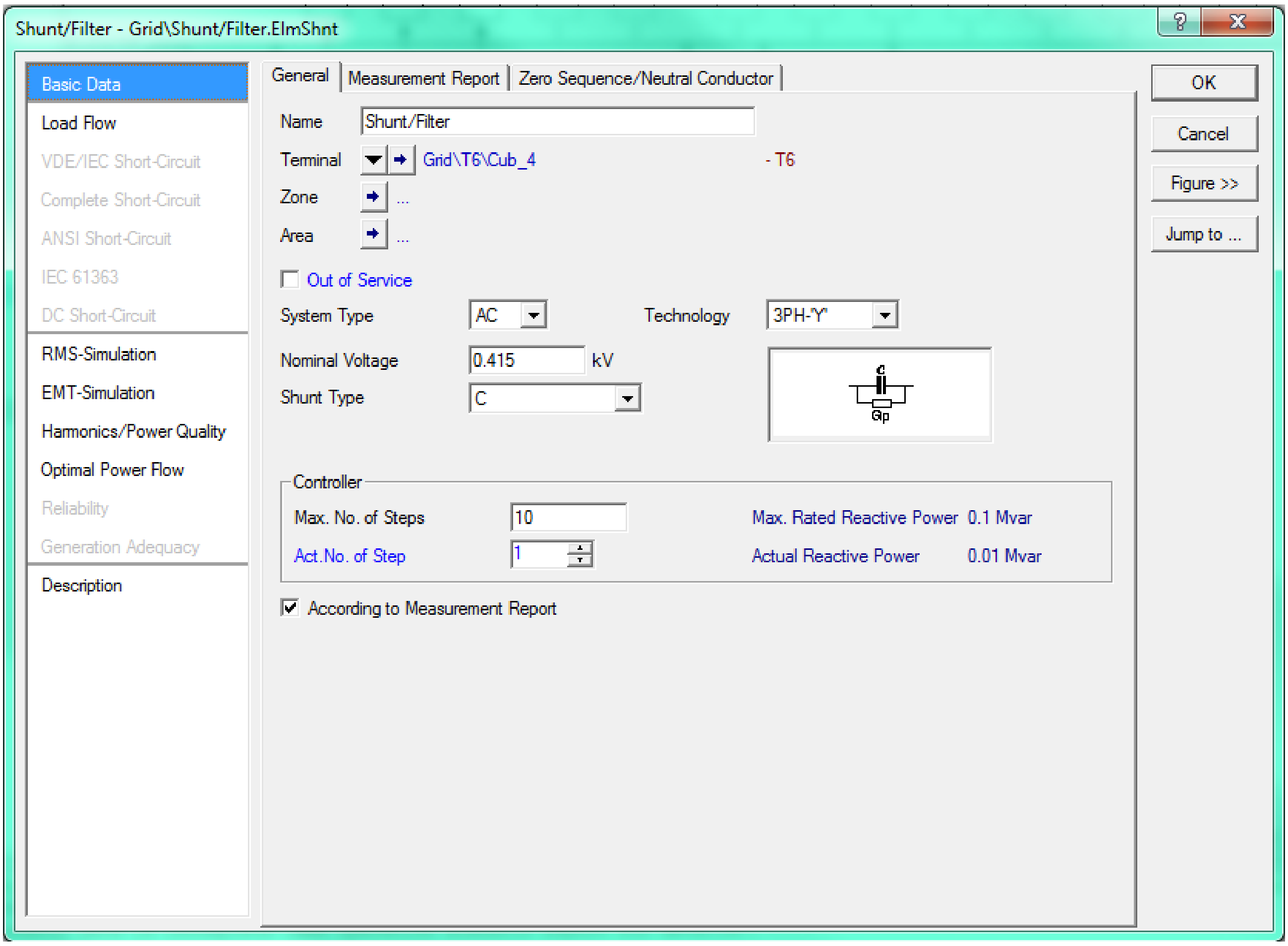

Figure 38 Shunt capacitor bank Basic Data tab.

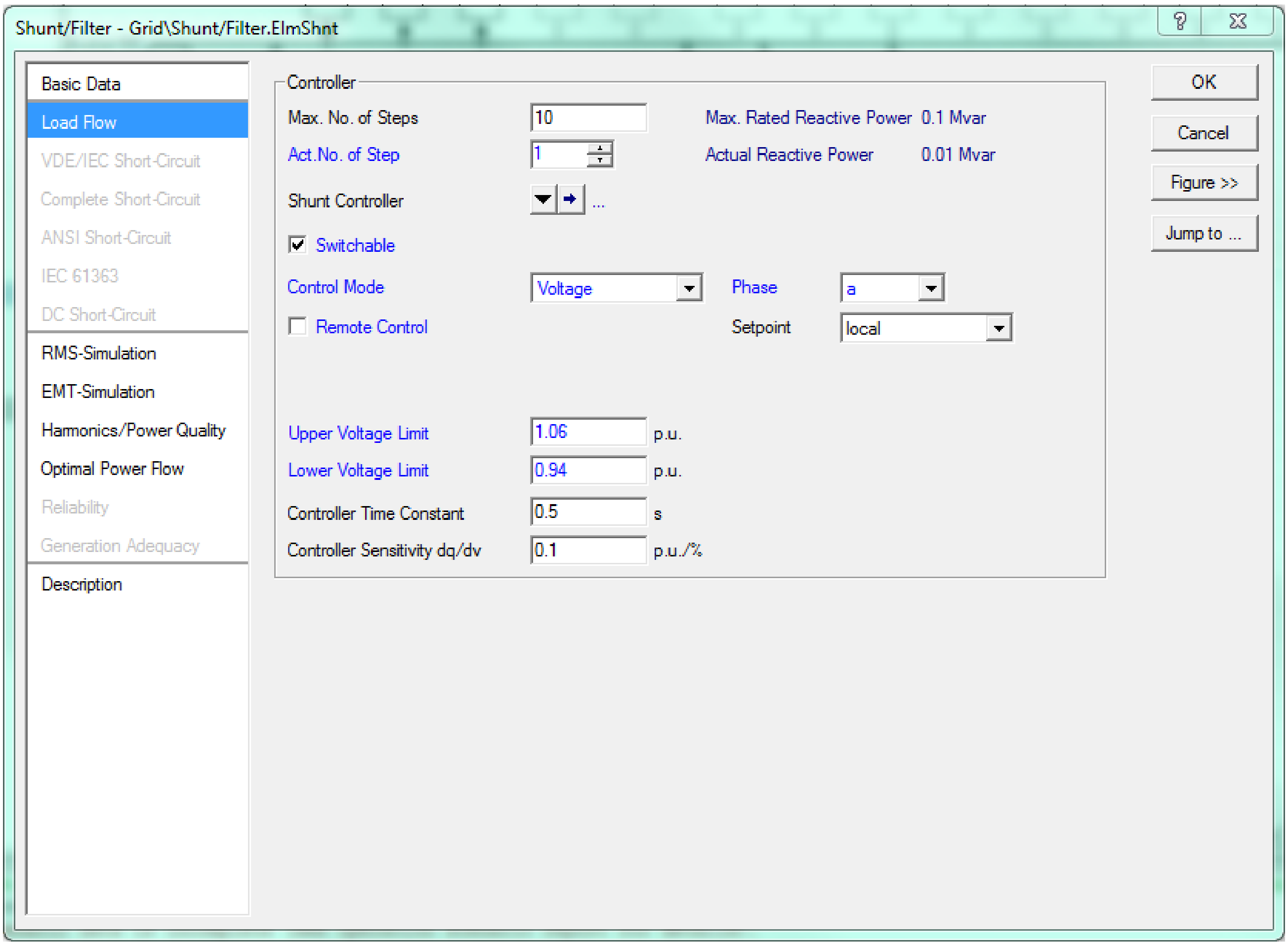

Figure 39 Shunt capacitor bank Load Flow tab

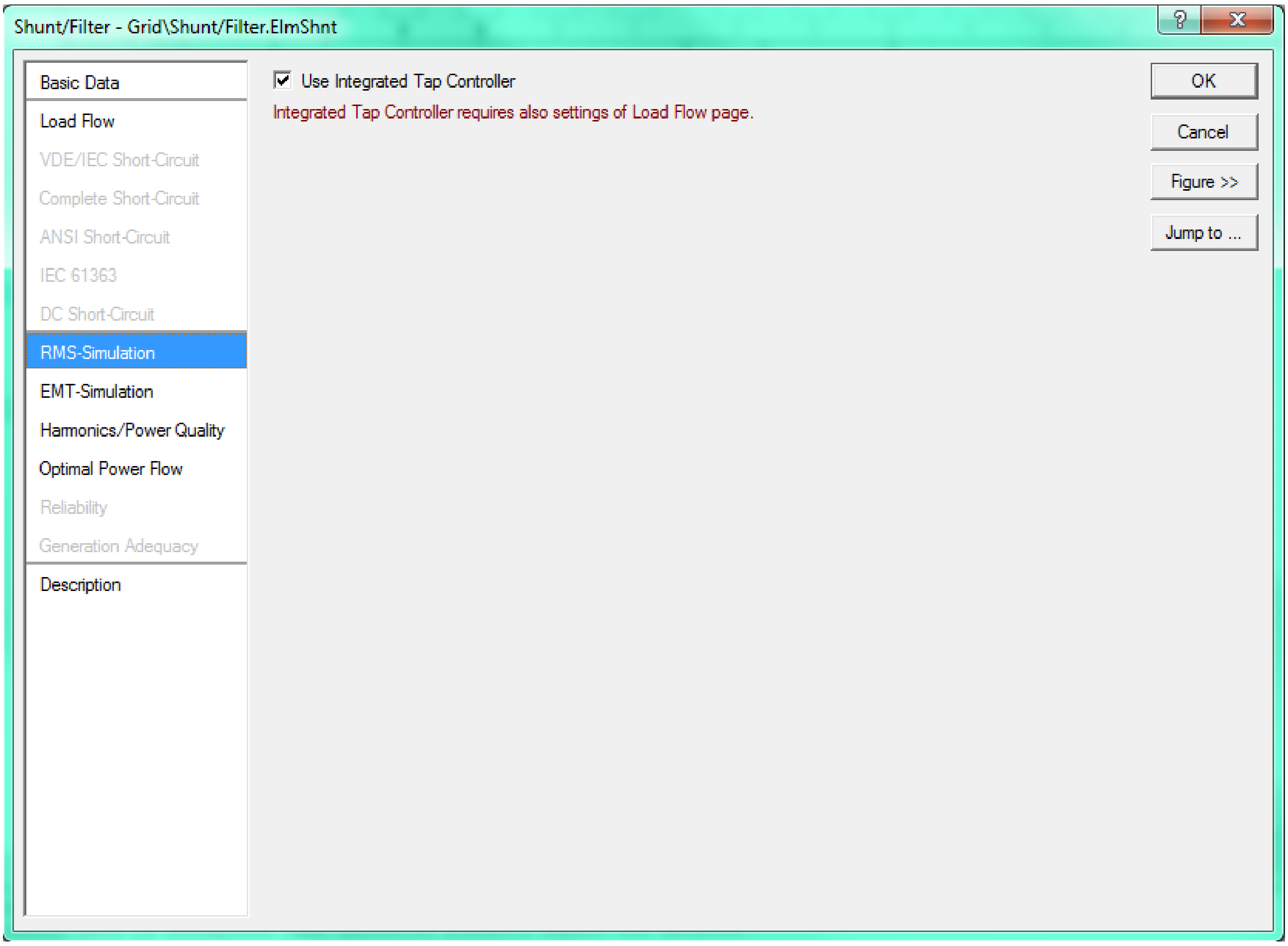

Figure 40 Shunt capacitor bank RMS Simulation tab.

11.8 Events

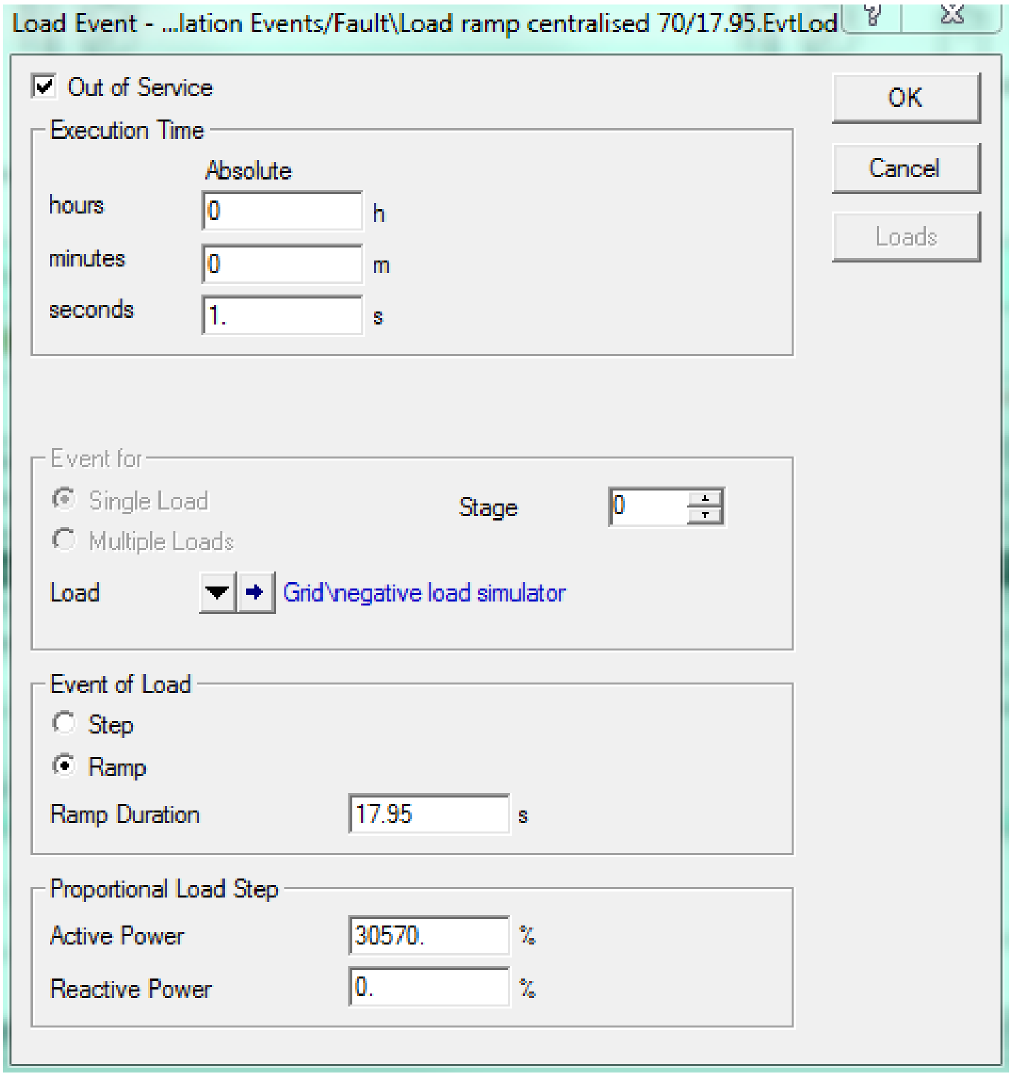

Figure 41 70% penetration load ramp event.

The load ramp event was used to increase the load shown in section 11.3 of these appendices. In this simulation the event occurs at 1 second of the RMS simulation runtime and continues to ramp up at the active power at 30570% for the following 17.95 seconds. The reason the percentage increase is so big is because the load initially starts at a very small vale so as not to interfere with the initial steady state running of the simulation's load flow analysis. In this case the load should ramp up to approximately 305.7kW effectively balancing out the PV supply for this particular simulation.

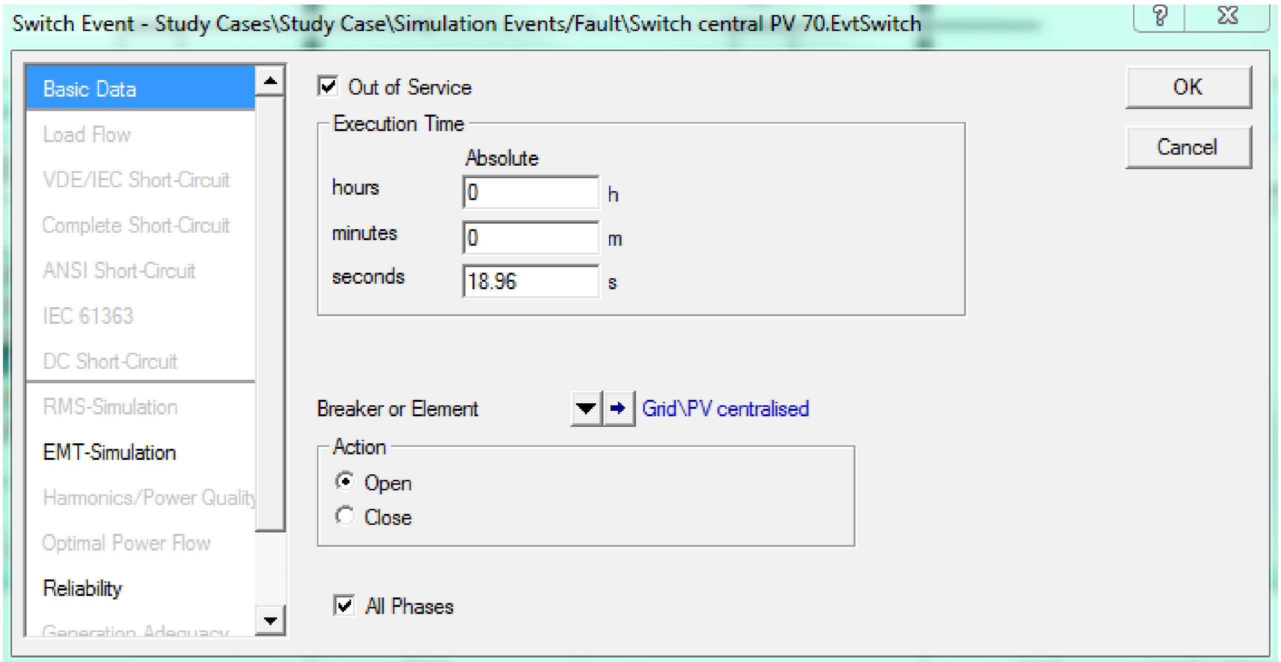

Figure 42 70% penetration static PV system switch event.

After the load ramping up is finished the both the load and the static PV system are simultaneously disconnected using switch events such as can be seen in Figure 42.

11.9 Centralised PV Penetration

All simulations in this report have modelled the PV as being a centralised system connected up to the generation busbar opposed to distributed generation.

11.9.1 60% penetration ramp response

The following images are taken from the 60 per cent instantaneous PV penetration simulations. In this simulation the solar output is ramped down from 262.1kW to zero over the course of 15.4 seconds. This corresponds to a power decrease of approximately 17.0kW/s.

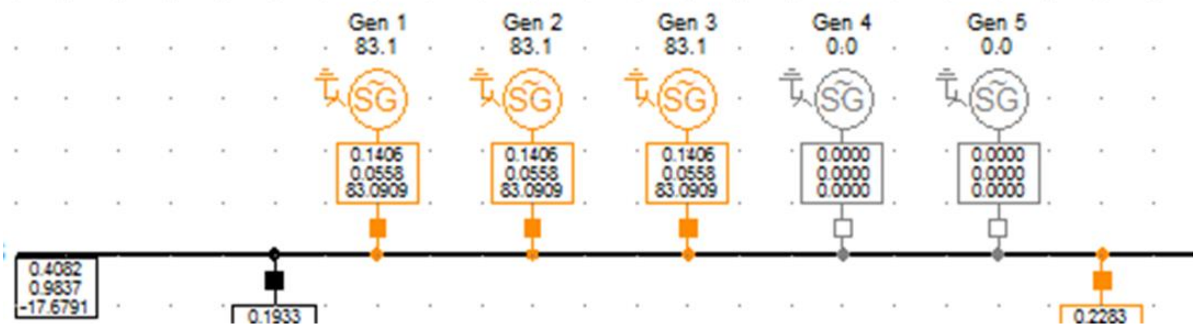

Figure 43 Generation busbar 60% penetration; ramp down.

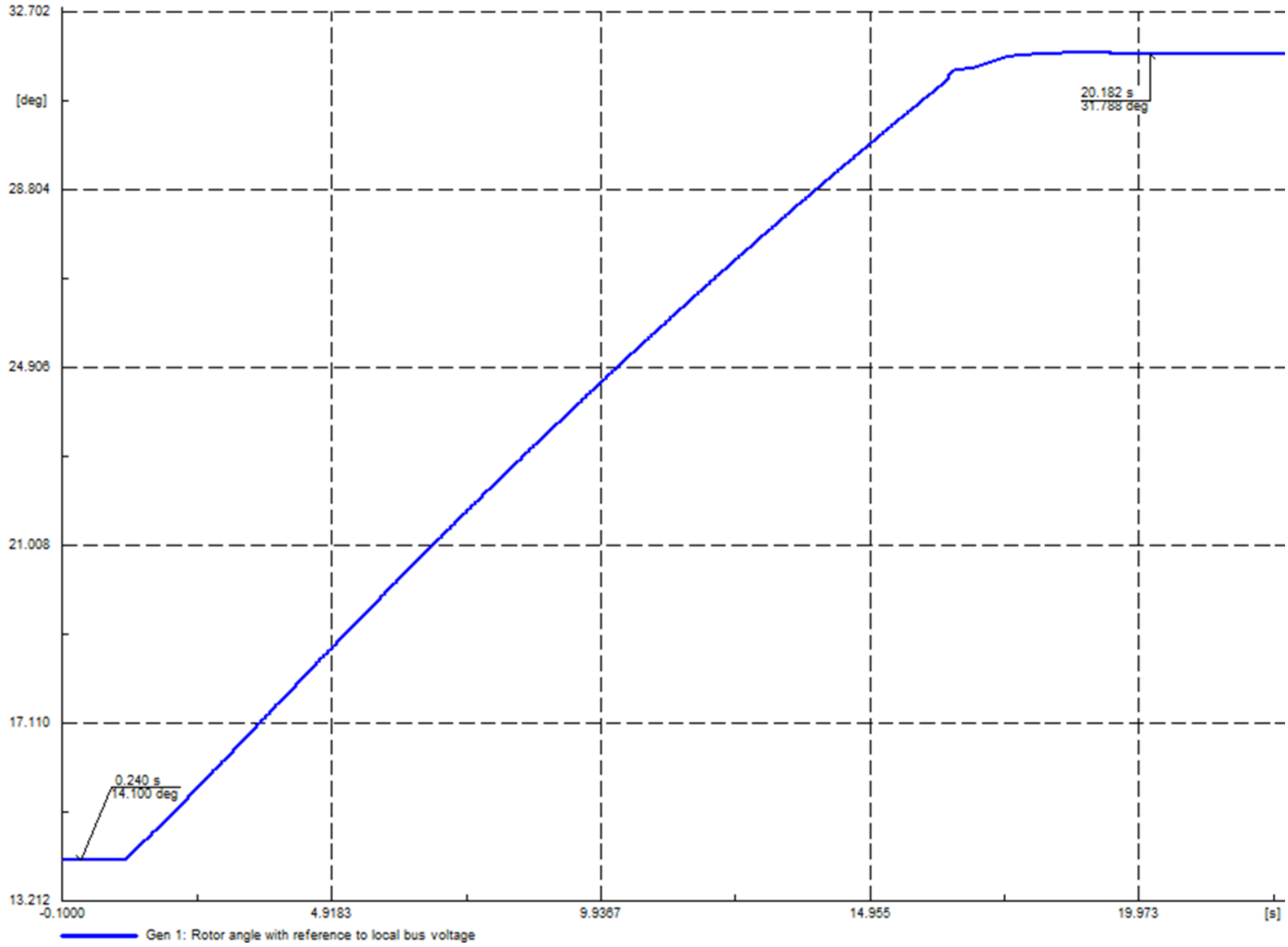

Figure 44 Rotor angle 60% penetration; ramp down response.

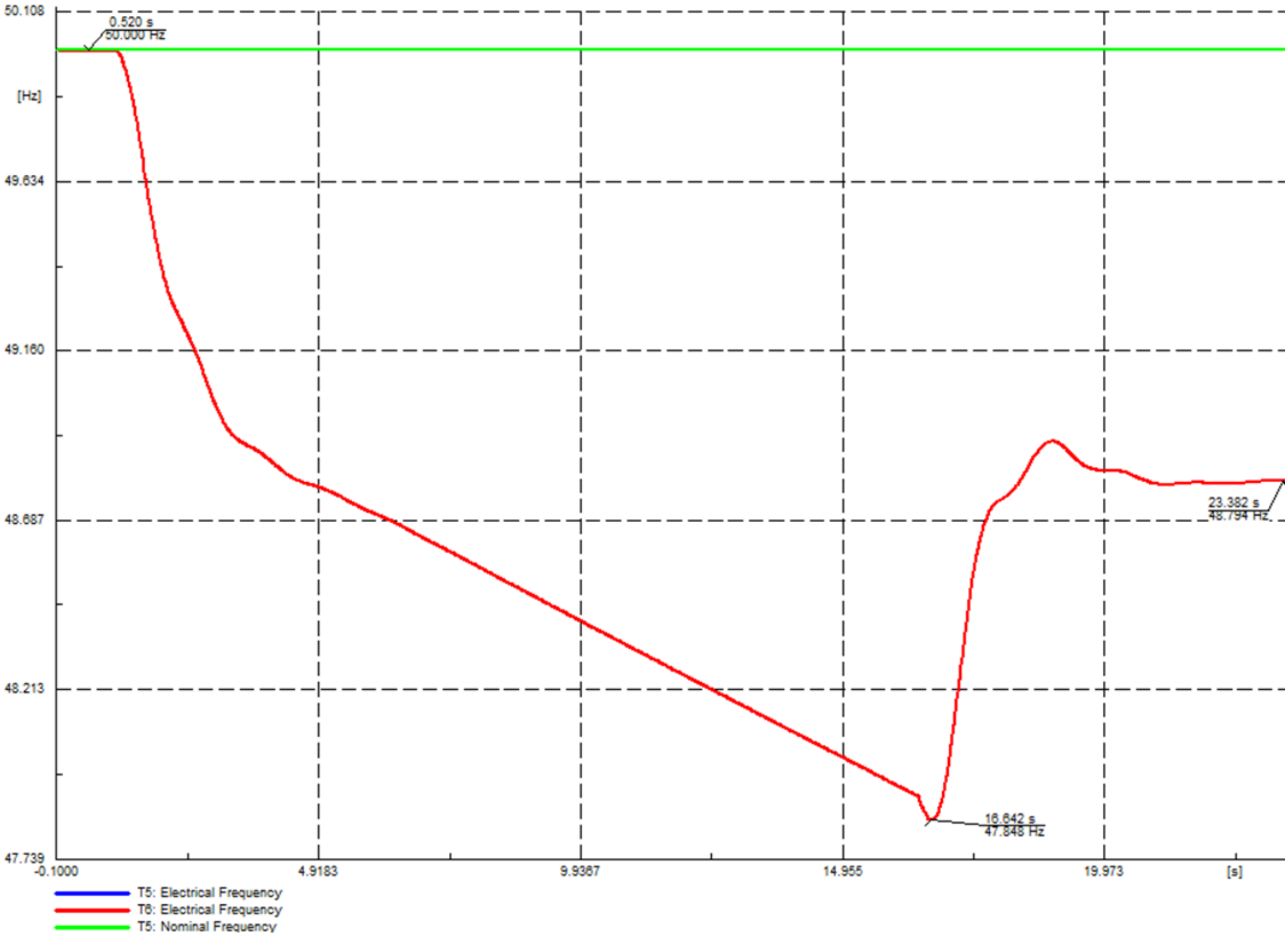

Figure 45 Load terminals frequency 60%penetration; ramp down response.

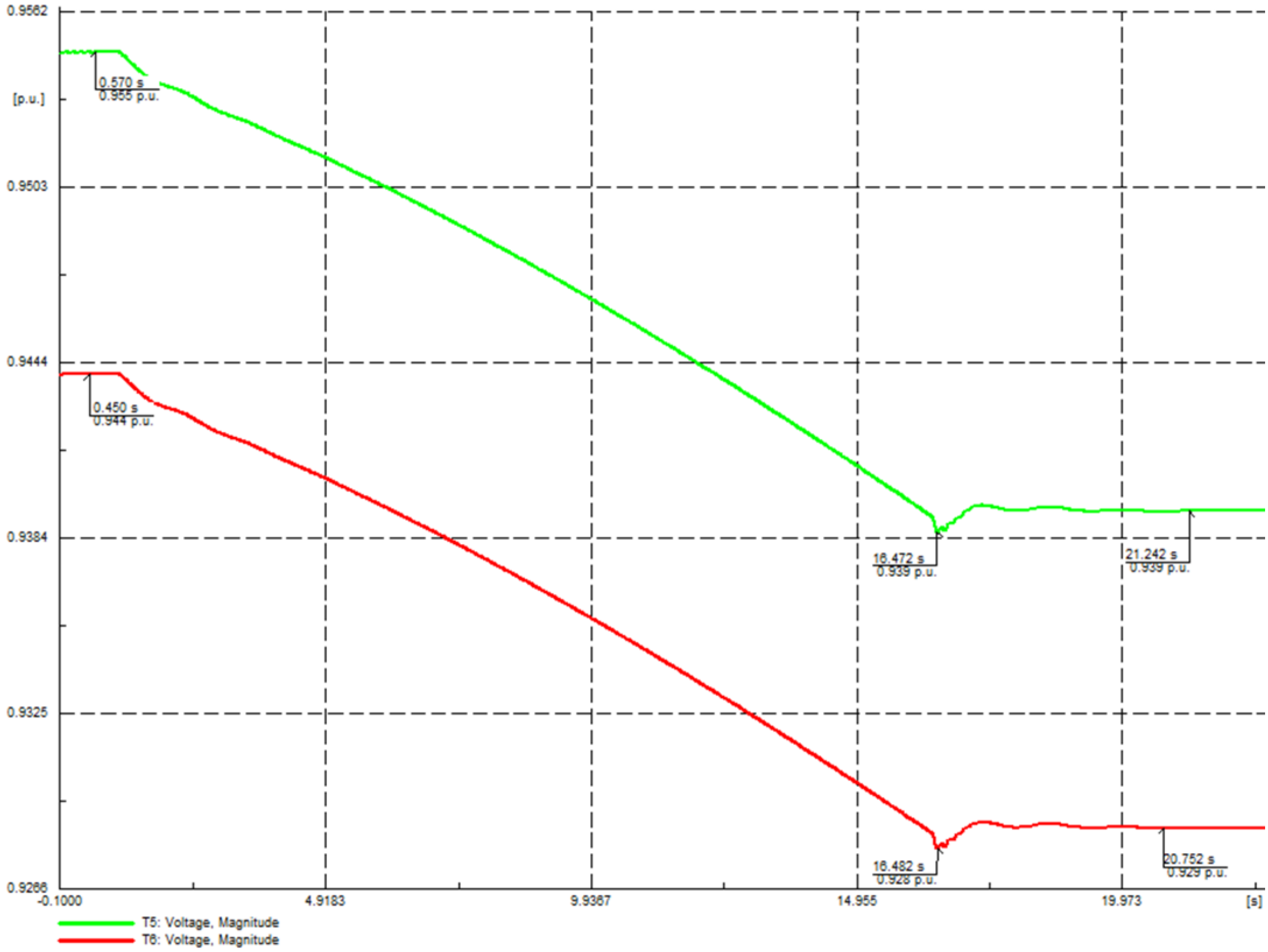

Figure 46 Load terminal voltage 60% penetration; ramp down response.

11.9.2 60% penetration ramp response with additional c-shunt banks

The 60 per cent instantaneous penetration simulation was simulated again but this time with the addition of switching shunt capacitor banks on the load terminals. The following figures show the plots produced from this simulation.

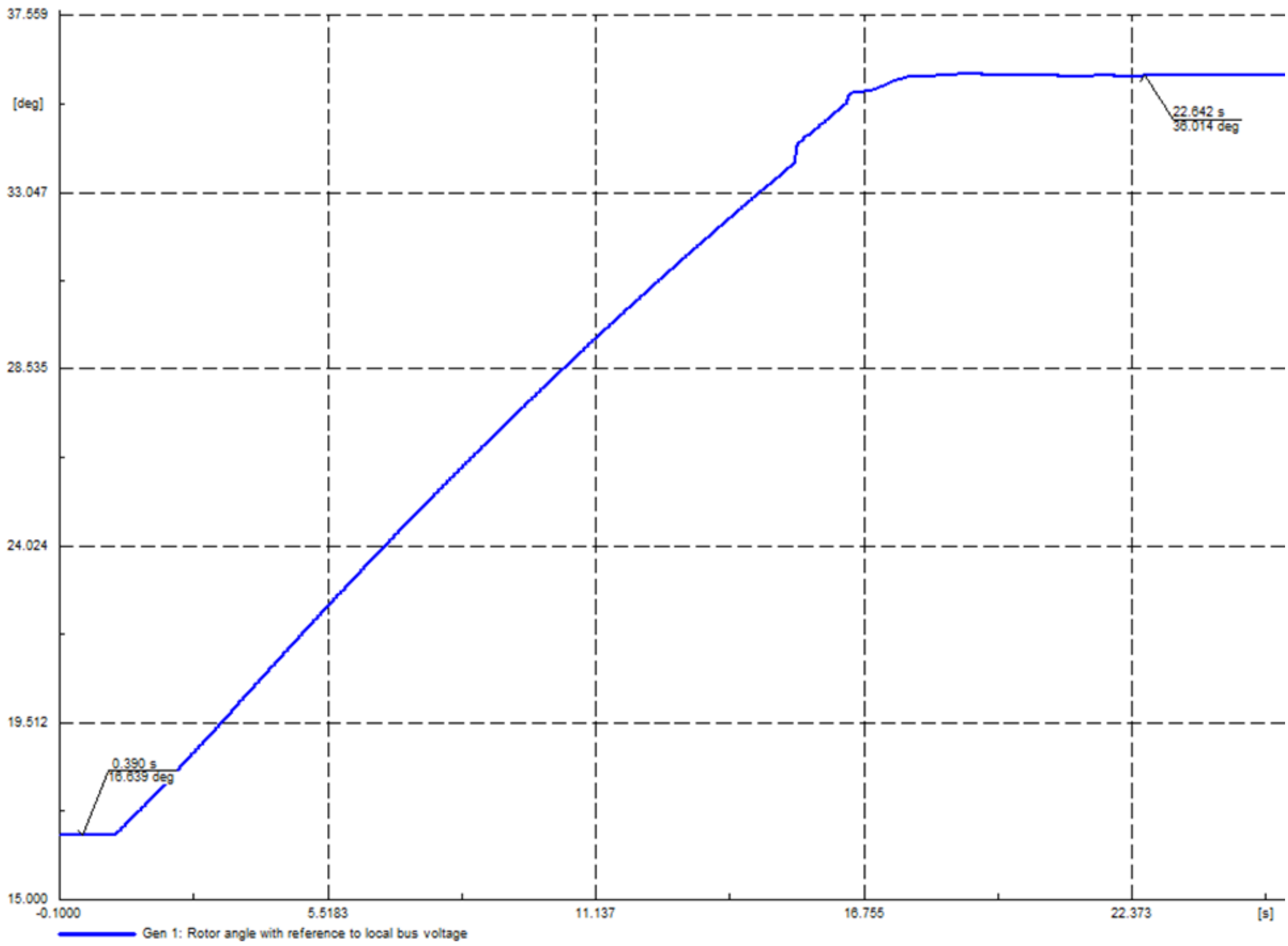

Figure 47 Rotor angle 60% penetration; ramp down response with shunt capacitor banks.

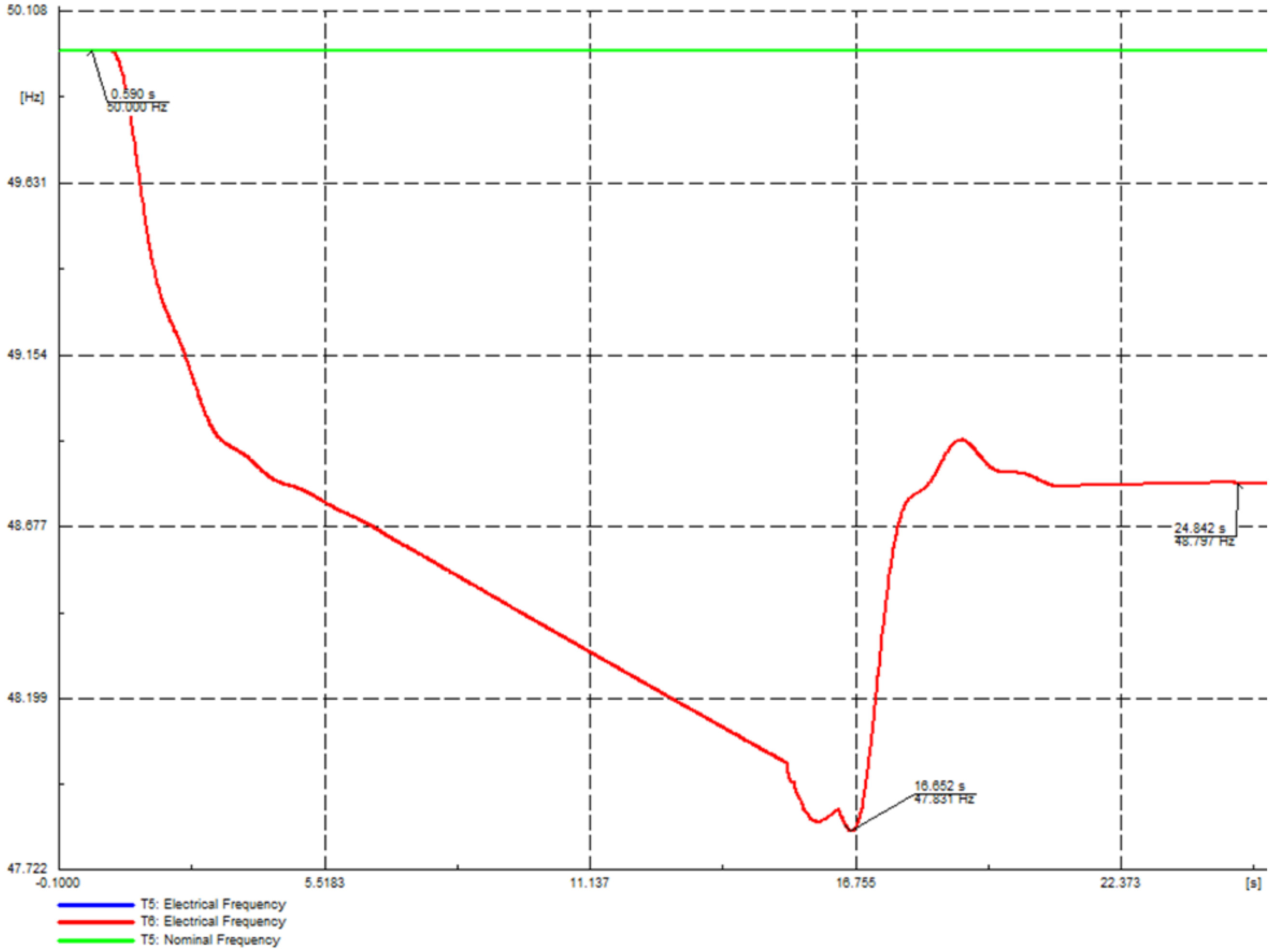

Figure 48 Load terminals frequency 60% penetration; ramp down response with shunt capacitor banks.

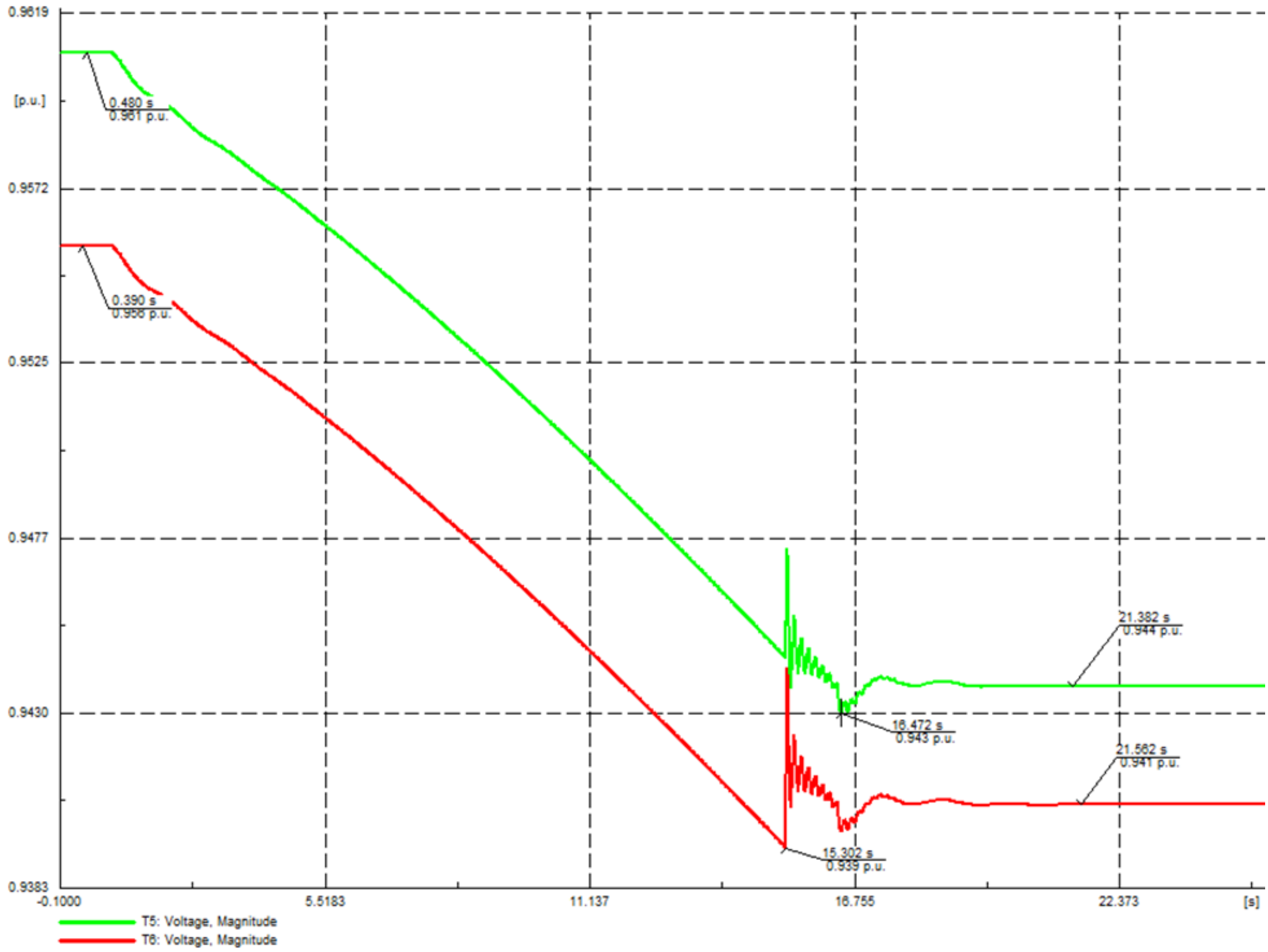

Figure 49 Load terminal voltage 60% penetration; ramp down response with shunt capacitor banks.

In Figure 49 above the switching action of the capacitor banks can be seen improving the load voltage quality.

11.9.3 60% penetration ramp response with a raised nominal voltage

In the following simulations it is worth noting that it was found raising the nominal voltage above 1.015 per a unit was not beneficial as it could cause the system to become overloaded. A moderate raise of 1.5% above the nominal voltage of the generation busbar did however maintain the load voltage above its allowable limit.

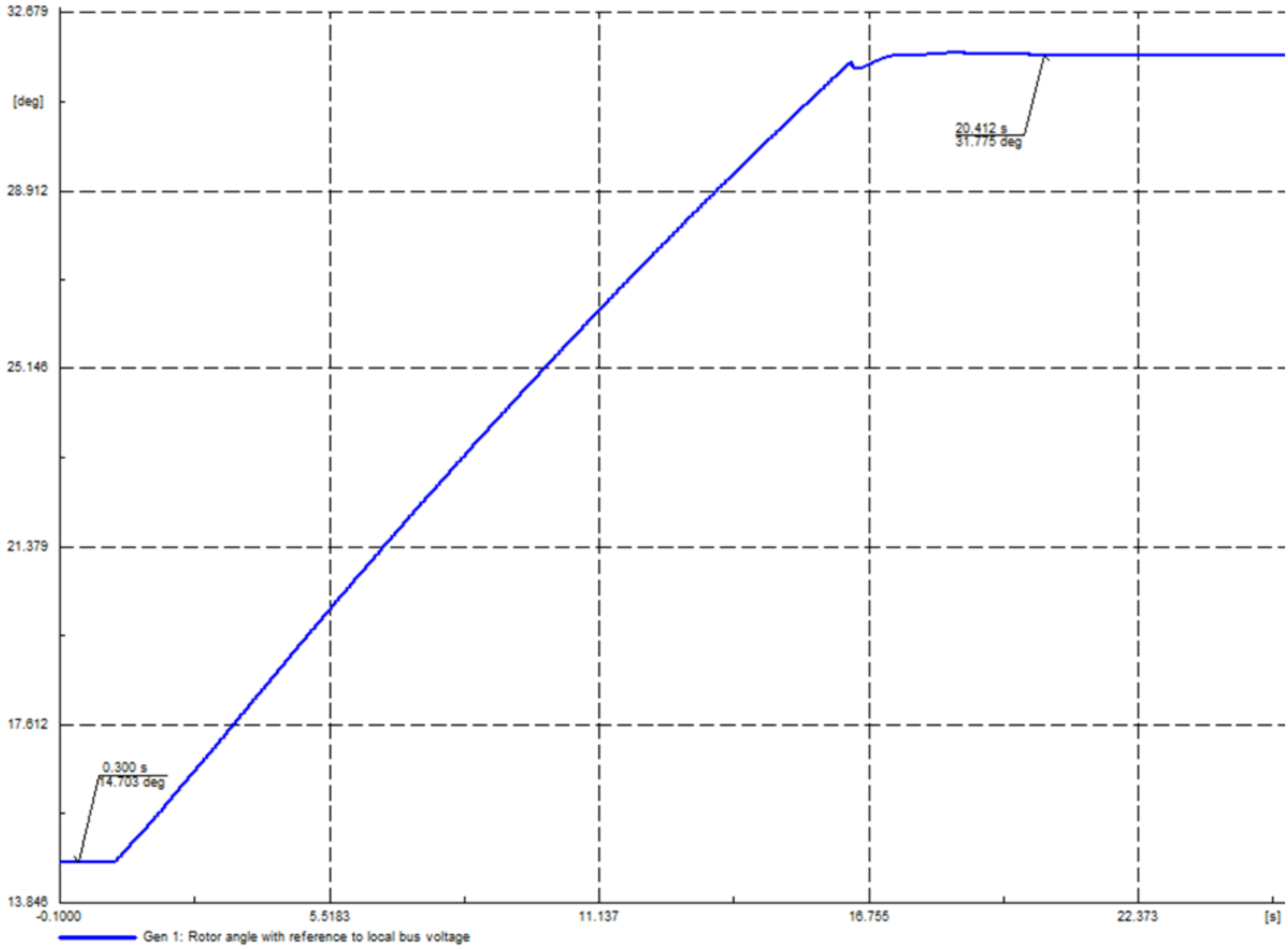

Figure 50 Rotor angle 60% penetration; ramp down response with raised nominal voltage.

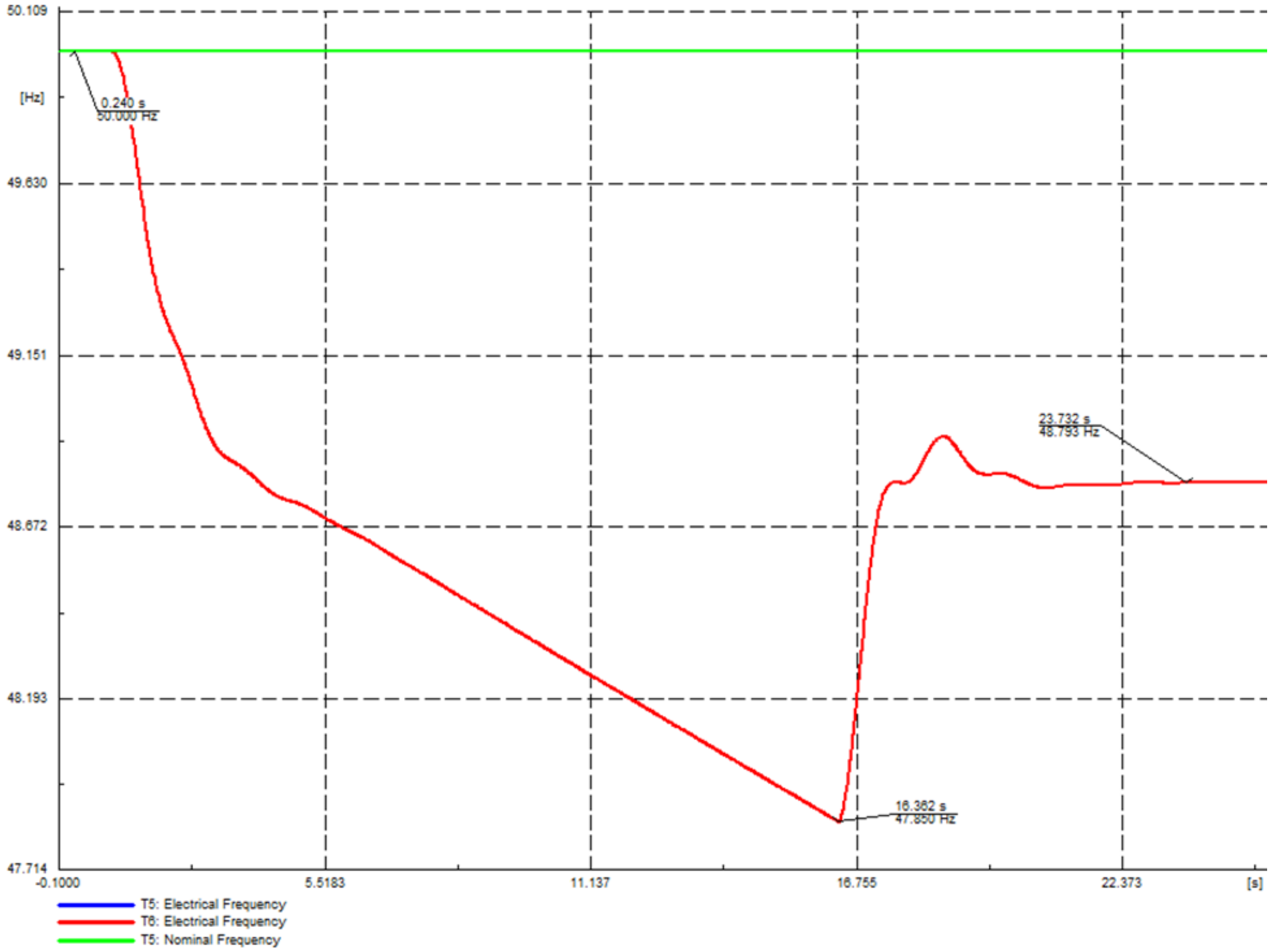

Figure 51 Load terminals frequency 60% penetration; ramp down response with raised nominal voltage.

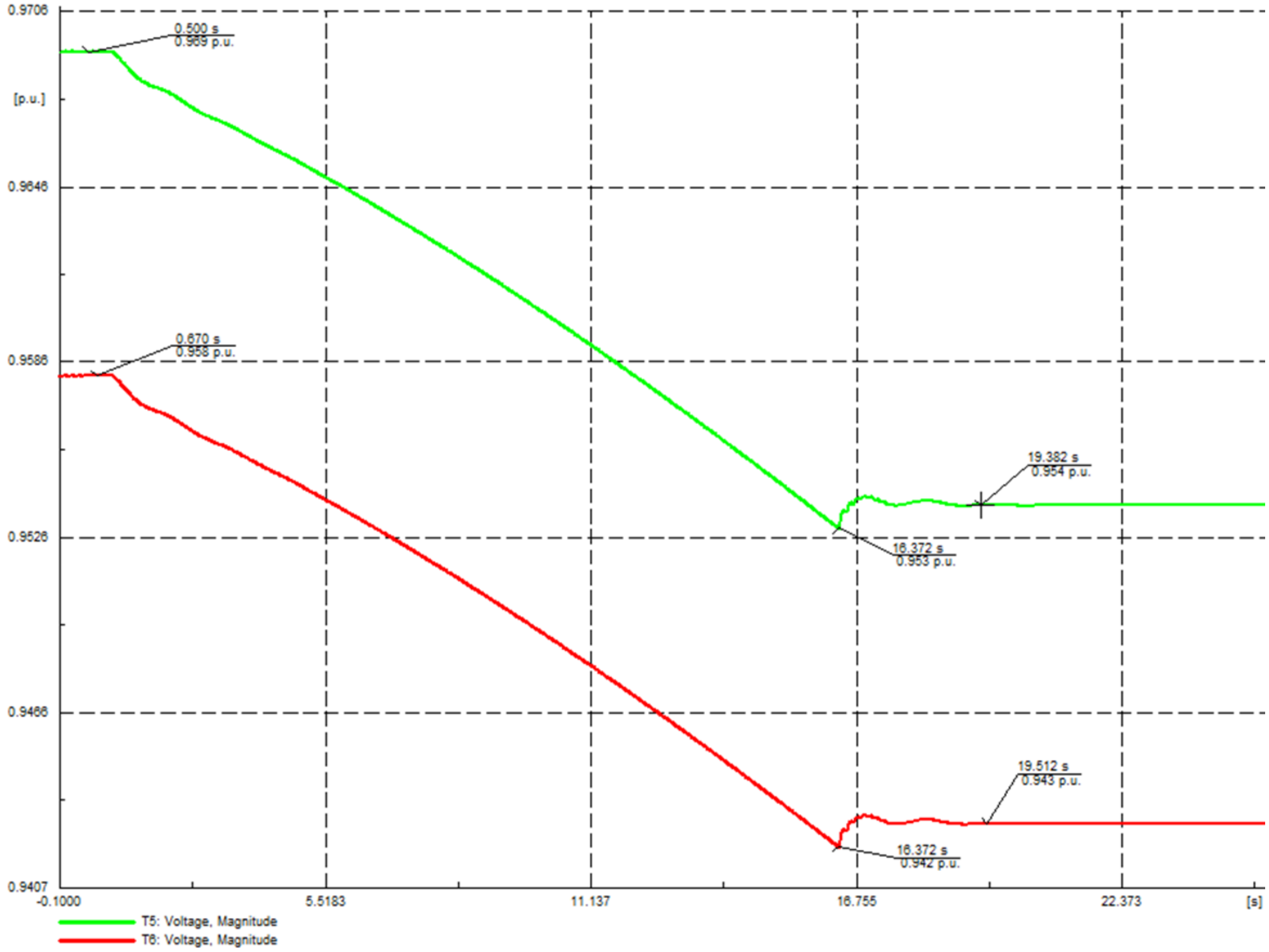

Figure 52 Load terminal voltage 60% penetration ramp down response with raised nominal voltage.

11.9.4 68.4% penetration ramp response

Due to specifying that the maximum system load only ever be 95% of the generators capacity this ended up being 68.4% penetration rather than 70%.

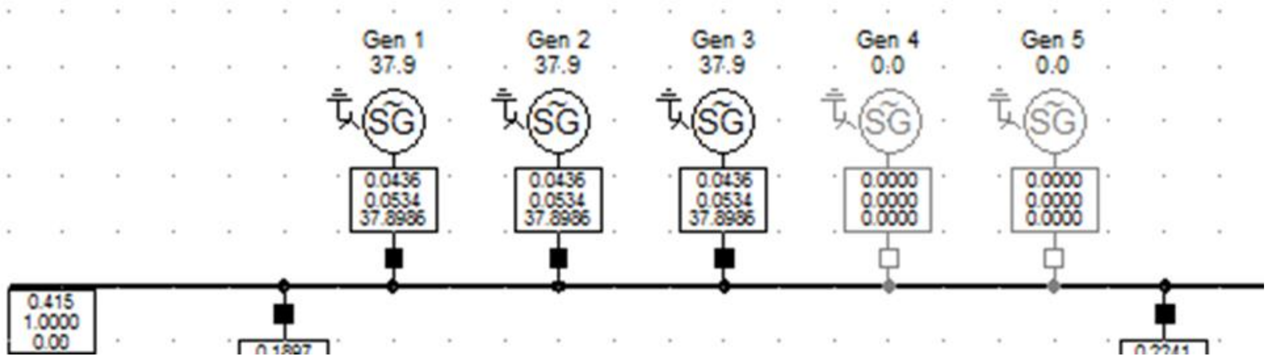

Figure 53 Generation load factor prior to the ramp down event.

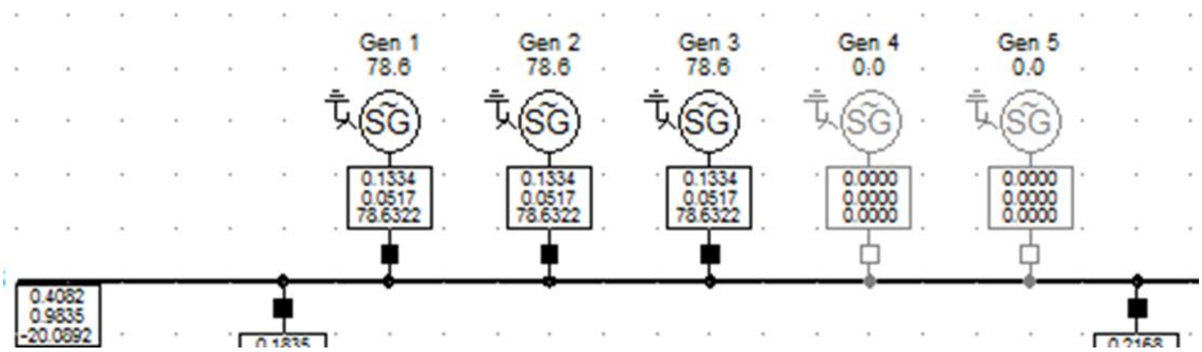

Figure 54 Generation load factor new steady state.

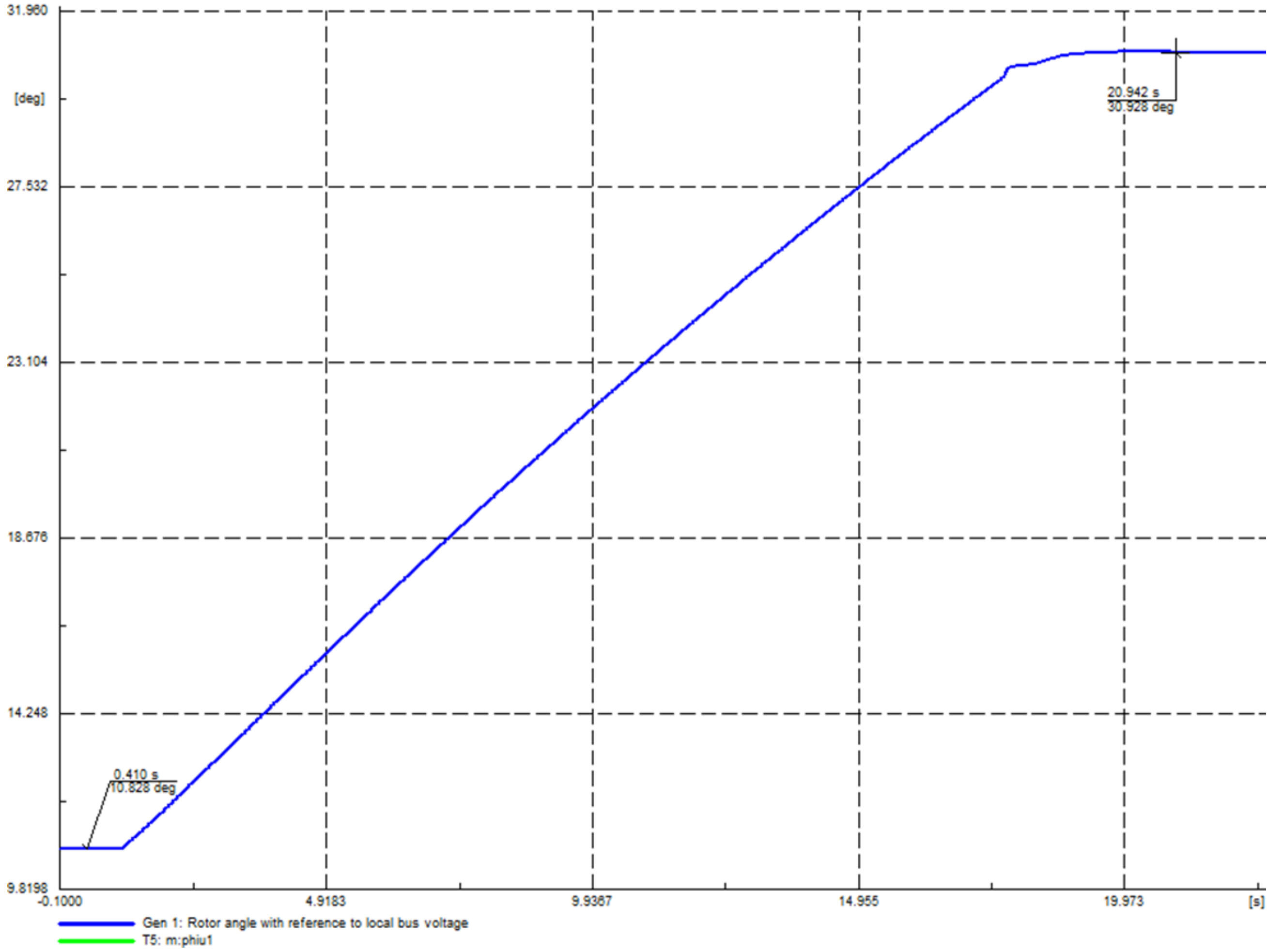

Figure 55 Rotor angle 68.4% penetration; ramp rate response.

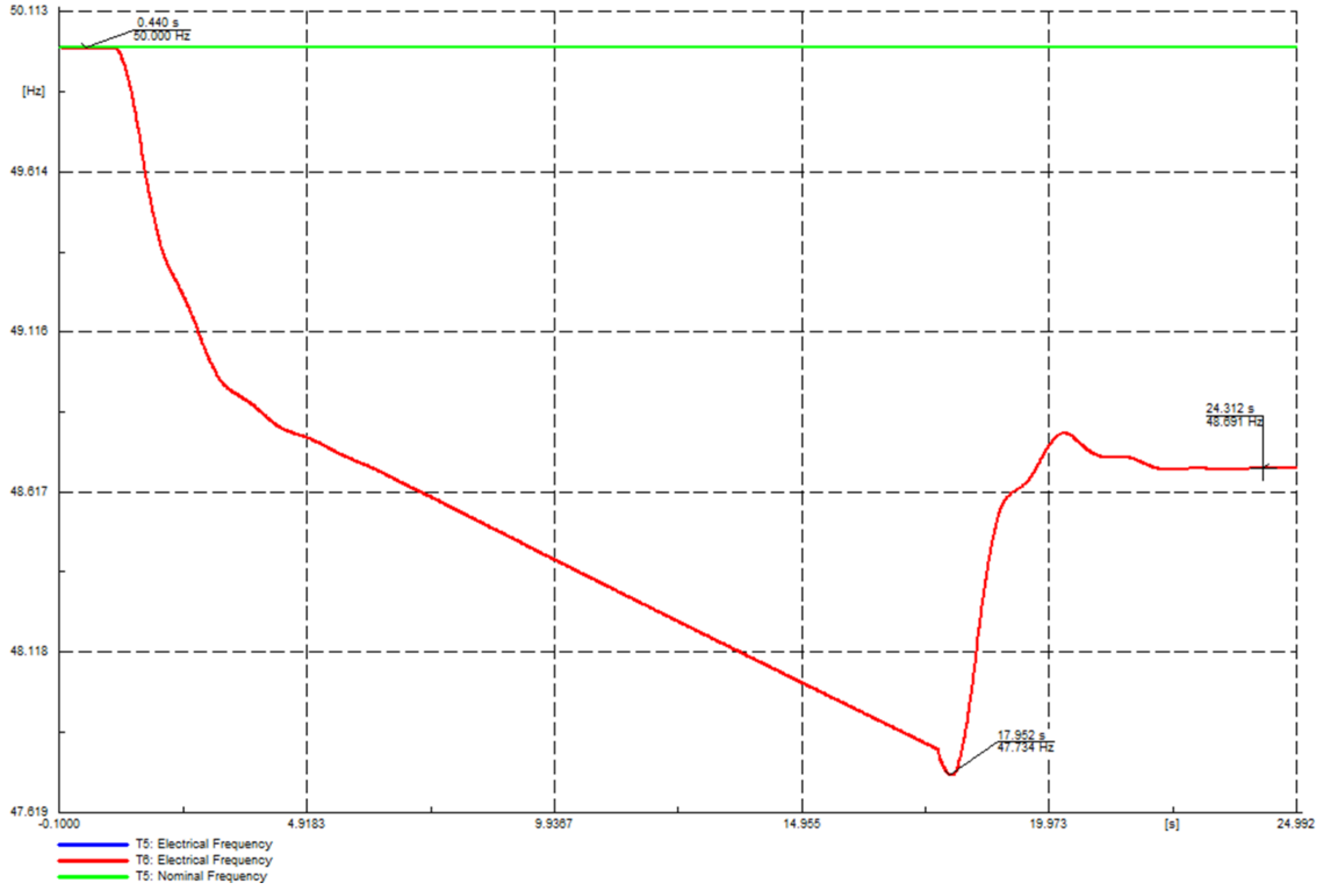

Figure 56 Load terminals frequency 68.4%penetration; ramp down response.

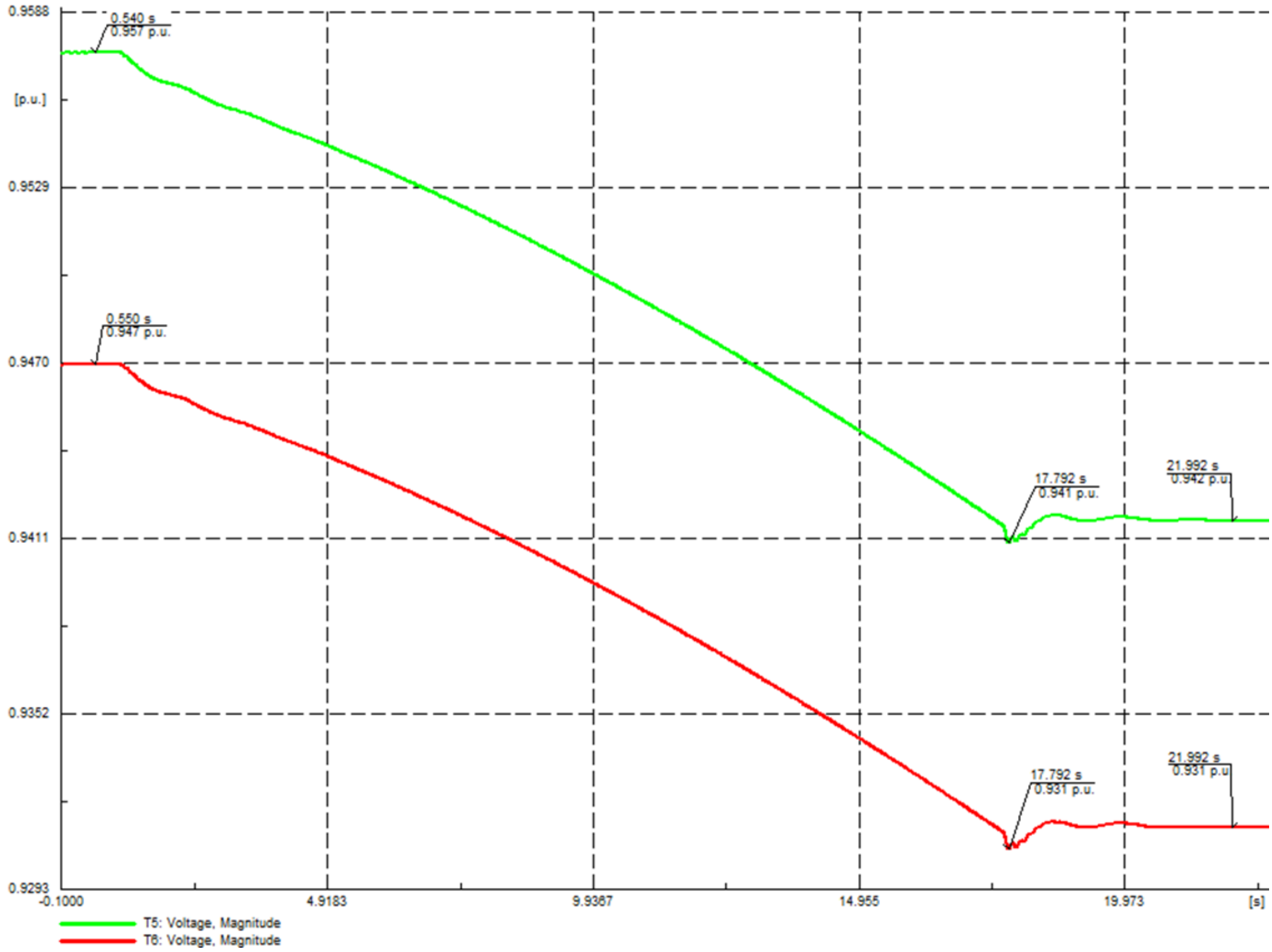

Figure 57 Load terminal voltage 68.4% penetration; ramp down response.

11.9.5 70% penetration ramp response

70 per cent penetration was the highest level of penetration trialled due to minimum loading requirements of the generators.

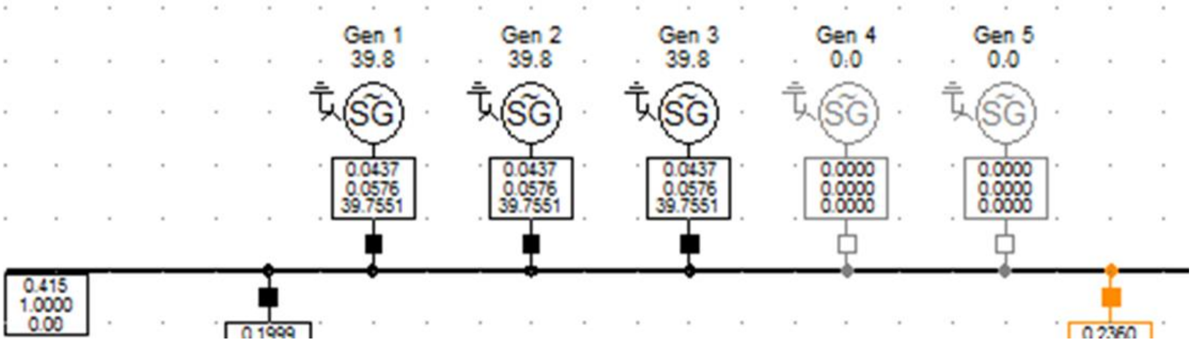

Figure 58 Generation busbar prior to 70% ramp down event.

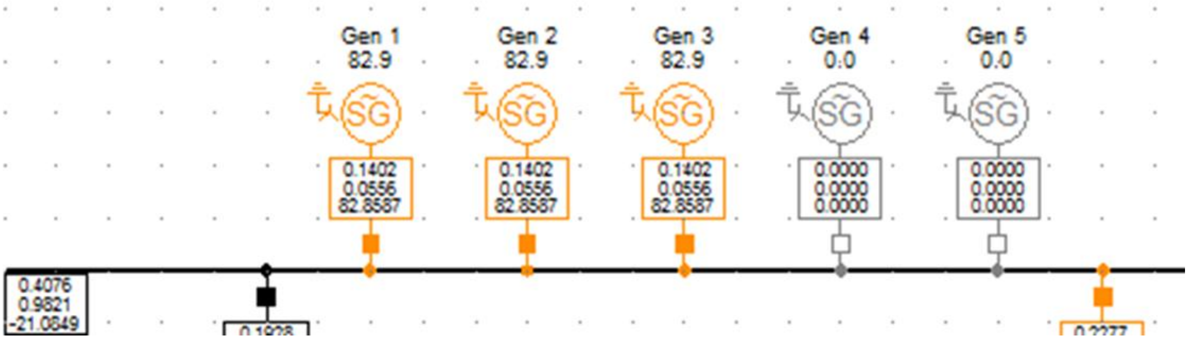

Figure 59 Generation busbar post 70% ramp down event.

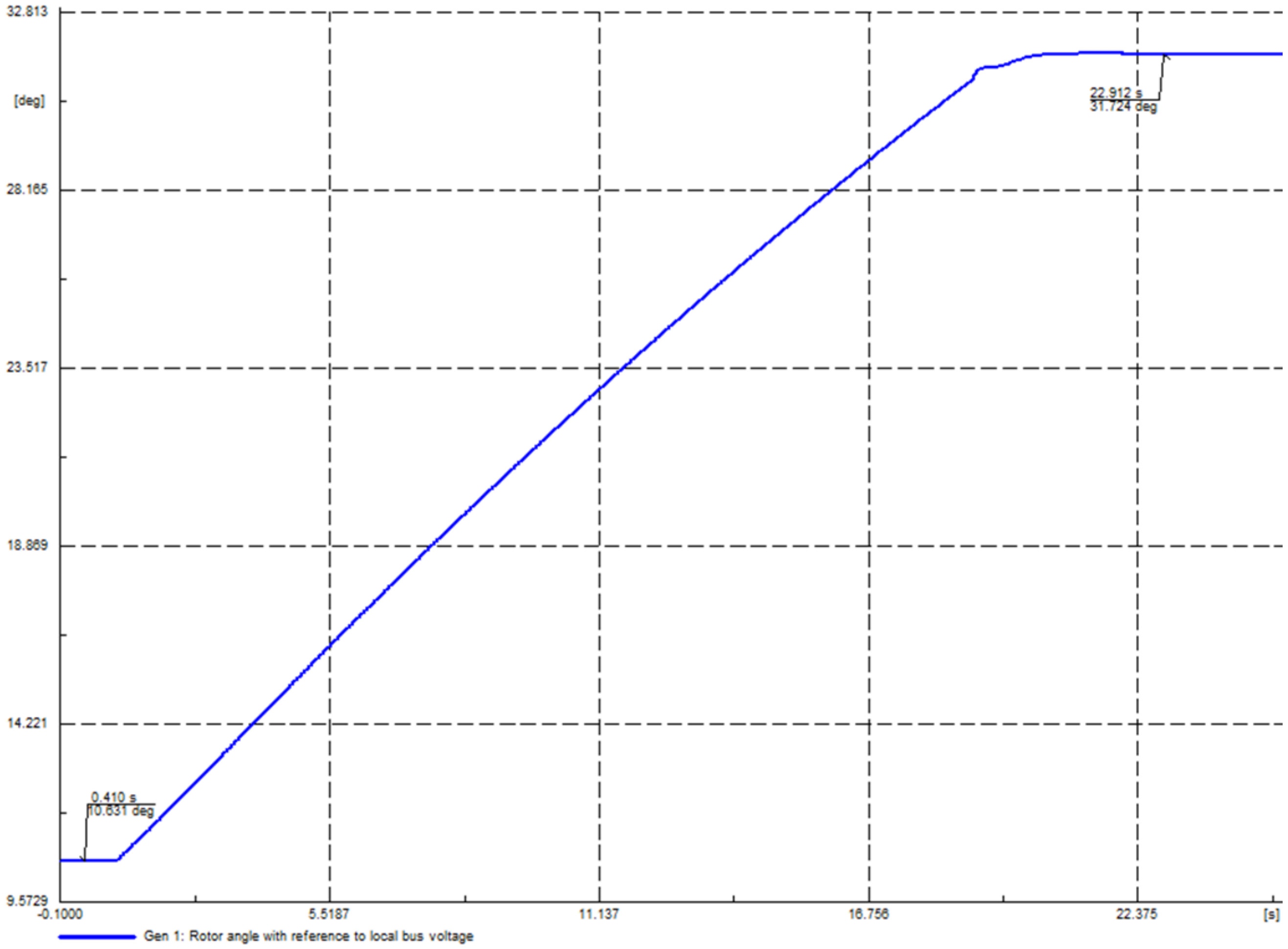

Figure 60 Rotor angle 70% penetration; ramp down response.

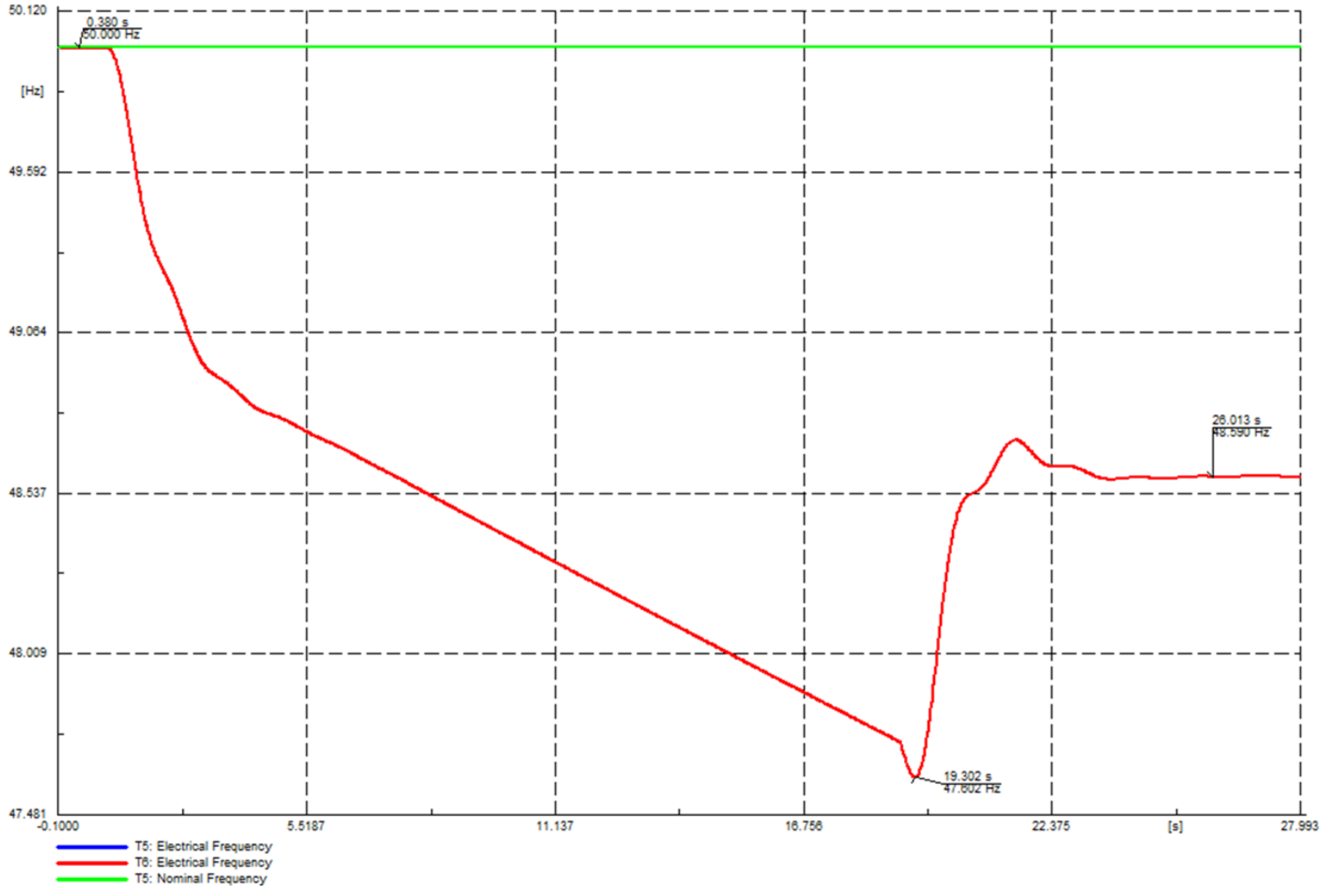

Figure 61 Load terminals frequency 70% penetration; ramp down response.

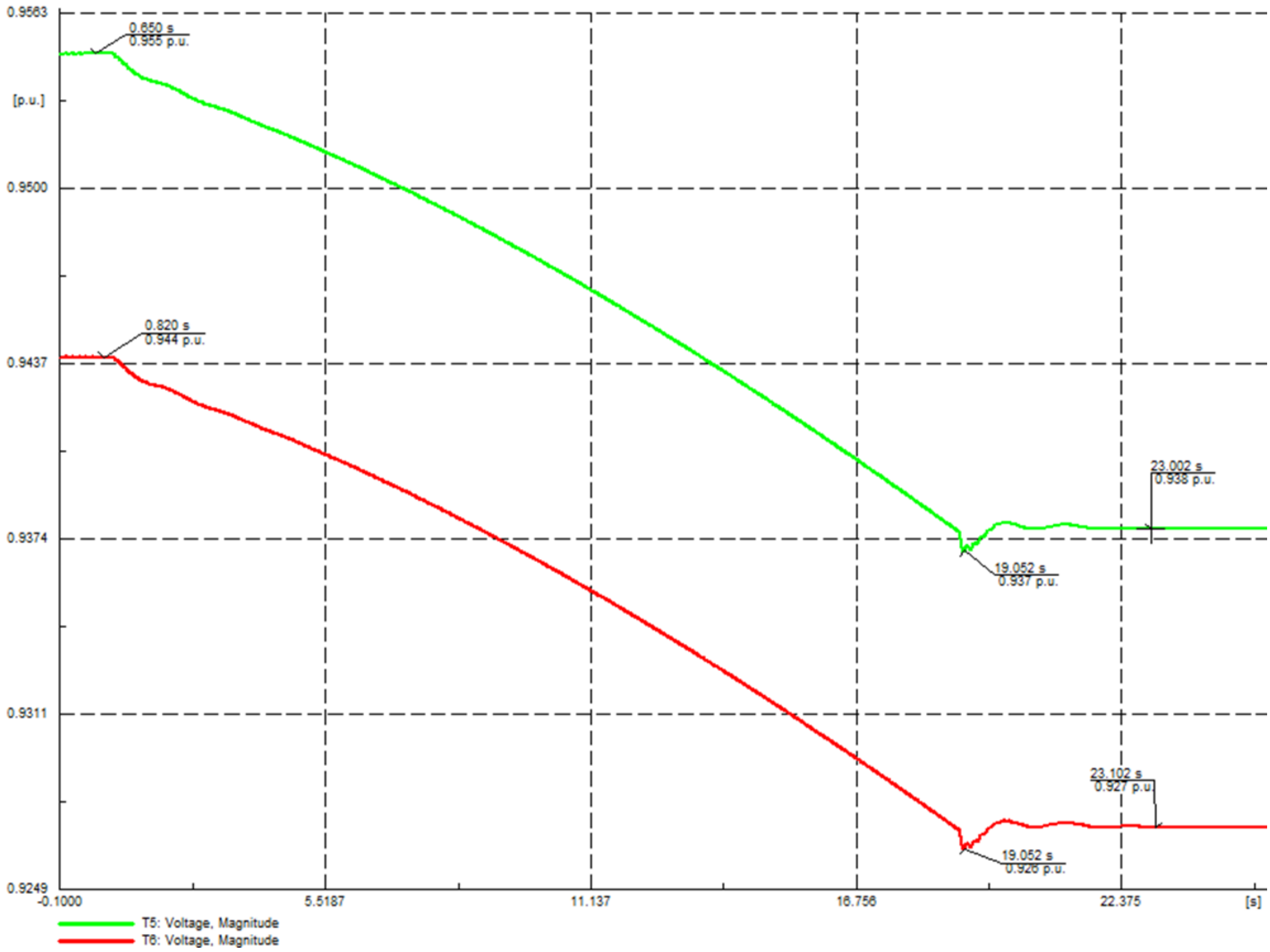

Figure 62 Load terminal voltage 70% penetration; ramp down response.

11.9.6 70% penetration ramp response with additional c-shunt banks

The use of shunt capacitor banks provided a similar result in the 70% penetration simulation as it did in the 60% penetration simulation.

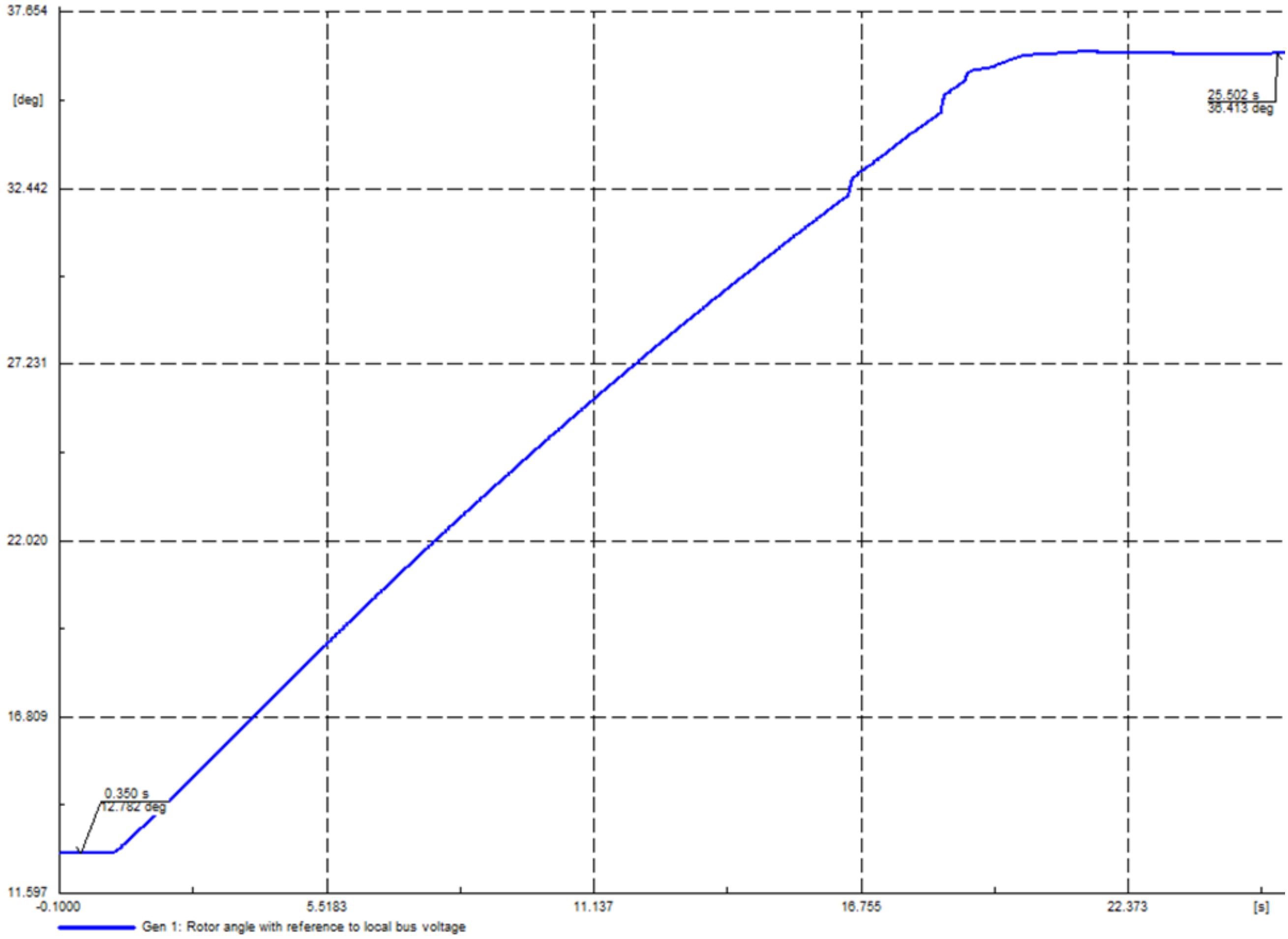

Figure 63 Rotor angle 70% penetration; ramp down response with shunt capacitor banks.

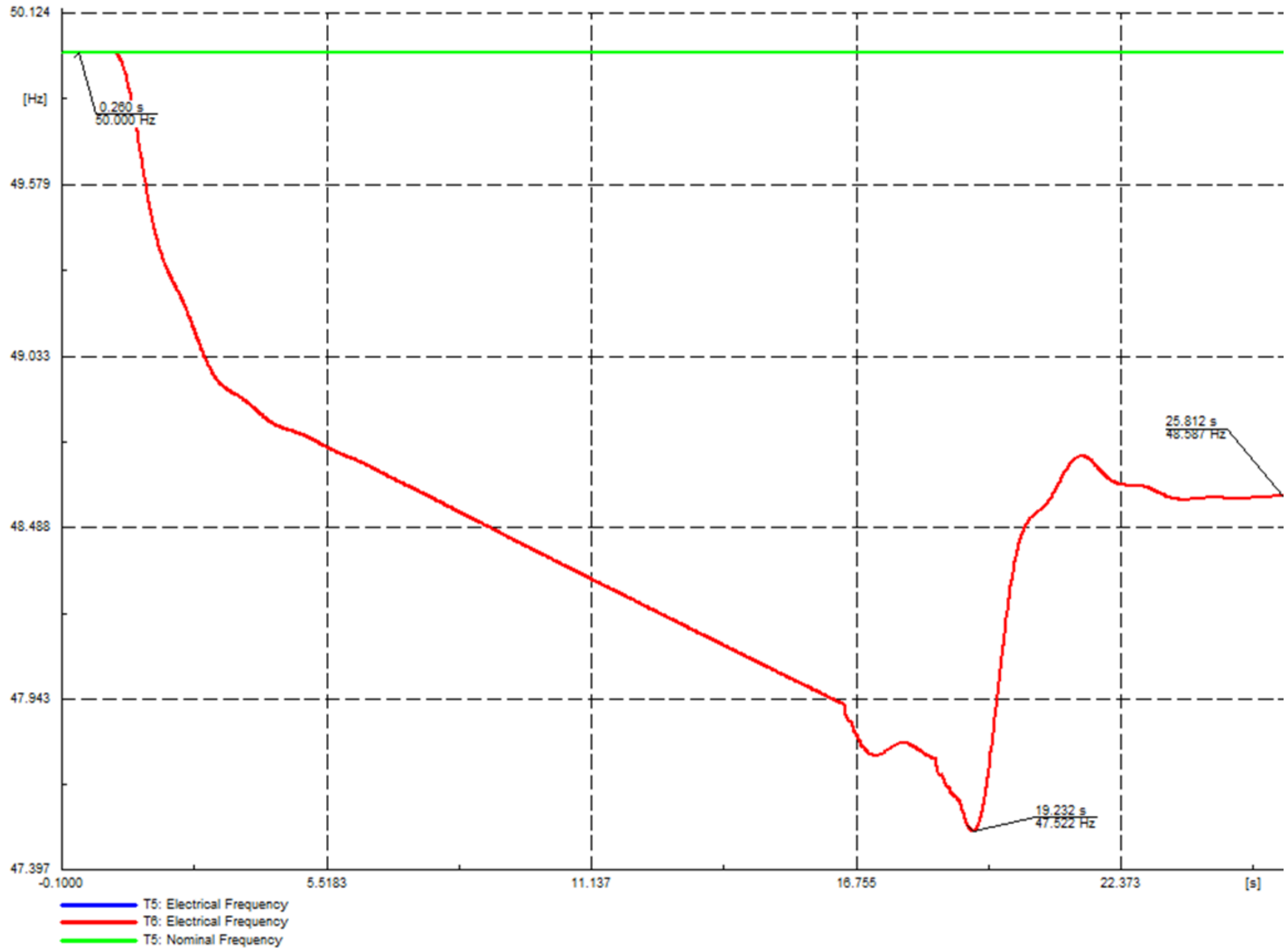

Figure 64 Load terminals frequency 60% penetration; ramp rate response with shunt capacitor banks.

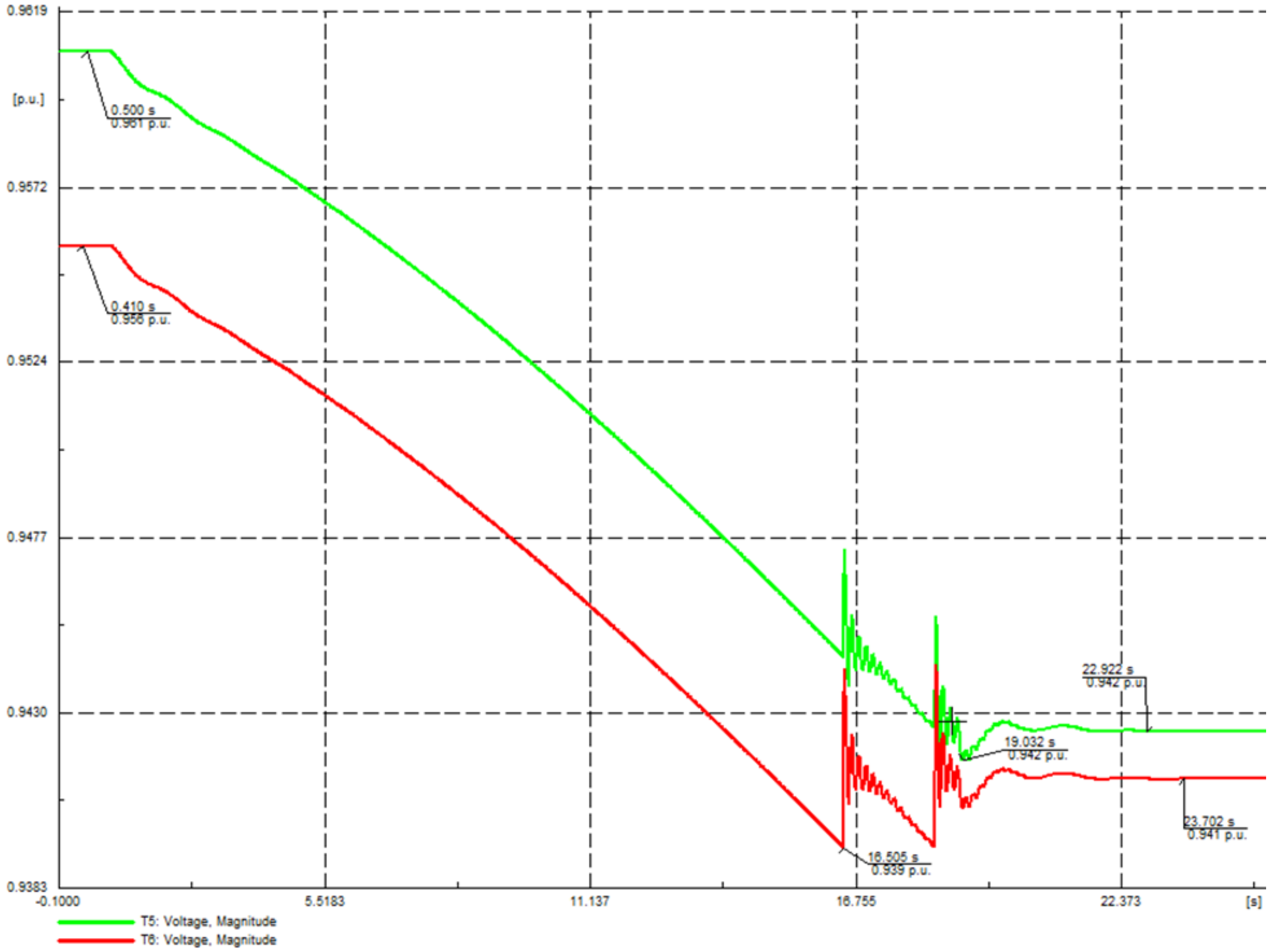

Figure 65 Load terminal voltage 70% penetration; ramp down response with shunt capacitor banks.

11.9.7 70% penetration ramp response with a raised nominal voltage

In the following simulations it is worth noting that it was found raising the nominal voltage above 1.015 per a unit was not beneficial as it could cause the system to become overloaded. The results in this section are similar to those obtained in the 60% penetration simulation.

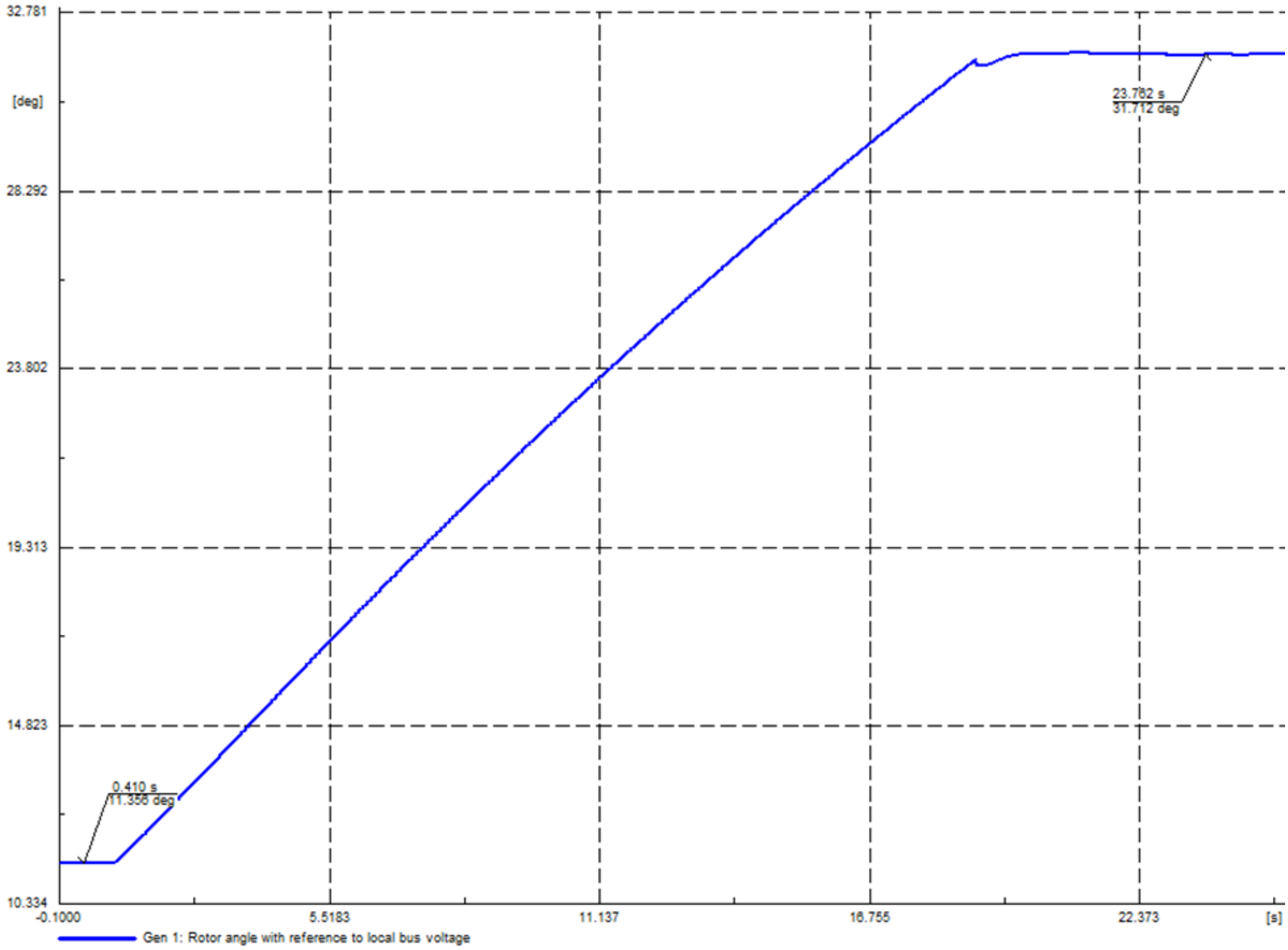

Figure 66 Rotor angle 70% penetration; ramp down response with raised nominal voltage.

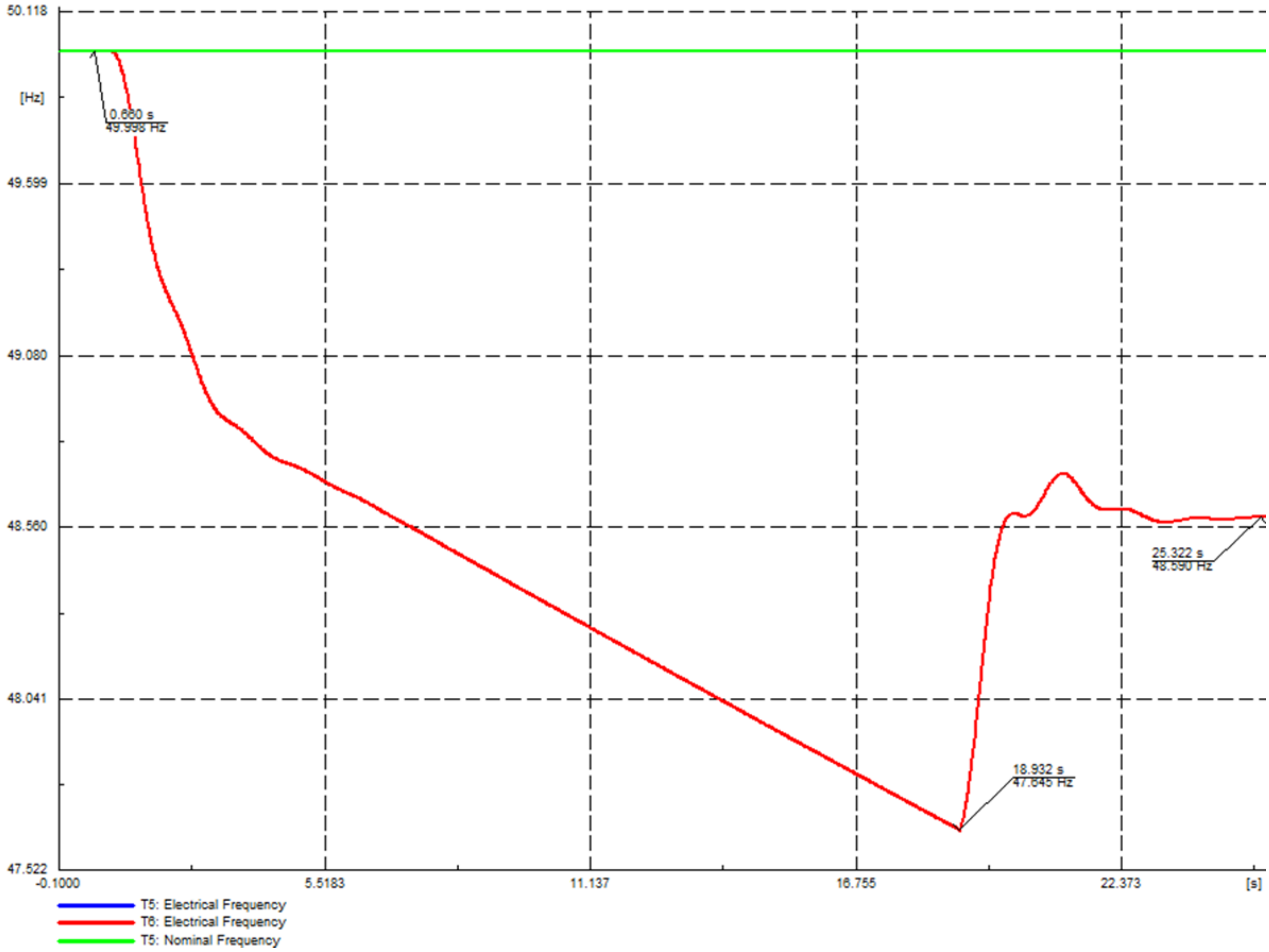

Figure 67 Load terminals frequency 70% penetration; ramp down response with raised nominal voltage.

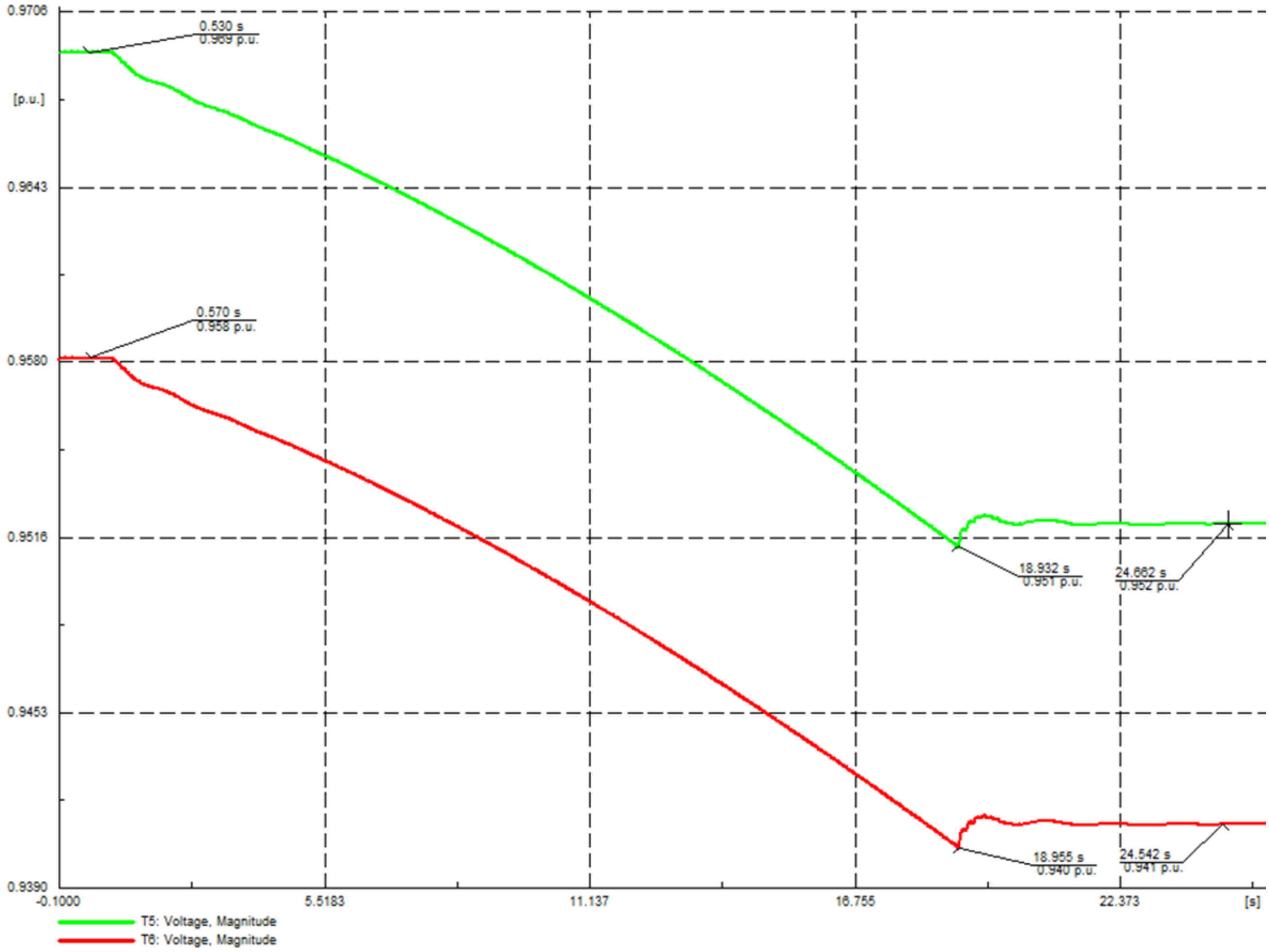

Figure 68 Load terminal voltage 70% penetration ramp down response with raised nominal voltage.

11.10 Load Step Simulations

Load step simulations were conducted to prove that multiple generators in parallel showed a better dynamic response to a single generator set even when the increase in power demand was the same. This improvement is largely due to percentage of demand increase of each generator being lower in the case of multiple generators as opposed to the single generator.

11.10.1 Single Generator Simulation

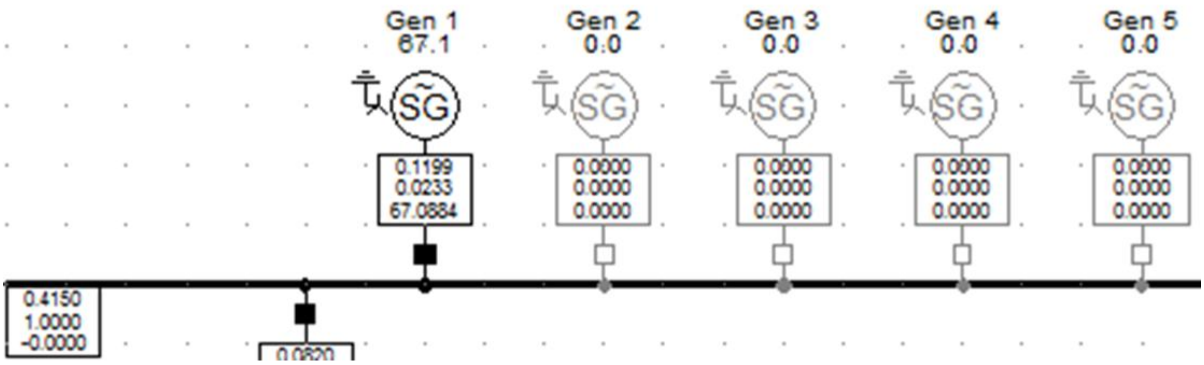

Figure 69 Single generator prior step response

Prior to the step in demand the only online generator (Gen 1) was stable at a 67.1% load factor.

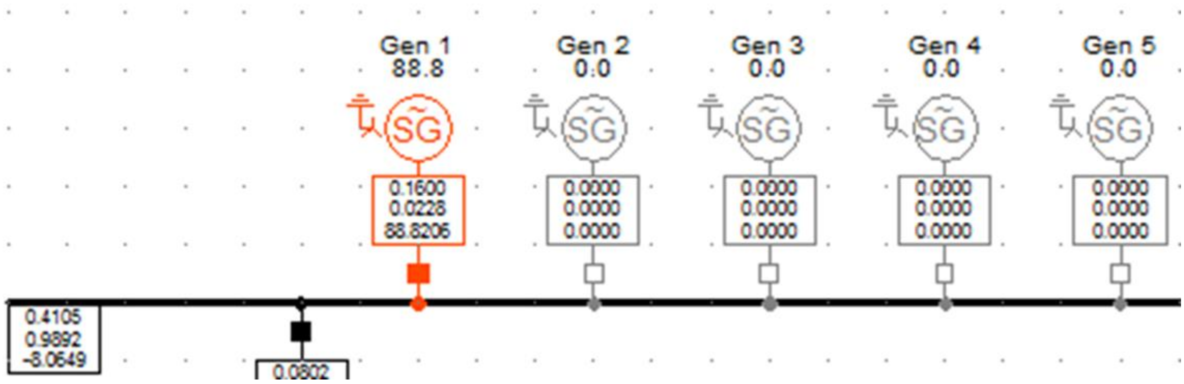

Figure 70 Single generator post step response

Once the system regained steady state from its step the generator load factor can be seen in Figure 70 above to be 88.8% of its rated load.

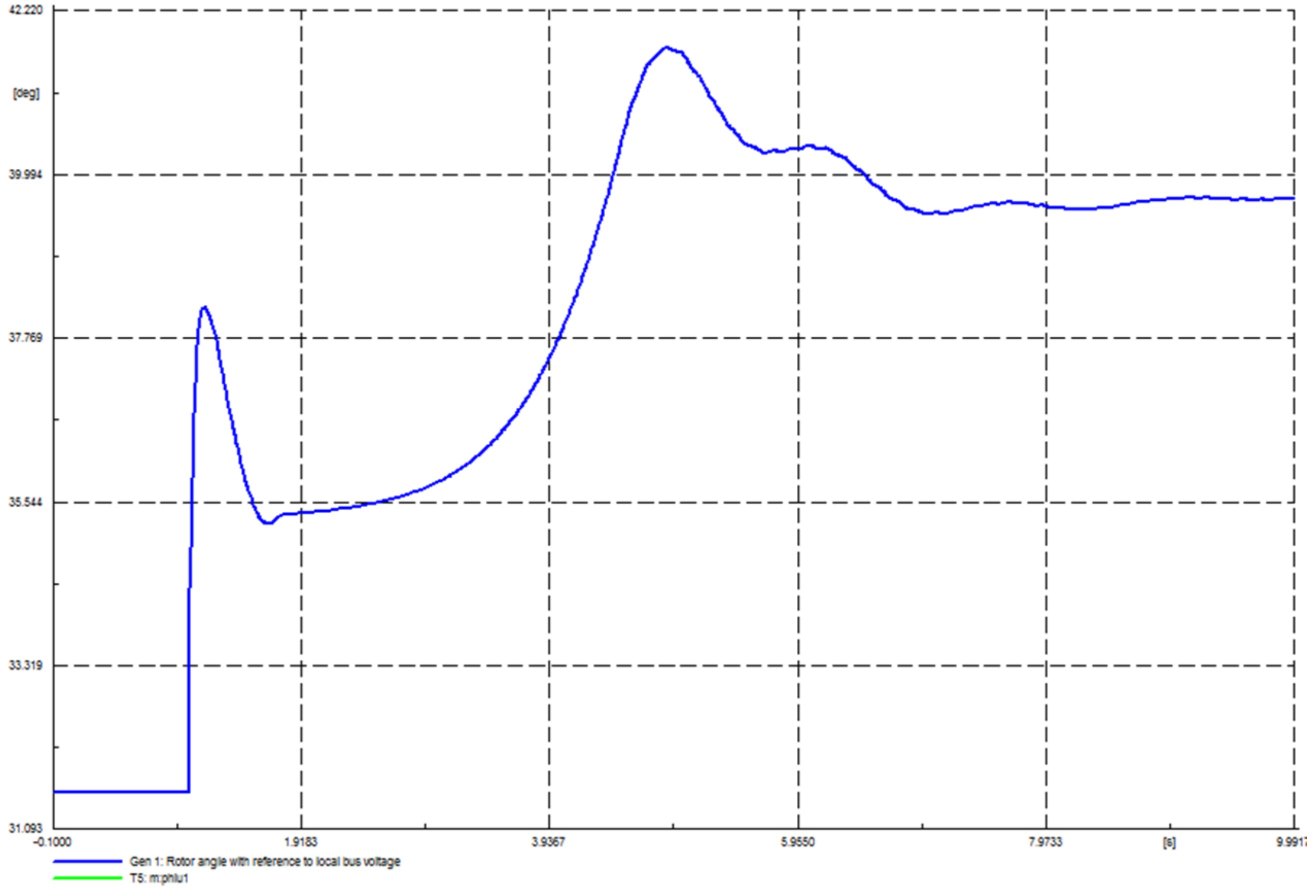

Figure 71 Single generator rotor angle step response.

The rotor angle expresses the generator's rotor angle with respect to the local generation bus voltage. For this simulation the initial steady state rotor angle was 31.6 degrees, had a maximum peak of approximately 41.7 degrees, and a new steady state 39.7 degrees.

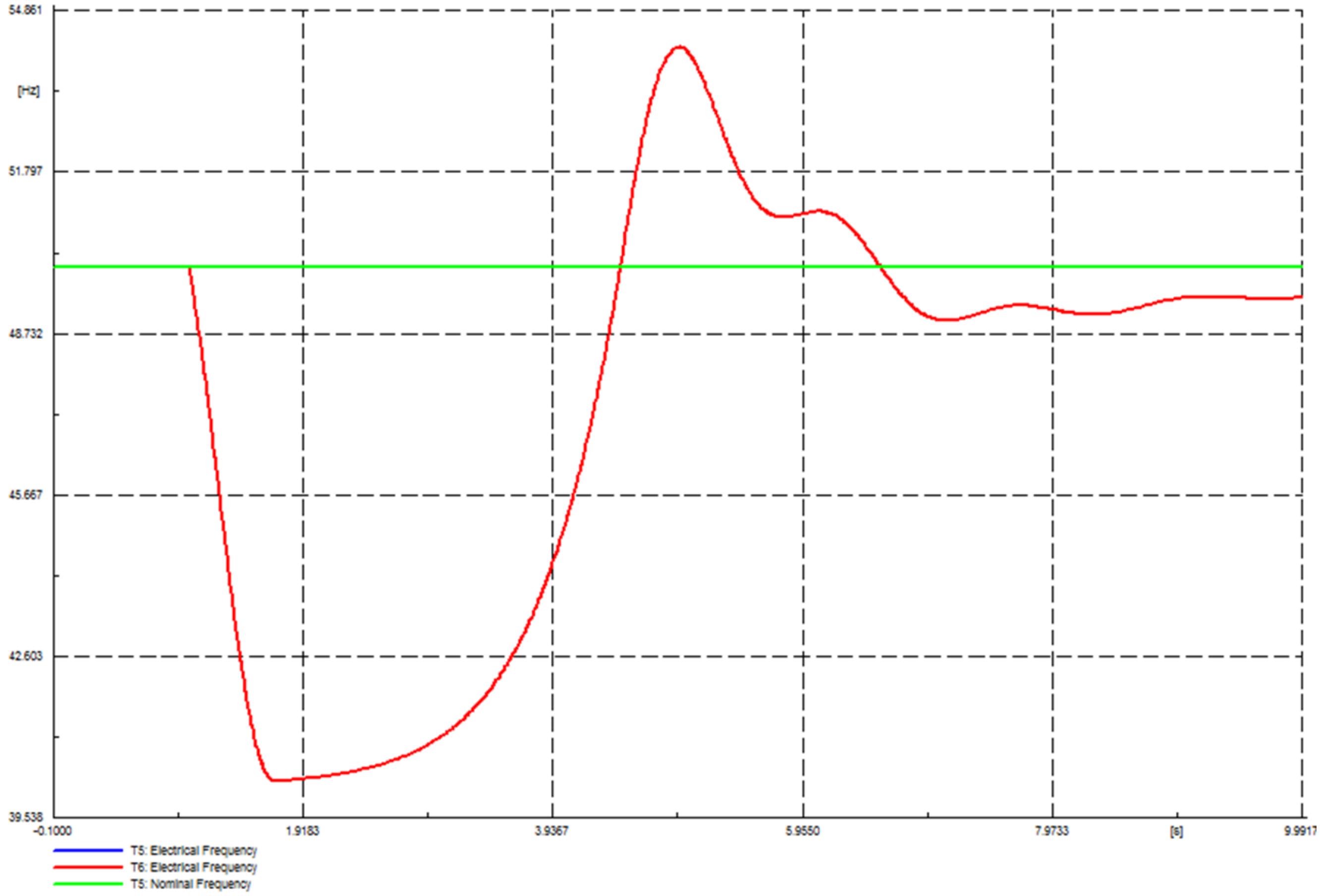

Figure 72 Single generator load frequency step response.

Figure 72 above compares the network's load terminals frequency response (the red plot) to the step in demand to the nominal 50 hertz (the green plot). It is worth noting that both load buses have the exact same frequency, this means that plotting both of them together only provides one plot. The lowest frequency point is 40.2 hertz, and the new steady state frequency is 49.4 hertz.

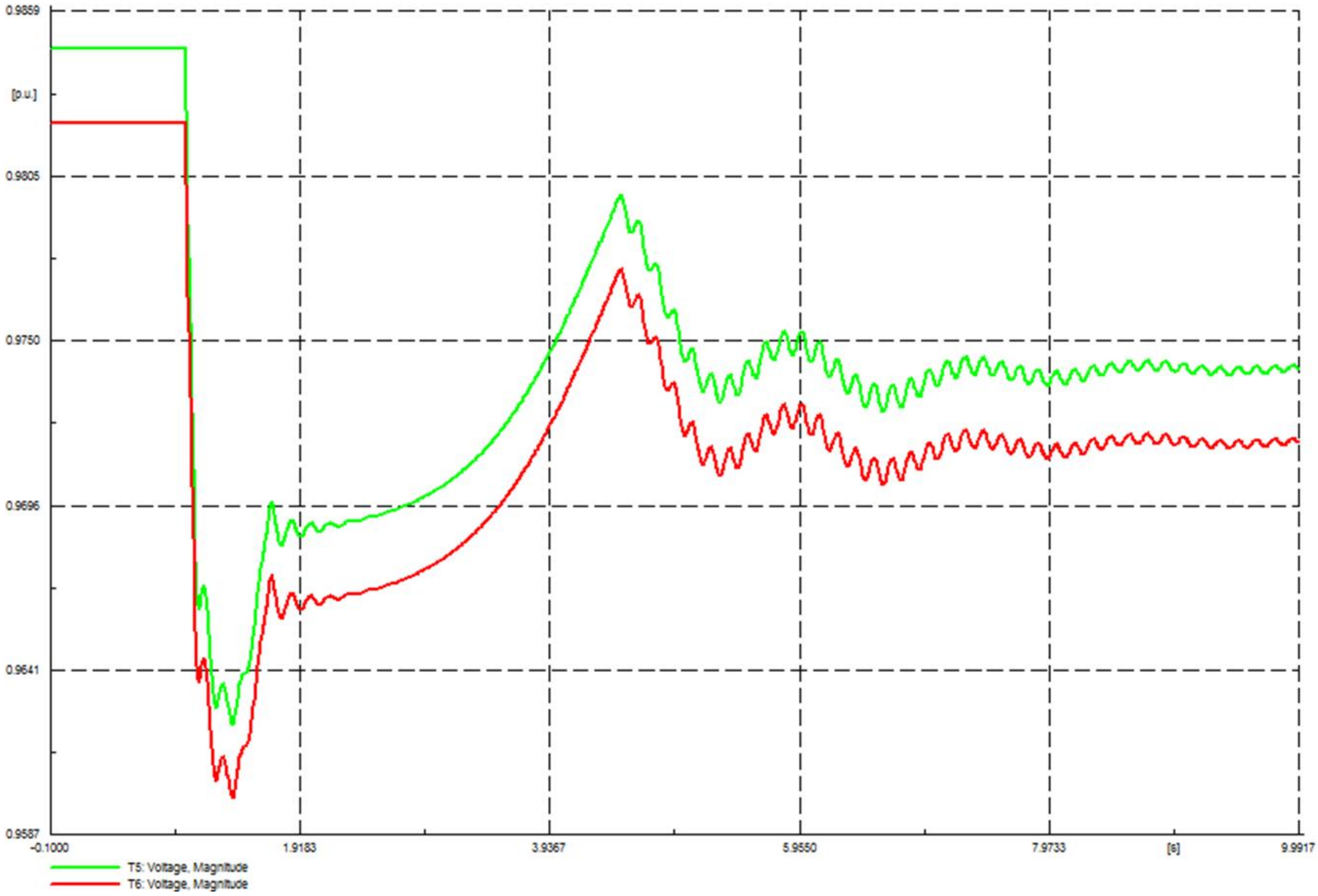

Figure 73 Single generator load terminal voltages step response.

Figure 73 above shows the load terminal voltage responses to load step increase.

Terminal 5 (community 1) starts at a steady state of 0.985 p.u., has a minimum peak of 0.962 p.u., and finds steady state again approximately 0.974 p.u.

Terminal 6 (community 2) starts at a steady state of 0.982 p.u., has a minimum peak of 0.960 p.u., and finds steady state again approximately 0.972 p.u.

11.10.2 Parallel Generator Simulation

Three generators have been used in parallel for the following simulations. The three generators combined are meeting the same load increase the one generator was meeting in the previous 'Single generator' simulations.

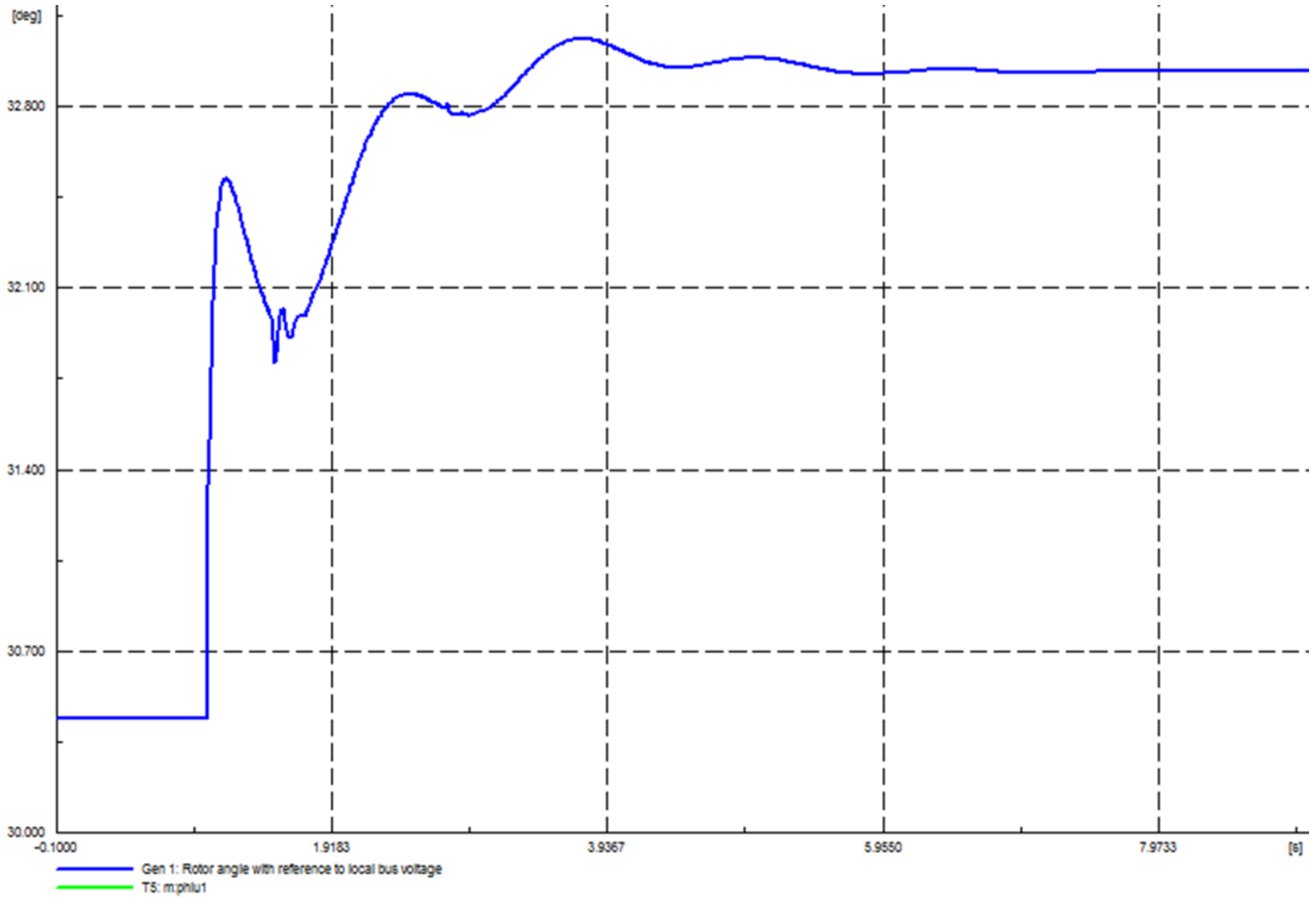

Figure 74 Three generators rotor angle step response of 'Gen 1'.

For this simulation Gen 1's initial steady state rotor angle was 30.4 degrees, had a maximum peak of approximately 33.1 degrees, and a new steady state of 32.9 degrees.

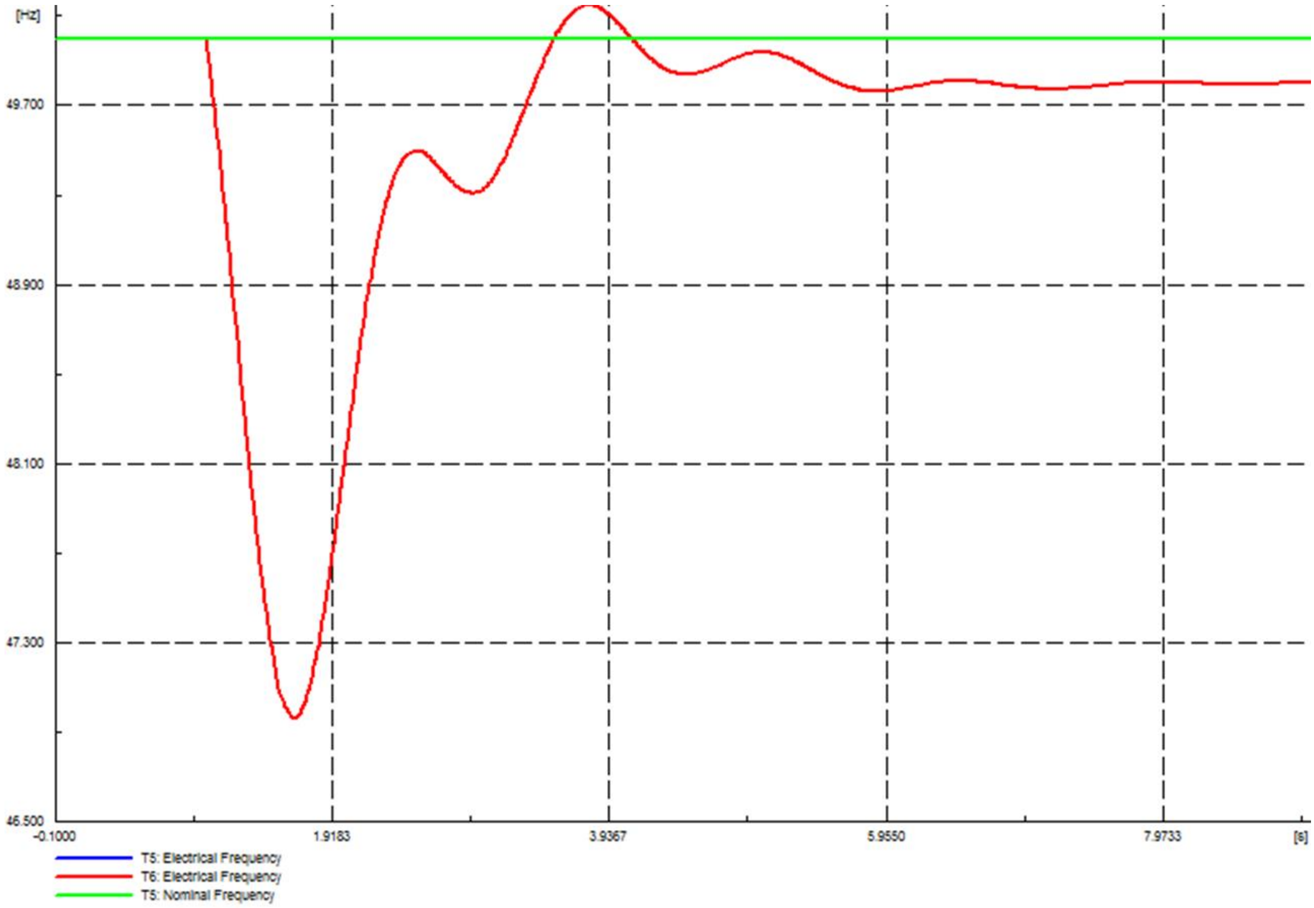

Figure 75 Three generators load frequency step response.

Figure 75 above compares the network's load terminals frequency response (the red plot) to the step in demand to the nominal 50 hertz (the green plot). It is worth noting that both load buses have the exact same frequency, this means that plotting both of them together only provides one plot. The lowest frequency point is 47.0 hertz, the highest is 50.1 hertz, and the new steady state frequency is 49.8 hertz.

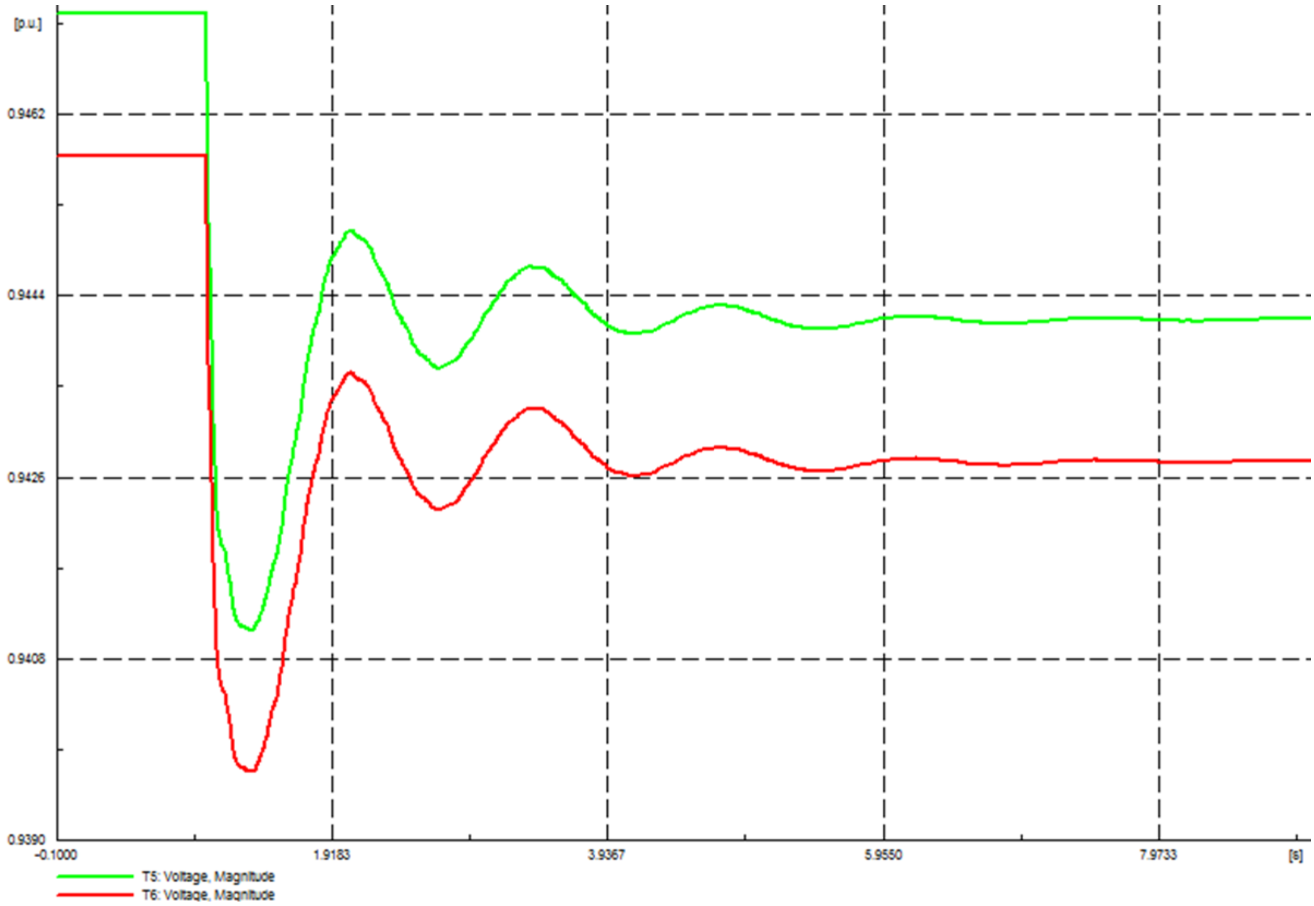

Figure 76 Three generators load terminal voltages step response.

Figure 76 above shows the load terminal voltage responses to a load step increase.

Terminal 5 (community 1) starts at a steady state of 0.947 p.u., has a minimum peak of 0.941 p.u., and finds steady state again approximately 0.944 p.u.

Terminal 6 (community 2) starts at a steady state of 0.946 p.u., has a minimum peak of 0.940 p.u., and finds steady state again approximately 0.943 p.u.