SA Power Networks

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REPORT

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Executive Summary

SA Power Networks (SAPN) is seeking to develop (and subsequently implement) a strategy for the efficient management of its Low Voltage (LV) network. The development of this strategy entails a cost-benefit review of a number of potential strategic options that could be used to manage the LV network in order to determine which delivers the greatest value to all stakeholders.

This cost-benefit review requires analysis of SAPN's electricity network within the Transform Model® network modelling environment. A precursor to the Transform modelling exercise is a quantitative investigation into SAPN's low voltage electricity network to calculate key capacity indices with respect to the amount of DER that can be accommodated in different network types within the SAPN distribution network.

In order to accomplish this, numerous network models were developed within DIgSILENT Power Factory to determine DER hosting limits and the network congestion parameters. The results from this study form some of the key inputs to the whole network parametric analysis using the Transform Model®, which then allows full techno-economic analysis to be performed to justify the best overall option for customers in terms of future management of the LV network.

The is document describes the process by which the DIgSILENT Power Factory models were created and executed and summarises some of the results obtained.

A separate document describes the construction of the Transform Model for SAPN[1] and the parametric feeders within it. Both of these documents should be viewed as annexes to the main document which describes the selection and justification of the most appropriate LV Management Strategy for SAPN to pursue to ensure value to all of its customer base.[2]

[1] "LV Management Strategy Annexe 2: Development of the Transform Model", EA Technology (November 2018)
[2] "LV Management Strategy", EA Technology (November 2018)

Contents

Figures

Tables

1. Low Voltage and High Voltage Network DER Hosting Capacity Study

SA Power Networks (SAPN) is seeking to develop (and subsequently implement) a strategy for the efficient management of its Low Voltage (LV) network via the investigation of several strategic options. Increased levels of customer uptake of Distributed Energy Resources (DER) mean that the traditional 'passive' approach to LV management will no longer be fit for purpose. The widespread connection of small-scale generation and storage means that understanding and managing the technical aspects of the network (such as power flows and voltage regulation) becomes more challenging.

To this end, network models were created to represent characteristic feeder types from within SAPN's network and capacity analysis (hosting) studies were carried on these models. These studies indicated network DER capacity limits.

The aim of the hosting study was to determine the maximum headroom available on the electricity network owned by SA Power Networks (SAPN) to accommodate the connection of DER before the occurrence of voltage and/or thermal violations. The breaking points of different networks under various scenarios were determined by performing several Quasi-Dynamic load flow studies on the network models using DIgSILENT Power Factory.

The network congestion parameters obtained from this analysis were then used in the Transform Model® to enable its techno-economic analysis to be undertaken[1]. The outputs from the Transform Model® process was then used within a cost-benefit analysis to investigate the value created within each of the possible strategy choices.

For this study, a total of twenty-one individual low voltage, three SWER (single wire Earth return) and six 11 kV high voltage SAPN distribution networks were modelled. The Quasi-Dynamic analysis was carried out for a period of 24 hours (and 365 days for some selected cases). The results obtained from this detailed analysis formed the inputs to the Transform Model® whose outputs were then used to develop future strategies for SAPN.

1.1 DIgSILENT Power Factory

The amount of electrical power being consumed within electricity networks change over daily and seasonal cycles on a minute to minute basis. This means that capacity available to be used by DER changes upon a minute to minute basis also. For this reason, a snapshot load flow does not necessarily capture the true available capacity within the network. In order to incorporate the range of possible operating scenarios on the network, it is important to analyse the network over a time range. This is achieved by carrying out a Quasi-Dynamic analysis of the network.

The Quasi-Dynamic simulation performs multiple load flow calculations repeated for a selected duration with user-defined time steps. This method allows for the variation of loads and generation over the simulation period. DIgSILENT Power Factory was used for the modelling and analysis of the SAPN owned electricity networks.

DIgSILENT Power Factory is a power system analysis software package commonly used in the analysis of transmission and distribution systems. Power Factory SP1 (2018) was used for this study. This version offers a toolbox that allows Quasi-Dynamic simulation which is used for the execution of time-based (medium to long-term) simulations. The tool is particularly suitable for planning studies in which the load and generation profiles are changing, albeit the changes during user-defined time step sizes are defined.

The Quasi-Dynamic tool in Power Factory allows for analysis of the network under user-defined load /generation profile for a specific snapshot of the network during individual time steps of the simulation. The Quasi-Dynamic tool performs multiple load flow calculations for a user-specified duration, with user-defined time step sizes. The software version and the individual base modules in Power Factory that are required to carry out the analysis are shown in Figure 1.

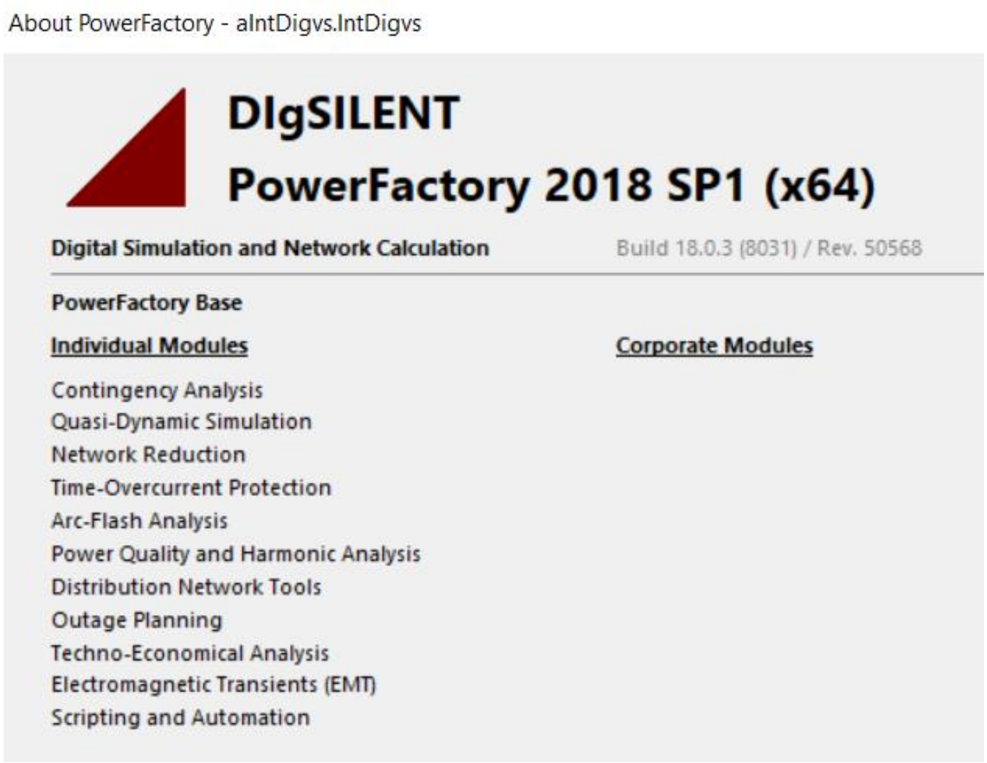


Figure 1 DIgSILENT Power Factory Version and included modules

1.2 Network Modelling and Analysis

1.2.1 Network Modelling

Power Factory has a graphical interface that allows users to build, compile, execute and analyse simulation cases of complex electrical networks. The networks were modelled in this interface using the components available in Power Factory library (transformers, loads, generators, cables etc). The details of individual elements can be found in the Power Factory user manual[3]. In addition to the existing models, a bespoke model of STATCOMs was also developed to investigate the impact or reactive power compensation on the network.

The following steps were undertaken to model the networks:

Low Voltage Networks.
To describe the variety of different types of LV Network, SAPN and EA Technology developed a list with 15 different classes of LV network, within which, each LV feeder or LV substation would be expected to reside. The below catagories were selected based on key factors that influence hosting capacities. The details of the grouping are discussed in section 4.2 of "LV Management Startegy Annexe 2: Development of the Transform Model". The list of network types is as follows:

- Central Business District
- Single Customer (Commercial)

[3] Power Factory User manual available at: https://www.digsilent.de/en/downloads.html

- Majority Commercial
- Mixed Customer Underground (UG)
- Mixed Customer Overhead (OH)
- New Underground
- Old Underground
- Small Overhead
- Medium Overhead
- Large Overhead
- Single Rural Customer
- 2-4 Customer Rural
- Rural Township (Low Voltage)
- Singe Wire Earth Return (Low Voltage)
- Single Wire Earth Return (Township)

SAPN nominated specific networks under each category which were then modelled in Power Factory. The nominated networks were representative of a large proportion of networks within each category.

The networks were modelled based on the inputs received from SAPN. The network topologies were obtained from Single Line Diagrams (SLD) of the networks, whilst other data required for modelling (such as transformer rating, cable parameters etc.) were provided by SAPN in the form of data sheets. In order to ensure the most accurate information was used, SAPN staff conducted some site surveys where they physically scoped a range of LV feeders to provide accurate conductor data. Using these inputs, the base network was modelled with the components available in Power Factory library.

The analysis of low voltage networks took account of loading and imbalance assumptions provided by SAPN intended to provide a general representation of the typical network performance in each of the network categories.

11 kV Networks
Although the strategy to be developed is concerned with the management of LV networks, it is not practical to consider the LV network in isolation. Rather, it was necessary to also consider the upstream 11kV network so as to understand the impact that voltage rise on these circuits might have on the LV network.

The network details of the 11 kV networks were received in the form of geographic information system (GIS) models with technical and geographical details embedded within them. An SLD was also provided. The network topology, circuit length and line data were individually extracted for the GIS interface and modelled on Power Factory. Other data required for modelling (such as transformer characteristics, cable parameters etc) were provided in the form of data sheets.

The list of 11 kV network types was as follows:

- CBD
- Urban Underground
- Urban Mix

- Urban Overhead
- Urban Fringe
- Rural Dense
- Rural Sparse

Figure 2 illustrates a sample LV network modelled on Power Factory using the graphical user interface with the components ribbon.

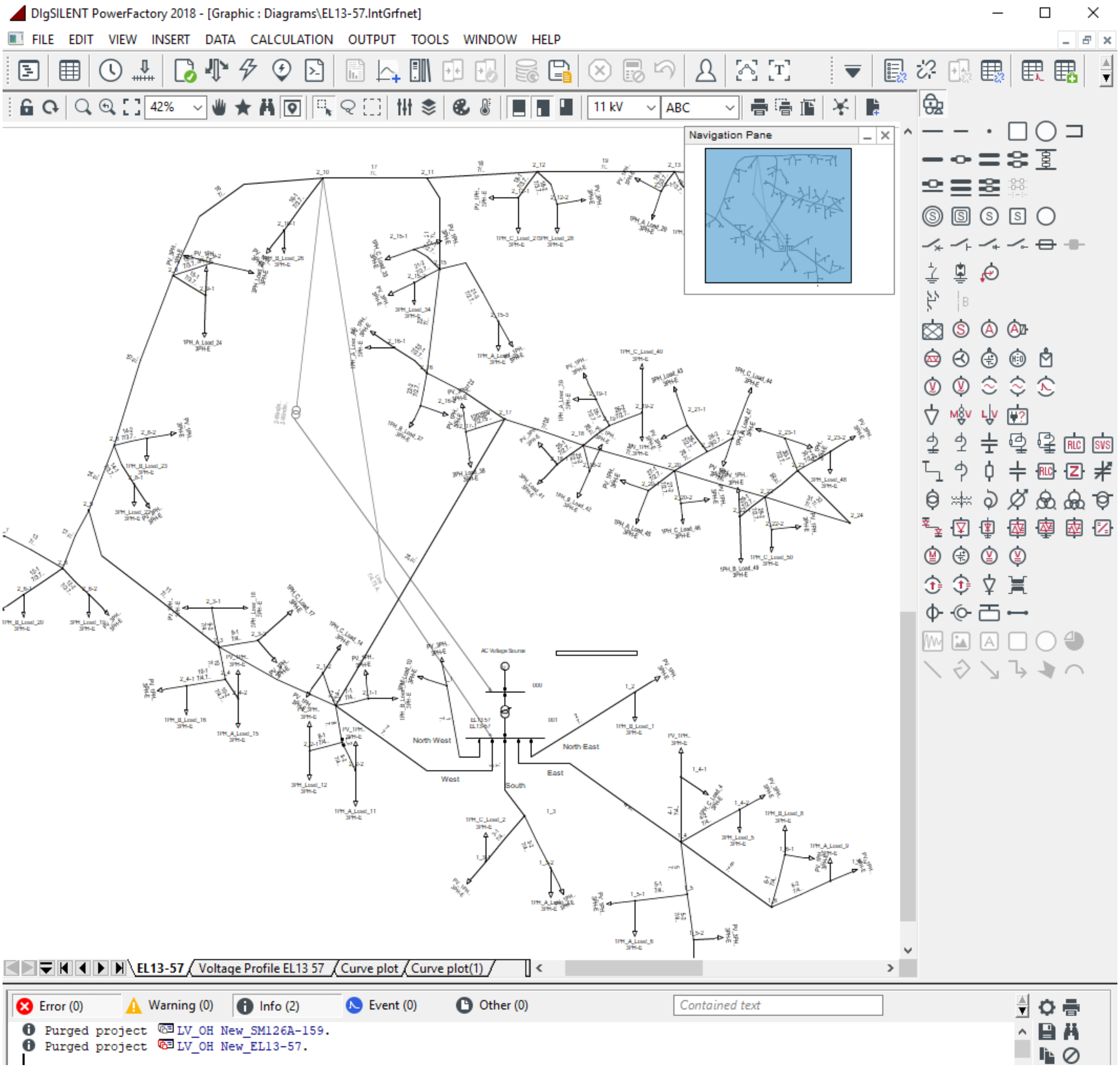


Figure 2 The graphical user interface in DIgSILENT Power Factory

In order to carry out Quasi-Dynamic Analysis the day-round load and generation profile for the desired duration need to be specified within the Power Factory model.

The load and generation profiles were input for individual components (or individual phases of the component when applicable) using the network model manager interface as shown in Figure 3.

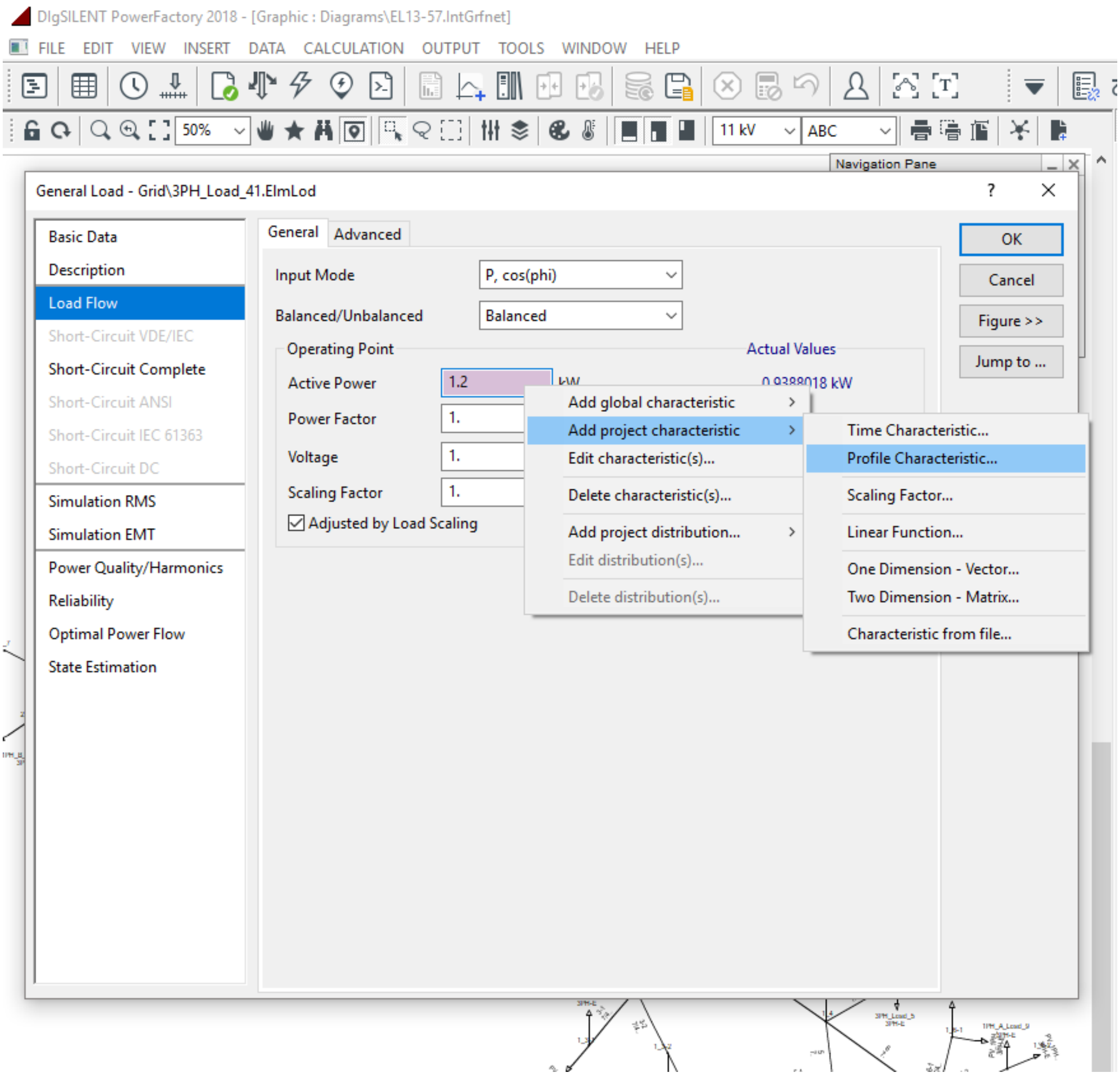


Figure 3 **Load and generation profile allocation**

1.2.2 Load profiles

The load profiles were calculated as follows:

Low Voltage Networks.
Based on the average consumption from metering data a uniform load with a peak consumption of 1.2 kW at 0.98 lagging power factor was used for individual customers connected to the LV networks. This value is agreed mutually with SAPN to generally represent the average consumption of the majority of domestic customers. While the underlying hosting capacity of the network is largely independent of the load observed on the feeder, this data is important in understanding the duration of exceedances over longer periods.

The loads were configured with 24 hours, half-hourly profile. The load profile of a typical summer day was used across all types of network groups including overhead (OH), underground (UG) and mixed networks.

The normalised load profile used for the loads is shown in Figure 4. There are 48 half hourly data with values ranging from zero to one. The values are used as a scaling factor for the respective half hour during the 24 hours simulation. For example, a value of 0.4 on the profile curve corresponds to the load operated at 40% of its rated capacity and a value of 1 corresponds to the load operating at its 100% rated capacity load. The figure below illustrates the 24 hours load profile used for the LV Quasi-Dynamic analysis on LV networks. In this example, the maximum and minimum consumption occurs at 7:30 pm and 4 am respectively.

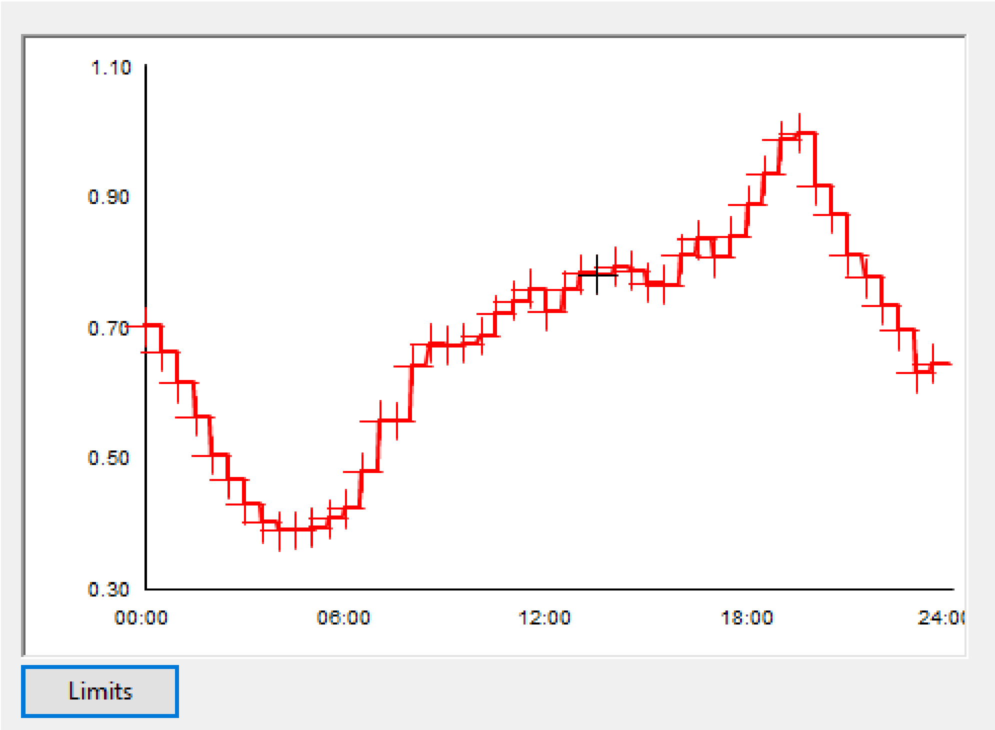


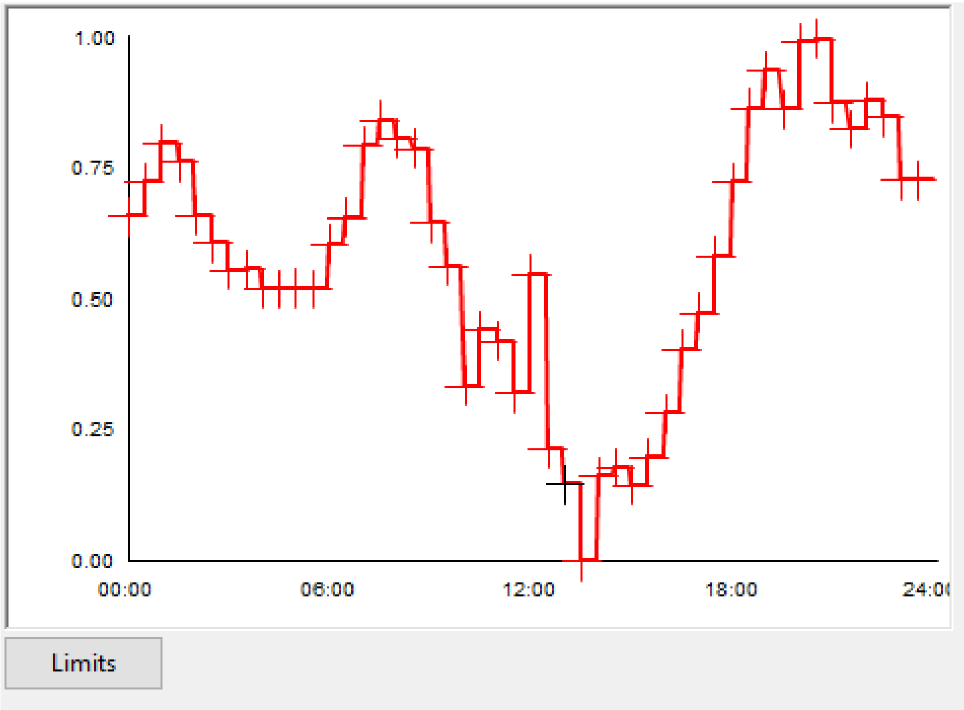
Figure 4 Load profile used for 0.4 kV networks

11 kV Networks

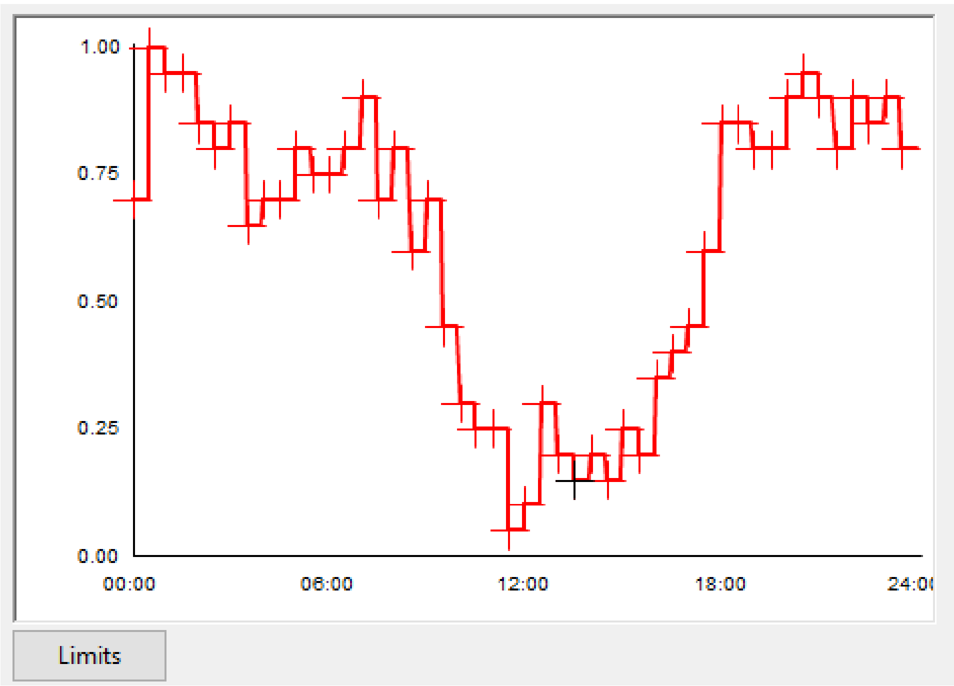
The load profiles for each of the 11 kV networks are calculated individually using the yearly half hour load profile supplied by SAPN. These load profiles were taken from real SCADA readings from respective feeder exit. The maximum consumption for a specific half hour over the year is selected to generate a representative 24 hours load profile. The maximum load for each half hour window was then used as the profile.

The diversity of loads was maintained by allocating the maximum half hourly load proportionally the nameplate rating of the load transformers, such that the summation of the individual loads equals the total maximum load of the network at that time of day. This profile was unique for each network since the allocation of loads is dependent on the nature of individual networks and are different for each 11 kV network as illustrated in Figure 5. This allocation methodology used is a common approach that is used globally by utilities since there are no reliable monitored data to show how much power was being consumed at each 11/LV substation. The profiles in Figure 5 (a) and (b) correspond to different 11 kV networks and are different due to the nature of the networks (e.g. the load profile in the rural and sparse network).

The steps followed to determine the load profiles for the year-long analysis is similar to the one discussed. However, the profile consists of used a total of 8760 hourly profiles that are input for the analysis



(a)



(b)

Figure 5 Load profile used for 11 kV networks for candidate networks (a) and (b)

1.2.3 Photo Voltaic Generation Profiles

The generation connected to the networks was mainly Photovoltaic (PV) panels and were assigned to the individual components similar to the assignment of loads. The generation profiles were calculated as follows.

Low Voltage Networks.
In low voltage networks, the PV panels were assumed to be uniformly distributed across individual customers within the network (i.e. every customer connected to the LV network is assumed to have an equal amount of installed PV generation). The capacity of each PV generator was initially set to a maximum of 1.2 kW while modelling the base network. Analysis outside of Power Factory explored the effect of growth upon these assumptions.

11 kV Networks
The allocation of PV generation at individual nodes was proportional to the connected loads. A method similar to the one followed for load allocation was used for the assignment of the PV capacities on individual nodes. The 11 kV networks studied consist mostly of balanced 3 phase loads (and generation).

The profile used for both the Low Voltage and 11 kV networks is shown in Figure 6. This generation profile corresponds to a typical summer day in South Australia. In this profile, the maximum generation occurred at 1:30 pm.

The major concerns for SAPN networks were overvoltage due to increasing penetration of PV generation on the network. The network is expected to be under higher stress (i.e. closer to the breaking point) during the summer generation profile (or at shoulder conditions) rather than in winter and this informed the selection of appropriate profiles.

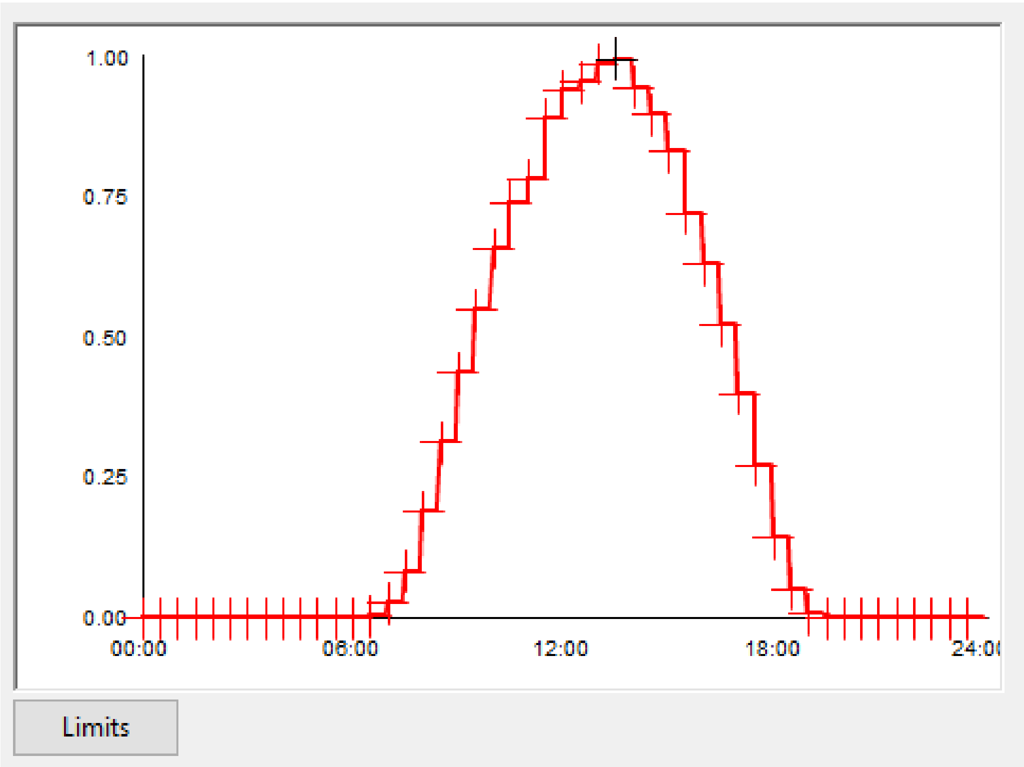


Figure 6 **PV Generation profile used for 0.4 kV and 11 kV networks**

1.2.4 Assumptions for the network modelling and analysis

Assumptions for the LV network modelling and analysis

- The distribution of load over different phases in the models was applied in accordance with SAPN nominated assumptions. Although most of the loads at LV levels tend to be single phase and tracking the connected phases of the individual customer is difficult. Therefore, for simplicity, it was ensured that the loads and generations were generally balanced across the entire network which is reflective of a network dominated by single phase connections.
- The base hosting capacities studies were performed with unity power factor generation.
- Voltage regulation due to transformer tap operation was not considered which is reflective of Low Voltage source transformers having off-load tap changers. These systems do not dynamically respond to changes in voltage and need to be de-energised to change tap position.

Assumptions for the 11 kV network modelling and analysis

- Load profiles were calculated for individual networks based on measured half-hourly data provided by SAPN. Identical PV profile was used for all the networks.
- For some of the networks, the half-hourly loading data was not available as there was no measured data. For such networks, the phase current (which was available) was used to calculate 3 phase kW values, this approach assumed that the received voltage was 10.99kV and the power factor of electrical demand was 0.99 lagging.
- PV generation connected at a node was proportional to the connected load at that node.
- A balanced load flow algorithm was used to solve networks with no single phase/2 phase loads.
- 10 kW load for 2 Phase (AB) loads are modelled as 3-phase loads with 5kW on Phase-A and 5kW on Phase-B and 0kW on Phase-C
- Two phase loads do not have specific phase allocation in the input data sheets. Such loads were allocated to two phases such that the overall network remained balanced.
- In some cases, the cable types were missing in the GIS model, hence cable types of similar feeders/branches were used for the Power Factory model.

2. Approach

2.1 Validation of models against the real network

SAPN selected the networks to be studied by interrogating its own data and engaging with internal stakeholders to ensure that networks which were truly ‘representative’ rather than outliers were chosen for modelling purposes. In order to ensure a full and accurate data set, SAPN engaged contractors to physically scope LV feeders to gather unknown conductor information.

Several examples of each category of network could then be modelled to confirm agreement between the modelled results and these were reviewed by SAPN to confirm that the figures were reasonable and were highlighting the likely issues and limits in line with anecdotal experience.

Finally, when considering the various engineering solutions that could be adopted to remediate the network issues encountered, SAPN engaged with some of its internal LV design team to ask them independently how they might solve the network problems. The results derived by the design team concurred with the approach taken in this work, giving extra assurance that the approach and the findings were indeed representative of real-world approaches and hence were valid and scalable across the network.

The following sub-sections describe in detail the approach taken and some of the sensitivities and additional studies performed to determine hosting capacity on the distribution network.

2.2 Determination of network limits

The study set out to establish the limiting amount of generation that can be allocated into each network.

The flowchart in Figure 7 shows the steps followed to determine this limit. The quasi-dynamic analysis is carried out on individual networks with pre-allocated load and generation level (as described in section 1.2.1). Unbalanced load flow algorithms were used to solve networks with single phase connections. The output plot of the Quasi-Dynamic analysis is analysed to check for voltage and thermal violations on the network. The PV is incremented in steps during each iteration. The iteration is repeated until the power generation results in an increase in voltage that breaches the upper voltage band (here shown as a 1% increase)

These steps are then repeated for each network for different power factors of load and generation. The results are noted for loads at unity power factor and a power factor of 0.98 (lagging) and for PV generation with unity power factor and power factors of 0.98 and 0.93 (lagging) to model the behaviour of legacy (pre-December 2017) PV systems and current and future AS4777.2 Volt/VAR compliant systems. The same set of steps are followed for both LV networks and the 11kV networks.

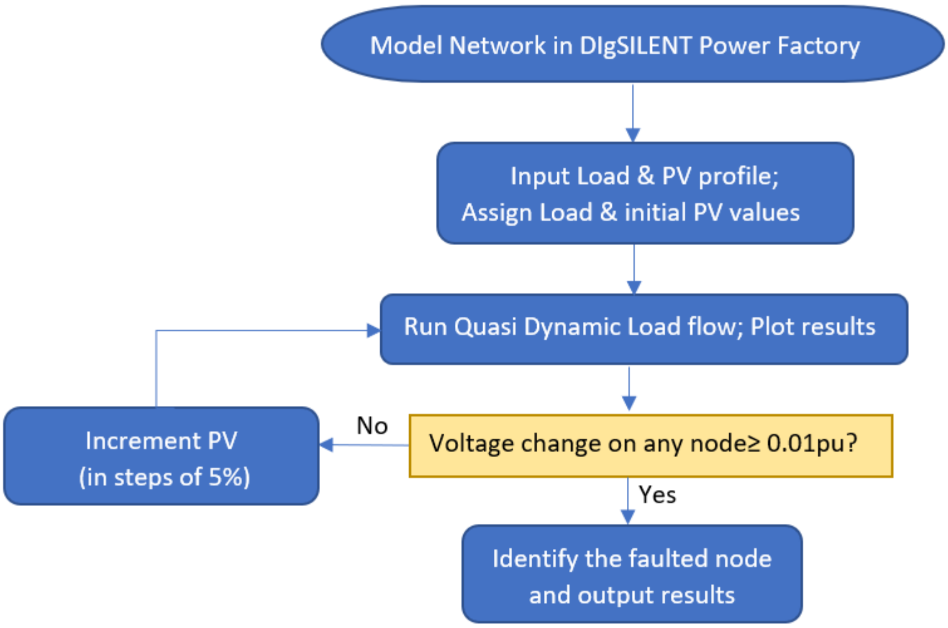


Figure 7 Flowchart of the steps taken to determine the limiting amount of PV

In addition to the voltage violation, several runs of load flows are carried out on the model. Load flow for the snap shot is carried out on the network to establish the thermal limit of the network. For this analysis, the individual load flows were conducted at the time of day when the load was highest. The instantaneous PV generation, at that time was set to zero. The flowchart in Figure 8 shows the steps followed for this.

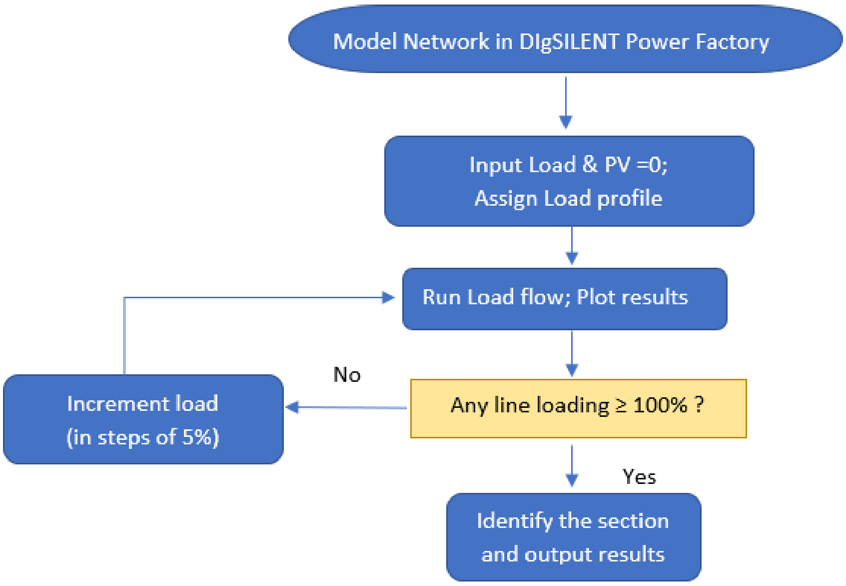


Figure 8 Flowchart of the steps taken to determine the thermal limit of the network

2.2.1 The output of the Quasi-Dynamic analysis results

The results from the Quasi-Dynamic analysis are displayed in the form of a detailed report and a graphical interpretation of the results are also displayed. Figure 9 illustrates a typical analysis report and Figure 10 illustrates a typical plot of voltages across customer nodes from a for a Quasi-Dynamic analysis. The report details the maximum and minimum voltages seen at individual nodes through the duration of the simulation.

Quasi-Dynamic Simulation Report: Voltage Ranges

Study Case: Study Case
Time Range: from 2018.03.18 00:00:00 to 2018.03.18 23:30:00

Max. voltage 1.10 [p.u.]
Min. voltage 0.990 [p.u.]
Start Time 2018.03.18 00:00:00 [Y.m.d H:M:S]
End Time 2018.03.18 23:30:00 [Y.m.d H:M:S]

	Terminal	Branch, Substation or Site	Voltage Max. [p.u.]	Time Point Max	Voltage Min. [p.u.]	Time Point Min
1	TL-27		1.100	2018.03.18 13:30:00	1.072	2018.03.18 19:30:00
2	T4-7		1.100	2018.03.18 13:30:00	1.072	2018.03.18 19:30:00
3	001		1.087	2018.03.18 04:00:00	1.086	2018.03.18 13:30:00
4	T4-6		1.100	2018.03.18 13:30:00	1.072	2018.03.18 19:30:00
5	T4-8		1.099	2018.03.18 13:30:00	1.073	2018.03.18 19:30:00
6	T4-5		1.098	2018.03.18 13:30:00	1.073	2018.03.18 19:30:00
7	TL-22		1.096	2018.03.18 13:30:00	1.074	2018.03.18 19:30:00
8	T3-10		1.096	2018.03.18 13:30:00	1.074	2018.03.18 19:30:00
9	T4-3		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00
10	TL-20		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00
11	TL-13		1.095	2018.03.18 13:30:00	1.078	2018.03.18 19:30:00
12	TL-26		1.100	2018.03.18 13:30:00	1.072	2018.03.18 19:30:00
13	TL-25		1.099	2018.03.18 13:30:00	1.073	2018.03.18 19:30:00
14	TL-24		1.098	2018.03.18 13:30:00	1.073	2018.03.18 19:30:00
15	TL-23		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00
16	T3-9		1.096	2018.03.18 13:30:00	1.074	2018.03.18 19:30:00
17	TL-21		1.096	2018.03.18 13:30:00	1.074	2018.03.18 19:30:00
18	T3-8		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00
19	TL-15		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00
20	TL-19		1.096	2018.03.18 13:30:00	1.075	2018.03.18 19:30:00

Ln 1 | 65 Line(s) of 65 | 1 Line(s) selected

Figure 9 Quasi-Dynamic analysis report

The plot provides a visual indication of the voltage profile over the simulation period. The nodes, time of the day during which the violation occurs are clearly highlighted.

The plot consists of the per unit voltage profile of the selected nodes. In this analysis, all the nodes are monitored to ensure that voltage violation on any part of the network is captured through this analysis.

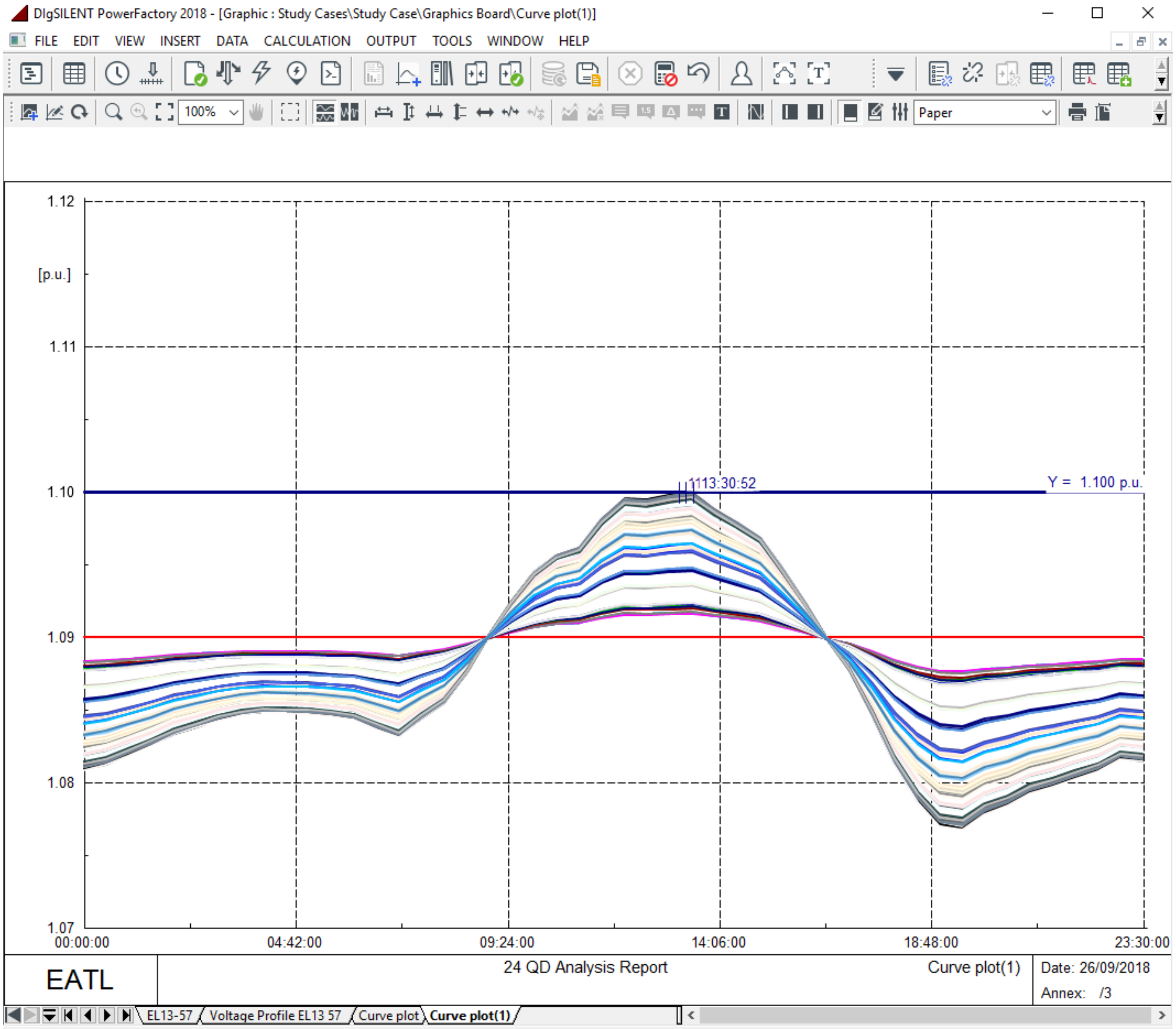


Figure 10 Output plot obtained from the Quasi Dynamic analysis

The report obtained can be exported to a suitable manageable format (e.g. CSV file). The parameters to be included in this report are user-defined. Therefore, the user can select the desired nodes and branches that need to be monitored. For this analysis voltages/power flows at all nodes/individual branches were monitored.

The results obtained for these simulations form the input to the Transform Model® and are therefore summarised into the format such that the data can be directly imported into the Transform Model®. Table 1 shows the format of results obtained from the network analysis using Power Factory. The results include the total reverse power following through the main transformer at the verge of network voltage exceedance, the location(s) of the network breakage, time of day. The total installed capacity of PV generation that caused the voltage exceedance and the allocated load at the time are also noted.

The output of this analysis is tabulated as shown in Table 1.

Table 1 Summary of Quasi Dynamic analysis of LV and SWER networks

Network Group	Circuit ID	Installed PV to Cause Voltage Exceedance (kW)	Reverse Power flow to cause Voltage Exceedance (kW)	Maximum loading (kW)	voltage at main Busbar (pu)
Med OH	AP 344D-15	69.6	30.2	291	1.091
Majority Commercial	AP351B-2034	69.6	58.4	178.33	1.091
Med OH	HH341A-81	153	71.1	548.92	1.09
Med OH	EL13-57	93.1	47.2	339.3	1.091
Med OH	HH177F-253	77.4	36.1	217.41	1.091
New UG	SM126A-159	22.4	15.91	156.55	1.094
New UG	HH121B-TC46352	108.8	77.07	424.56	1.092
New UG	HH409F-29068	98.9	58.6	389.48	1.091
New UG	HH496C-26079	94.5	52.46	373.16	1.092
New UG	AP125B-15350	117.5	73.3	322.78	1.091
Majority Commercial	AP529E-30156	84	61.5	165.55	1.091
Old UG	EL14-TC54743	72	26.9	199.69	1.09
Large OH	ME427E-34	91.2	46.2		1.09
Old UG	EL01Q-TC39683	60	26.9		1.089
	ME116C-19**	112	68.8		1.09
Large OH	HH102B-38**	126	60.4		1.088
Med OH	AP149H**	74.4	29.4		1.088
	HH121E-269	51.3	33.6		1.088
Rural	R01-1 (7/14 cable)	2.2	1.2		1.092
	R01-1 (6/1/3.75 Al)	2.4	1.4		1.093
Rural	ST51-24 (7/14 cable)	10	6.2		1.094
	ST51-24 (6/1/3.75 Al)	12.4	8.3		1.094
Rural	LM41-9 (7/14 cable)	41.6	29.5		1.093
	LM41-9 (6/1/3.75 Al)	58.5	46.5		1.093
SWER	GU-37 Cookes Hill	127.6	47.5		1.094
SWER	MTB-82 Bremer	182.4	42.3		1.092
SWER	M-23 Rockleigh Mitigation	211.2	16.7		1.09

** load at power factor of 0.98 lagging (consuming VAR) and PV at unity power factor

Table 2 Summary of Quasi Dynamic analysis results of 11kV networks

Network Group	Circuit ID	Installed PV to Cause Voltage Exceedance (MW)	Reverse Power flow to cause Voltage Exceedance (MW)	Maximum loading (MW)
Urban Fringe	MV62	2.25	1.53	10.23
Urban OH	HH386C	4.9	4.39	6.81
Urban Mix	NL11P	4	2.6	9.25
Rural Sparse	MB81	1.56	0.48	3.49
Rural Dense	SA520D	3.6	2.7	4.36
Urban UG	MV33	0.8	0.25	

2.3 Impact of Reactive power injection by PV Inverters

The impact of reactive power injection by PV Inverters was analysed in a series of sensitivity studies. Technical Standard- TS 129/4.3[4] requires inverter connected PV generation on the SAPN network to operate in a desired 'Power Quality Response Mode'. This mode sets out the Volt/VAR characteristics of the connected generation such that PV generator (inverter) is consuming higher reactive power (VARs) as the network voltage increases in order to ensure improved power quality.

For this study the operating power factor for each voltage range was calculated based on the Volt/VAR characteristics outlined by TS129/4.3. The power factors of the PV inverters used to simulate the droop characteristic of the Power Quality Response Modes is as shown in Table 3. This effectively simulates the desired droop characteristic by ensuring the PV is consuming higher VAR as the network voltage increases. Several iterations of load flow studies were performed on the network until the limit whilst correcting the power factor of PV generation during each iteration based on the voltage levels of the network during the previous iteration. The maximum allowable capacity of PV generation that can be installed on the network in the presence of the inverter Volt/VAR characteristic is thus obtained.

Table 3 Power factors of the PV inverters

Node voltage range (pu)	Power factor of PV Inverters
1.087 to 1.9	0.965 (Consuming VAR)
1.091 to 1.095	0.936 (Consuming VAR)
1.0951 to 1.098	0.918 (Consuming VAR)
1.0981 to 1.1	0.897 (Consuming VAR)

In addition to the droop characteristic, a number of simulations were then carried out with PV generation having fixed power factors ranging from 0.92 (lagging) to unity. The available capacity of PV with the droop characteristic versus the capacities achieved with fixed power factors was compared for three different networks groups. Based on the comparison for the three network groups (a mixture of new and old underground and overhead networks) a fixed power factor of 0.93 lagging (consuming VAR) was found to be most comparable to capacity achieved with the droop characteristics. This approximation ensured that the capacity of PV generation that was used in the Transform Model accounted for the Volt/VAR characteristics outlined by TS129/4.3.

2.4 Annual Analysis of LV datasets

In addition to 24-hour analysis, an annual study was carried in order to determine what proportion of time voltage exceedances occurred. A Quasi Dynamic analysis was carried out for the entire year using hourly load and generation profiles. One of the inputs received from SAPN included the half hourly details of load and PV generation across the year to facilitate this analysis.

The hourly loads and the generation traces were normalised by the maximum load and PV generation such that its values ranged from 0 to 1. Similar to the 24-hour analysis the profile values were used as a scaling factor for the respective hour during the simulation. For example, a value of 0.4 on the profile curve corresponds to the load operated at 40% of its rated capacity and a value of 1 corresponds to the load operating at its 100% rated capacity load. A total of 8760 hourly data were used for the annual analysis. The annual analysis was performed for six LV networks (these included 'New UG', 'Med OH' and 'Large OH' types). Each network was analysed at 0,1,2,3,4 and 5kW of PV generation. The output of this analysis informed the Transform Model what proportion of time voltage exceedances occurred over the duration of a year.

[4] TS129 Technical connection requirements for small inverter energy systems (Capacity ≤30kW). Available at: https://www.sapowernetworks.com.au/public/download.jsp?id=67909

2.5 HV Voltage Profile set in LV voltage

An analysis was carried out to investigate the impact of voltage rise from the 11 kV networks on the LV networks due to adjacent LV networks having high PV penetration. In order to achieve this, the half hourly phase voltages and currents for candidate LV network (large overhead network) were used, that was included by SAPN in one of the input data sets. This data was then converted to hourly data for this analysis by averaging the two half hourly data points.

Using this hourly data, the voltage at the HV side of the 11 kV/400 V transformer was calculated by including the voltage drop across the transformer (using the transformer details provided by SAPN; i.e. capacity, impedance etc). The terminal voltage at the HV side was calculated in per unit for individual hourly interval thus generating a source voltage profile.

This HV voltage profile obtained was then introduced into the annual Quasi Dynamic analysis of the candidate LV network. The annual load and PV generation profiles used for this analysis were same as the one used for the other Annual Quasi Dynamic analysis, as described in section 2.4. The network was analysed at 0,1,2,3,4 and 5kW of PV generation. Based on the results from this analysis, the allowable voltage rise on the representative feeders within the Transform Model® was refined and the allowable voltage rise on urban networks, for example, was reduced to reflect the impact of the voltage profile on the 11kV feeder.

2.6 Random Allocation of PV locations

A study was carried out to examine the effect of PV being distributed randomly on LV networks upon the voltage levels on the network. This study was carried out on a candidate network (large overhead network) on which a total of 91kW (17x5 kW + 1x6 KW) of PV at unity power factor was randomly allocated on 18 of the 48 nodes. The total PV capacity was identical to the capacity of PV allowable with uniform allocation.

The simulation was repeated ten times with the PV being allocated on 18 nodes randomly during each iteration. The maximum terminal voltage was observed at different locations and phase for each iteration, however the variance observed with random and uniform allocation were negligible with values ranging between 1.097 to 1.103 pu.

This demonstrated that the random allocation of PV to customer nodes within any given representative network did not have a material impact on the calculated results, and hence it was not necessary to consider multiple version soft h same feeder where different customers installed PV.

2.7 Solution Effectiveness

A number of network interventions were selected to be implemented on the modelled network to estimate the amount of capacity which they create. This uplift in capacity would then be used in the Transform Model® during the cost-benefit analysis.

The analysis described in section 2.2 is repeated on individual networks with the inclusion of the below mentioned network solutions. The analysis results show the amount of additional headroom created by each of these solutions. The summary of the results is shown in Table 4 and Table 5. The additional capacity unlocked is then used within the Transform Model® which incorporated the financial aspects of these individual solutions.

The solutions implemented into networks in the Power Factory models include:

Cable overlay
In this approach, the cable which exceeds the thermal limit is replaced with a cable of suitable higher rating.

Uprate Transformer
This solution increased the transformer size to a larger standard size, increasing the rating by at least 100% (for example a 200kVA to 500kVA transformer).

Infill Transformer
This approach was instigated in instances of feeders with voltage problems. A new transformer was placed midway down a feeder experiencing voltage problems. This approach adopted the rule which would not add another transformer to a feeder that has already had an infill transformer added.

Figure 11 shows the implementation of an infill transformer. Suitable normally open points (NOPs) are introduced to ensure better load sharing. The positioning of NOPs is typically determined using the result of the previous iteration of the Quasi-Dynamic analysis and are largely intuitive.

The location selected for the infill transformers was independently checked by SAPN network design staff who concurred that the positioning of the transformers was appropriate to resolve the issues encountered.

Split Feeder
This approach ran a new feeder from the source transformer to a midway point on each large outgoing feeder using the same conductor type as current network. The positioning of the split was determined using the result of the Quasi-Dynamic analysis before the solution was implemented.

Rebalance Phases
Change phasing of customers so phases are balanced. Rearrange phasing of loads and verify if there are any improvements in the PV hosting capacity.

Incorporating STATCOM
This approach sought to mitigate voltage problems without widescale network re-design. It assumes the installation of a static reactive compensator (STATCOM). A STATCOM is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. It is connected to the end of a long feeder which is expecting to experience an overvoltage.

A bespoke STATCOM model, operating in Vdc-Q mode was used for the simulation. This mode ensures a fixed (user-defined) amount of reactive power (Q) is absorbed/supplied by the STATCOM whilst maintain a stable DC supply voltage at (V_{dc}). Table 5Figure 13 shows a candidate network where the STATCOM was employed at the end of the feeder.

Table 4 **Solution effectiveness**

Network Group	Circuit ID	Solution implementation	Installed PV to Cause Voltage Exceedance (kW)	Reverse Power flow to cause Voltage Exceedance (kW)	voltage at main Busbar (pu)
Large OH	ME427E-34	Base Case	91.2	46.2	1.092
		Uprate Transformer (500kVA)	110.4	64.65	1.092
		Infill Transformer	105.6	59.9	1.093
		Split Feeder	144	97.97	1.093
		Rebalance Phases	105.6	54.58	1.092
Med OH	EL13-57	Base Case	93.1	47.2	1.092
		Uprate Transformer (500kVA)	93.1	51.23	1.091
		Infill Transformer	122.5	80.63	1.093
		Split Feeder	88.2	46.33	1.092
		Rebalance Phases	88.2	45.8	1.093
Med OH	HH177F	Base Case	77.4	36.1	1.091
		Uprate Transformer (500kVA)	73.1	33.45	1.091
		Infill Transformer	94.6	54.66	1.094
		Split Feeder	73.1	31.35	1.094
		Rebalance Phases	network balanced		
New UG	AP125B-15350	Base Case	117.5	73.73	1.092
		Uprate Transformer (500kVA)	108.1	63.5	1.092
		Infill Transformer	122.2	77.75	1.092
		Split Feeder	103	58.95	1.092
		Rebalance Phases	94	49.55	1.092
New UG	HH121B-TC46352	Base Case	108.8	77.07	1.092
		Uprate Transformer (500kVA)	98.6	69.7	1.1
		Infill Transformer	153	120.76	1.093
		Split Feeder	136	103.76	1.093
		Rebalance Phases	network balanced		

** load at power factor of 0.98 lagging (consuming VAR) and PV at unity power factor

Table 5 **Solution implementation (STATCOM)**

Network Group	Circuit ID	Reactive power set point (STATOM)	Installed PV** to Cause Voltage Exceedance (kW)	Reverse Powerflow to cause Voltage Exceedance (kW)
Large OH	ME427E-34	10	129.6	84.21
		20	148.8	103.42
		50	225.6	176.44
Rural	R01-1 (7/14 cable)	5	4.5	3.67
		10	7	5.91
Rural	R01-1 (6/1/3.75 Al)	5	5	4.19
		10	8.7	7.37
New UG	HH121B	10	115.6	83.36
		20	129.2	96.96
		50	166.6	132.54

** at Fixed power factor of 0.98 lagging (consuming VAR)

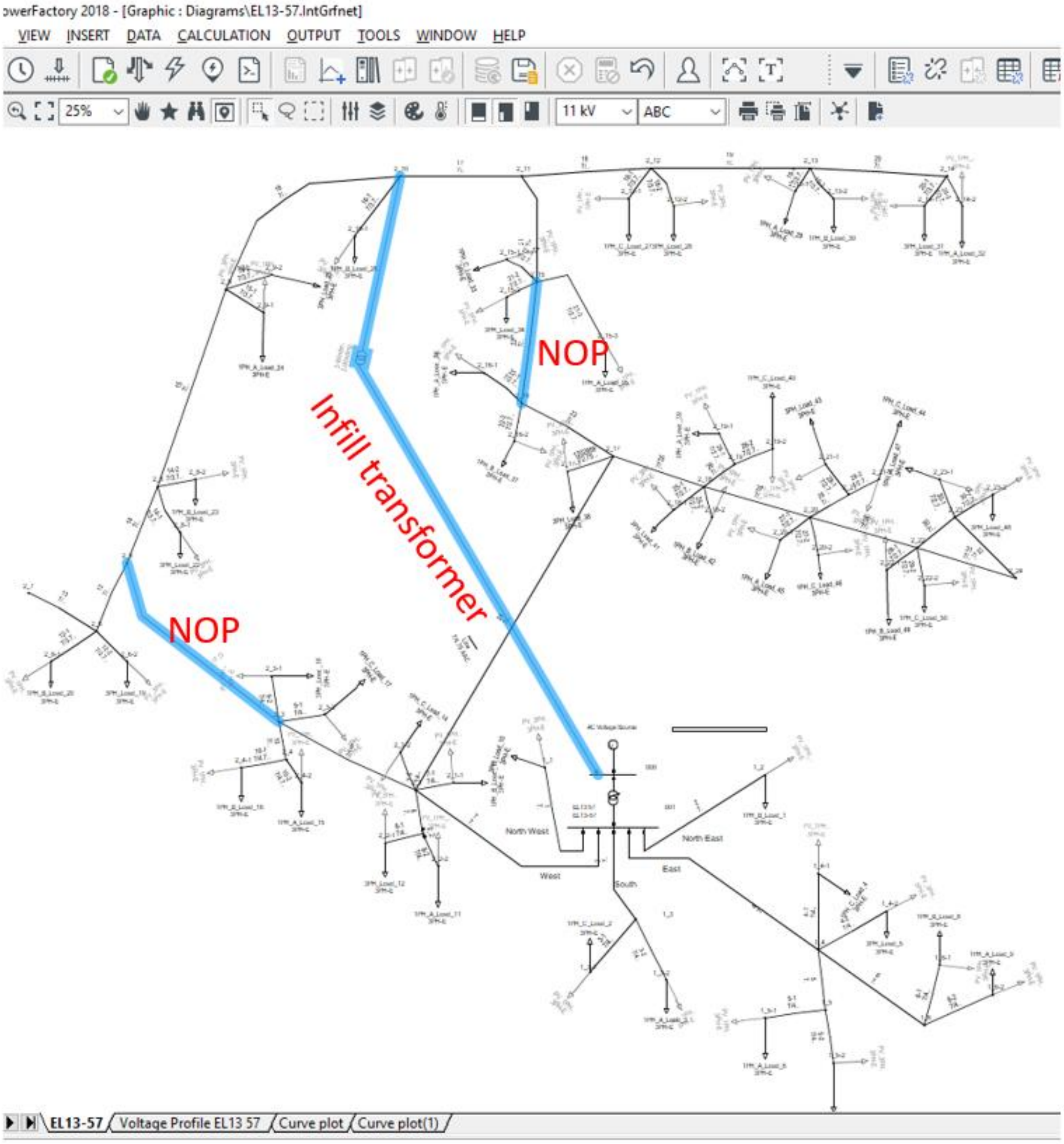


Figure 11 **Implementation of an infill transformer**

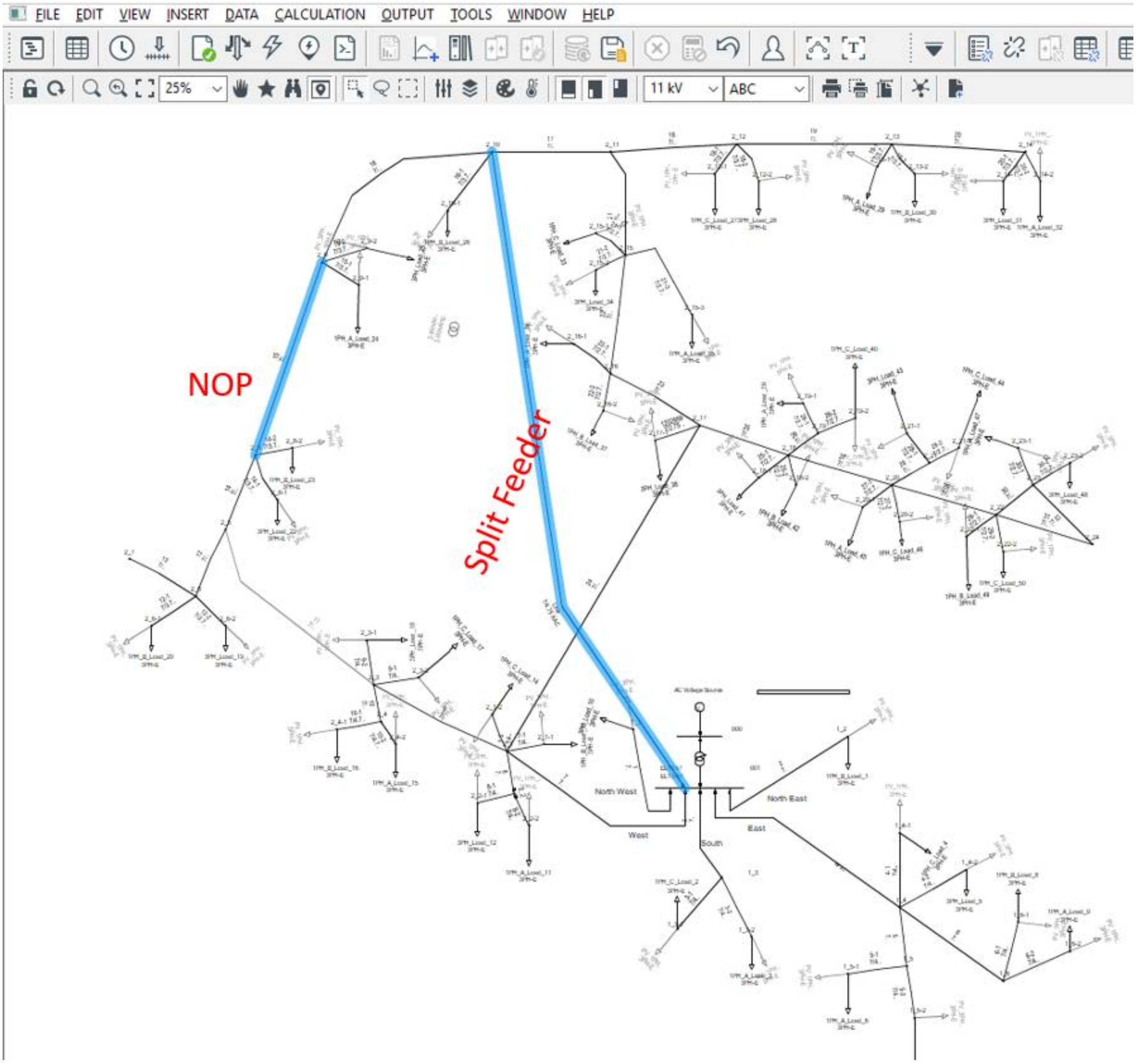


Figure 12 Implementation of a Split feeder

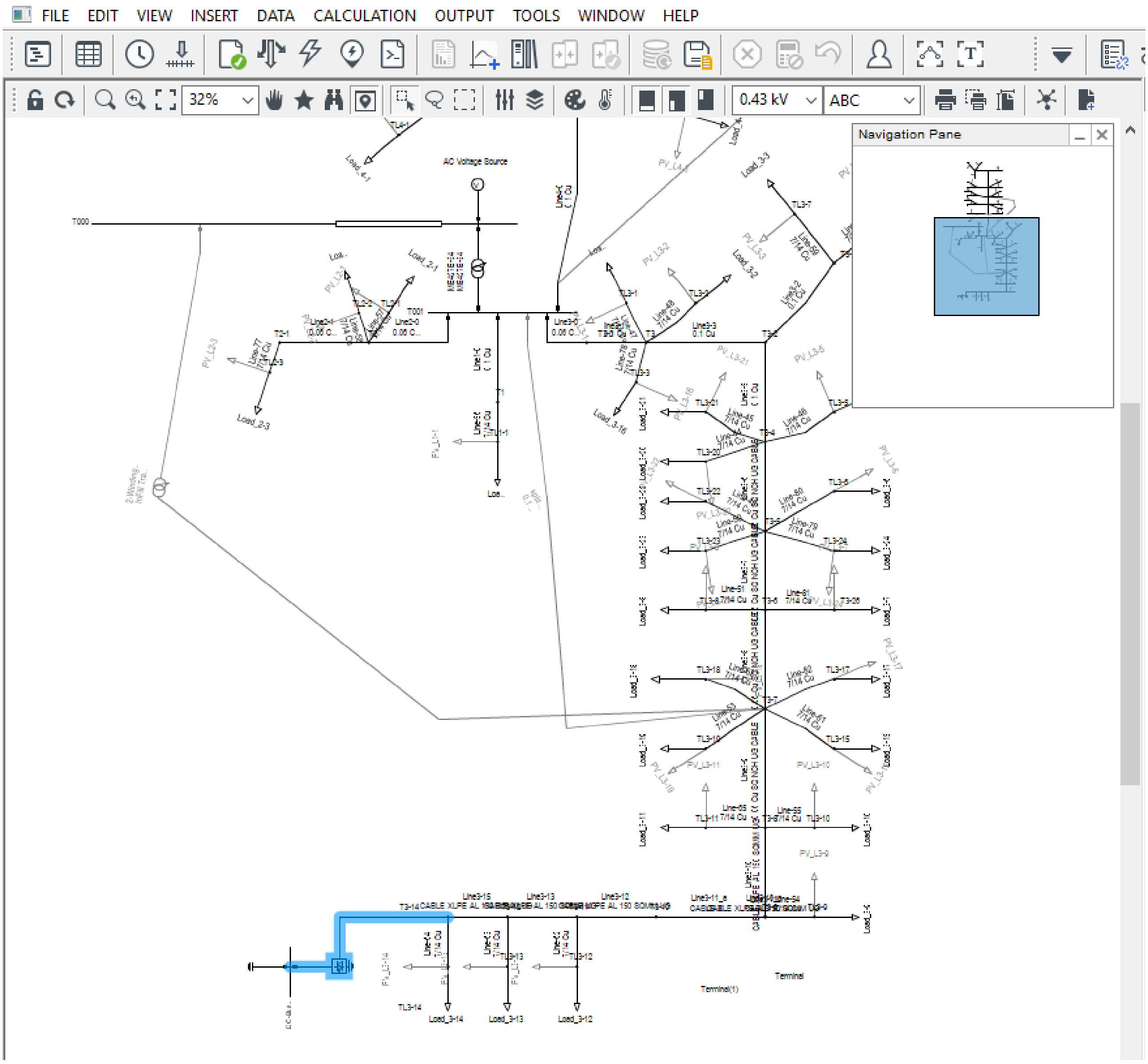


Figure 13 Implementation of a STATCOM

3. Conclusions

For this study, a total of 21 unique Low Voltage (LV) and 6 unique 11 kV high voltage (HV) SAPN distribution networks were modelled using DIgSILENT Power Factory. The Quasi-Dynamic analysis was studied for a period of 24 hours (and 365 days for select cases). The study determined the maximum headroom available on the distribution to accommodate Distributed Energy Resources (DER). The network capacity limits were defined before the occurrence of a voltage violation on the network. Furthermore, the thermal limits of individual networks were also determined.

The results obtained from this detailed analysis were formatted to be suitable the Transform Model. The outputs from the modelling conducted within Transform were then used to inform the development of the LV Management Strategy for SAPN. By taking the physical limits of the network from this work, exploring the likely number of instances when these limits would be breached and the cost of avoiding these breaches using Transform, it was possible to ultimately arrive at the most cost-effective LV Management Strategy that would deliver value to all of SAPN's customers.

The results of this work and its overall recommendations are described in the LV Management Strategy document[2].

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