Modelling of Embedded PV Generation in Distribution Networks

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***Abstract*—In recent years the amount of embedded PV generation in distribution networks has increased significantly. Currently, there is no standard approach on how to model the effect of this generation on the network. This paper aims to provide some guidelines on how to model embedded PV generation in distribution networks. A number of approaches are considered the first being a distributed approach to modelling the PV generation with several models located along the LV feeder. Simplification strategies were then identified, with different strategies being more appropriate for different cases. It was identified that for short and medium length feeders with an even distribution of load and PV generation that a single model located in the centre of the feeder would provide acceptable results, while for long feeders a lumped model at the end of the feeder would be more appropriate. The effect of heavier weighting of PV and load at different points on the feeder was also investigated.**

***Index Terms*-- Distributed power generation, Photovoltaic systems, Power distribution, Power system modeling, Solar power generation.**

I. Introduction

With the significant amount of grid-connected photovoltaic (PV) generation currently installed their effect is having a non-trivial midday impact on power networks. Large penetrations of distributed PV generation have an impact on the power system, particularly the areas of voltage variation and power quality. Moreover, the variation in generation output can affect the stability of the power system.

Modelling of embedded PV generation in distribution networks is considered one of the biggest challenges in power systems. Currently there is no standard grid connected PV system model available in the libraries of major simulation packages. At best, some developed models are insufficiently validated. Hence, there is a need to develop and deploy valid and generic power flow and stability models for interconnection studies and verify the model by conducting hardware experiments to ensure their usefulness for power system operators and planners [1, 2]. Power system planners require models of distributed PV generation in order to run simulations on the power network and identify whether it can withstand certain contingency events [3], in other words the development of models is vital to understand the impact that distributed PV generation has on the stability and operation of the grid [4].

Some of the common impacts of embedded solar generation in the power system are voltage fluctuations, increase in power losses, modification of feeder section loadings, reverse power flow, power quality, an increase in short circuit capacity at the point of connection and fault protection malfunctions. Voltage variation is the most recognised impact due to the variation in power output. The degree of voltage rise depends on the configuration of the feeder and the location of the embedded solar systems in the power system [5]. However, the PV system can also contribute to the feeder voltage regulation positively and result in an improved voltage profile [6].

Reverse power flow at section, feeder and substation levels can occur when there is a proliferation of embedded solar generation in power systems. It can negatively alter the protection coordination and the line voltage regulators operation [6]. Since distribution feeders are intended for unidirectional power flows, reverse power flow may change the overcurrent protection coordination in high penetration scenarios [6].

Regarding the modelling of PV generation in distribution networks the authors in [6] consider modelling a single six mile radial feeder. They model the effect of distributed PV generation as negative load. They consider four separate inverter control strategies, compliance with the current IEEE 1547 standard (unity power factor operation), voltage control, maximum reactive power control and power factor control. For the latter three cases the inverter reactive power capability was modelled using Static VAR Devices. They identified that at low penetrations (5%) inverters did not make a significant impact on the feeder's voltage regulation during peak load. For medium level penetration (10%) inverter voltage support could lead to a reduction of the size of up to 40% for voltage support capacitors. For high level penetration (30-50%) PV inverters

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may be able to provide the feeder voltage support and entirely displace voltage support capacitors.

In [7], the effect of PV generation was also considered as a negative load arguing that PVs act more like current sources than voltage sources in the network. He identified cases of voltage rise on long high impedance feeders with high PV penetration and noted that for higher penetrations voltage rise across the network increased. However, he stated that that if 70% of houses have a 1.1 kW system installed, power factor and voltage levels in the distribution network would be acceptable. Another interesting point he raised is that due to inverter anti-islanding protection on over-voltage there may be current swings of up to 140 A through the network and this could affect voltage stability and potentially cause faults.

The authors in [8] used a very different approach when considering the impact of PV on distribution networks. They modelled the demand and the power produced from the PV cells of individual houses for the city of Leicester. Data was modelled every minute. Some of their major findings were that reverse power flow only occurred in 45% of cables for the case of 50% PV. They also identified that reverse power flow through the primary substation was highly unlikely for the case of 50% of homes having PV installations.

II. Modelling Approach

A. MATLAB/Simulink 100 kW Grid Connected PV Average Model

In this research the MATLAB/Simulink average model of a 100 kW grid connected PV array [9] formed the starting point of our research. However, the model required several modifications. These are listed as follows:

1. Changing the default system frequency to 50 Hz
2. The three phase source representing the grid was set to have a three phase short circuit level of 350 MVA instead of 2500 MVA.
3. Pi model lines were replaced with short line modelled (R, X) lines.
4. The substation voltage level was changed from 120 kV to 110 kV
5. The distribution voltage level was changed from 25 kV to 22 kV
6. The voltage level at the point of common coupling of the inverter was changed from 260 V to 415 V.

The changes to voltage levels required the following changes to the transformer turns ratios:

1. The 120 kV/25 kV transformer was changed to 110 kV/22kV
2. The 25 kV/250 V transformer was changed to 22 kV/415 V

B. Other Assumptions

1. The average distance between load, PV generation and 22 kV/ 415 V transformers was set to 300 metres. A similar assumption was made in [10].
2. Power factor of network was 0.9 lagging
3. 50 houses were considered to be connected to each 22 kV/415 V transformer.
4. Each house was assumed to consume 812.5 W based on the winter figure given in [11].
5. Consequently, the base load at each 22 kV/415 V transformer was approximated to be 40 kW and 20 kVAR based on assumptions 2, 3 and 4 of this section.
6. Inverters operate at unity power factor
7. Constant irradiance (1000 W/m^2) was used such that the base power output of a single instance of the inverter model would be 25 kW.
8. AAC conductor (conductor code 54), R=0.1859 Ω/km and X=0.3345 Ω/km was used for all conductors in the network.
9. Only steady state behaviour was considered
10. The effect of voltage regulators, reactive power compensation on the feeder or tap-changing transformers was not considered in the modelling.

Fig. 1 shows a single instance of the model, which includes the PV model, boost converter and inverter.

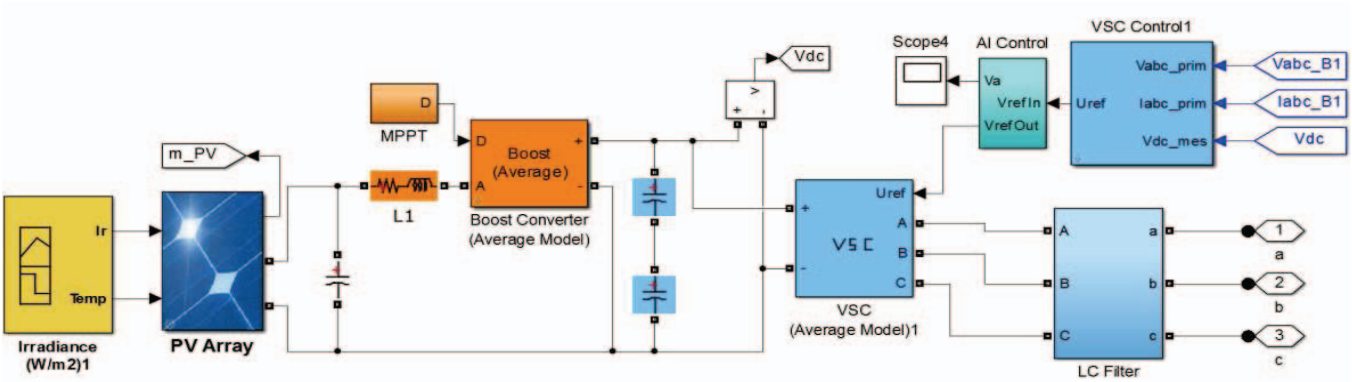

Fig. 1. MATLAB/Simulink grid connected PV inverter average model comprising of a PV array model, boost converter, voltage source converter and LC filter

C. *Setup of the Network*

A single instance of the PV inverter model of Fig. 1 was placed at each point designated as 'PV' in Fig. 2. The base load of 40 kW, 20 kVAR was placed at each point designated as 'L'. This setup is henceforth referred to as 'Even Distribution'.

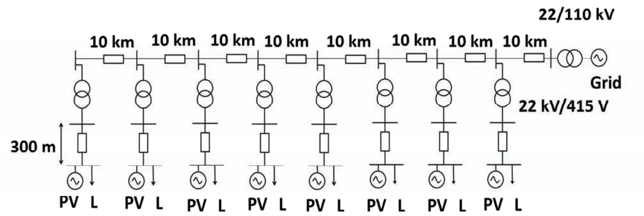

Fig. 2. Distribution feeder used in case studies

III. Results

Six case studies were carried out and the results are shown below. The setup used is shown in Fig. 2 to represent the PV systems and loads on a distribution feeder. Different simplification strategies were employed throughout the results, namely, aggregating the sum of the PV and load in the centre, at the end of the feeder and at the substation.

A. *Case Study 1: Short Distribution Feeder*

The PV systems and loads are evenly distributed on a 40 km distribution feeder. Fig. 3 shows the voltage of the node along the feeder.

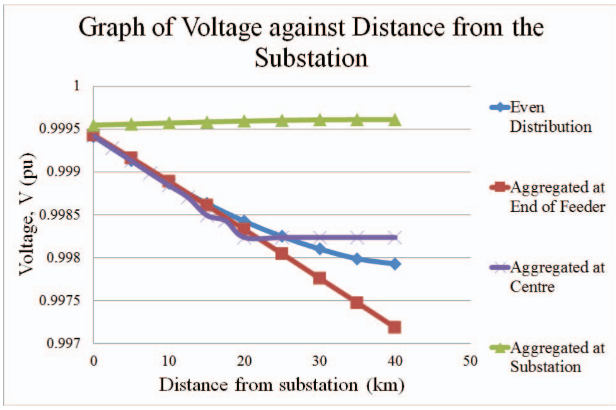

Fig. 3. Voltage profile of the node along a 40 km distribution feeder

It is seen that a single model aggregating all PV systems and loads at the centre is determined to represent the scenario accurately compared to the other methods. Aggregating at the substation has the largest error among all the three methods, due to its inability to represent feeder losses.

B. *Case Study 2: Medium Distribution Feeder*

The PV systems and loads are evenly distributed on a distribution feeder of 80 km. Fig. 4 shows the voltage of the node along the feeder.

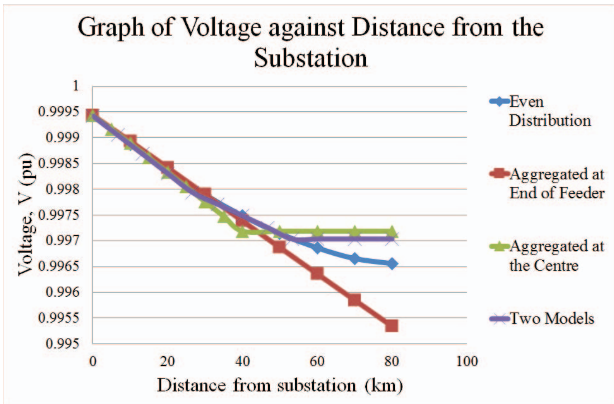

Fig. 4. Voltage profile of the node along an 80 km distribution feeder

It is again seen that a model aggregating all PV systems and loads at the centre is determined to represent the scenario accurately compared to the other methods. Another observation shows that two models aggregated at a quarter and three quarter points along the feeder can represent the scenario more accurately. The one line diagram for this simplification method is shown in Fig. 5.

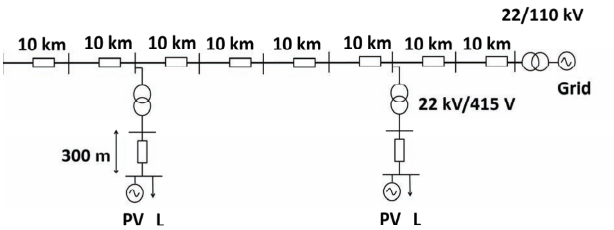

Fig. 5. Detailed two-model simplification with models located at the one-quarter and three-quarter points of the feeder

C. *Case Study 3: Long Distribution Feeder*

The PV systems and loads are evenly distributed on a distribution feeder of 250 km. Fig. 6 shows the voltage of the node along the feeder.

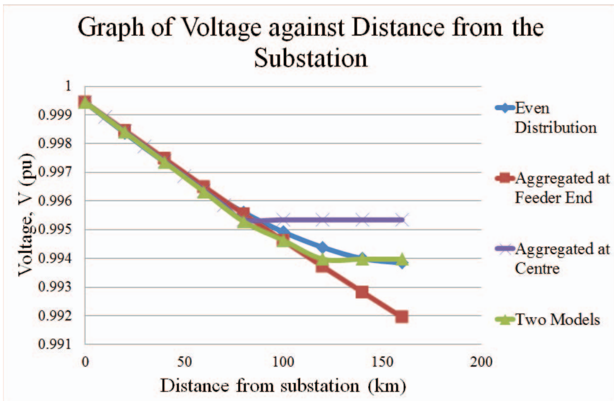

Fig. 6. Voltage profile of the node along a 160 km distribution feeder

A model aggregating all PV systems and loads at the end of feeder is now representing the scenario more accurately compared to a single model in the centre of the feeder, due to the larger line losses. However, having two models located at the quarter and three quarter points along the feeder can represent the scenario even more accurately.

D. *Case Study 4: Heavily Loaded PV Systems and Loads at Feeder End*

The PV systems and load are now heavily loaded at the end of the distribution feeder to investigate the effect of localised concentration of PV and the consequent modelling approach that should be used. The feeder length is kept at 100 km in this case. Fig. 7 shows the voltage profile when the PV systems are heavily loaded at the end of the feeder. As expected, a model aggregating the PV and load as a single model at the end of feeder represents the situation more accurately compared to a single centre aggregated model.

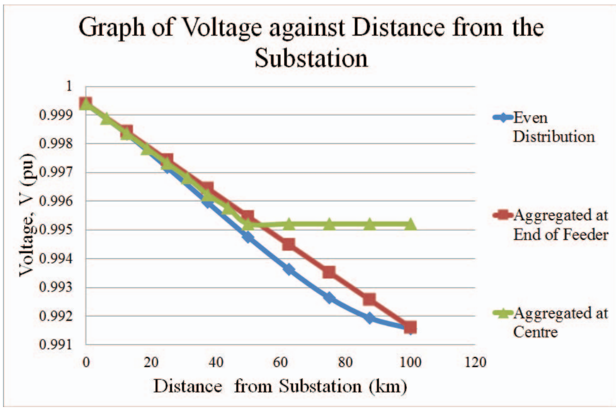

Fig. 7. Voltage profile for PV systems heavily loaded at the end of the feeder

E. *Case Study 5: Heavily Loaded PV Systems and Loads at Substation*

The PV systems and load are now heavily loaded at the substation to investigate the effect of loadings on the modelling at distribution level. Similarly, the feeder length is kept at 100 km. Fig. 8 shows the voltage profile when the PV systems are heavily loaded at the substation. It is now seen that an aggregated model at the substation represents the voltage profile more accurately than a centre or end of feeder aggregation approach.

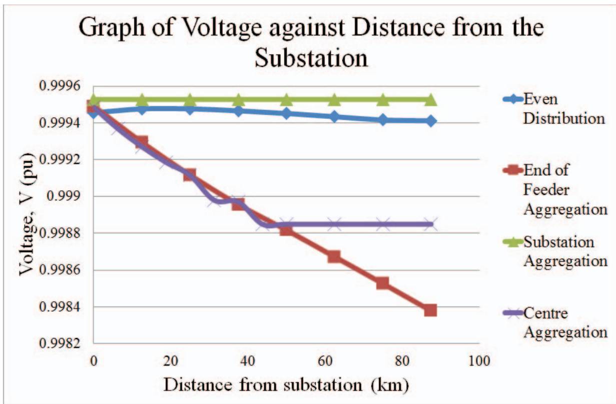

Fig. 8. Voltage profile for PV systems heavily loaded at substation

F. *Case Study 6: Heavily Loaded PV Systems and Loads at Centre of the Feeder*

The PV systems and load are now heavily loaded at the centre of the distribution feeder to investigate the effect of this type of localised loading on the modelling of PV generation at the distribution level. The feeder length is kept at 100 km in this case.

Fig. 9 shows the voltage profile when the PV systems are heavily loaded at the centre of the feeder. As expected, a model aggregating at the centre of the feeder is a more accurate simplification than when an end of feeder aggregation approach is used.

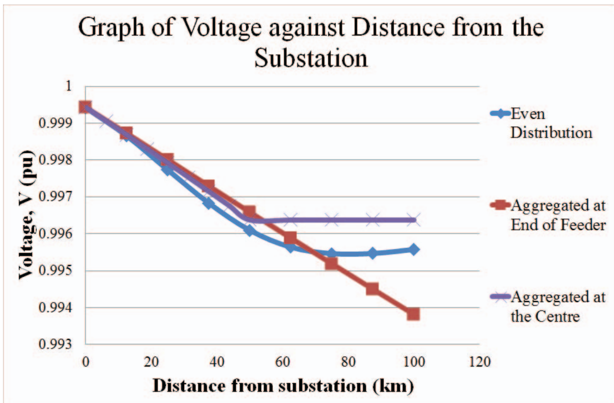

Fig. 9. Voltage profile for PV systems heavily loaded in the centre of the feeder

IV. MODELLING RECCOMENDATIONS

The recommendations for the simplification strategy to be used for the modelling distributed PV generation can be summarised in the following steps:

Step 1: Determine whether the PV and load is distributed evenly along the feeder.
If it is distributed evenly go to Step 2.
If it is not go to Step 6.

Step 2: Determine the line length range. If the lines are less than 40 km (considering the impedance of AAC conductor (conductor code 54), R=0.1859 Ω/km and X=0.3345 Ω/km) go to Step 3.
If the line length is in the range of 40-160 km go to Step 4
If the line length is greater than 160 km go to Step 5

Step 3: Aggregate the PV and load as a single model (equal to the sum of the PV generation) in the centre of the feeder. This concludes the modelling simplification for this case.

Step 4: Determine whether a simple or detailed representation is required. If a simple representation is required aggregate the PV and load as a single model in the centre of the feeder. If a detailed model is required, use two PV and load models located at the ¼ and ¾ points along the feeder. This concludes the modelling simplification for this case.

Step 5: Determine whether a simple or detailed representation is required. If a simple representation is sufficient aggregate the PV and load as a single model at the end of the feeder. If a detailed model is required use two PV and load models located at the ¼ and ¾ points along the feeder. This concludes the modelling simplification for this case.

Step 6: Determine where the PV and load is most heavily concentrated.
If it is near the end of the feeder go to Step 7.
If it is near the substation go to Step 8.
If it is at another point along the feeder go to Step 9.

Step 7: Aggregate the PV generation as a single model at the end of the feeder.

Step 8: Aggregate the PV as a single model at the substation

Step 9: Aggregate the PV as a single model at the average point of PV generation along the feeder.

V. CONCLUSION

The proliferation of embedded solar generation in power systems will have significant impacts and interconnection studies have to be conducted to ensure power system stability and reliability. Based on the modelling at distribution level, it is seen that the integration of PV systems will cause voltage variations depending on the power generated by the PV systems. The integration of embedded solar generation is found to result in an improved voltage profile at distribution level in the case studies conducted.

Modelling simplification strategies are provided to distribution engineers in system planning. A single model aggregated at the centre of the feeder is recommended for short and medium feeders whereas a model at the end of the feeder is recommended for long distribution feeder. Two models can be used to increase the accuracy of the modelling by placing each model at the one quarter and three quarter points on the distribution feeder.

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