Analysis and Control of DG Influence on Voltage Profile in Distribution Network

Mirza Šarić[1](✉), Jasna Hivziefendić[2], and Lejla Bandić[2]

[1] Public Enterprise Elektroprivreda of Bosnia and Herzegovina, Mostar, Bosnia and Herzegovina
m.saric@epbih.ba

[2] International Burch University, Sarajevo, Bosnia and Herzegovina
{jasna.hivziefendic,lejla.bandic}@ibu.edu.ba

Abstract. Power generated by the Distributed Generator (DG) must satisfy high quality standards and ensure compatibility with network operation and customer supply requirements. The power system needs to maintain stable operating conditions and continue to meet customer load demand for the entire range of generations. This paper presents results of investigations related to reactive power and voltage control requirements for distribution network with DG. The load flow analysis is performed for minimum and maximum load levels for no generation case and range of generations up to the DG capacity for all lines in service and following single line outages. Voltage developments in the network are recorded and discussed in terms of DG reactive power requirements. Results indicate that the variable power factor operation of larger DG units must be employed in order to ensure static voltage stability and limit voltage fluctuations. This paper makes a contribution to the electrical engineering practice in terms of providing additional evidence of DG influence on static voltage profile developments and control in the practical electrical distribution system. This paper also presents basic analysis for reactive yard design required for voltage control by larger DG units.

1 Introduction

Voltage stability is one of the most fundamental phenomena that must be achieved in order to ensure safe operation of the power system. It is one of the three important categories of the power system stability. The illustration of power stability classification is shown in Fig. 1. Voltage is related to active and reactive power flows in the system. Voltage instability is caused by reactive power imbalance and can be classified as long term instability (load increase⇔ ← load recovery after faults, reactive losses in line ⊣\Γ⟵loss of reactive supply) and short term (caused by the disturbance) [1]. Voltage stability analysis is discussed in [1], using the relation between active power and voltage magnitude in the load node, (U-P or nose curve). Very important characteristic of the voltage stability issue is that phenomena involved are nonlinear [2]. In order to simplify the voltage stability analysis, a number of indicators based on small

M. Hadžikadić and S. Avdaković (eds.), *Advanced Technologies, Systems, and Applications II*, Lecture Notes in Networks and Systems 28,
https://doi.org/10.1007/978-3-319-71321-2_3

signal properties of the system, derived from linearized models are used, such as Voltage Sensitivity Factor, defined as the change in voltage at node as a function of reactive power injection at that node, ΔU/ΔE indicator where U is the bus voltage and E is the controllable voltage value and finally and Q_g/Q_l criterion which relates the load reactive power to the reactive power generated by the synchronous machines [1]. Voltage profile analysis is one of the most important and frequently considered quantities in the DG allocation problem domain. It can be considered as both objective function and as inequality constraint. DG allocation for voltage stability enhancement is a well documented topic and it continues to be a vibrant area of research [3–5]. The same applies to optimal voltage control strategies considering DG [6]. Reference [7] discusses a simplified voltage stability method in distribution system, considering DG. Further, [4] presents a study on combined capacitor and DG allocation for voltage stability improvement while [5] considers voltage improvements, losses and load variability. One of the most fundamental voltage magnitude condition, by which the resulting voltage V_i at all points in the network must be within prescribed limits, is defined by the European norm EN50160. According to this norm, the voltage variations must be within ±10% of nominal voltage, in other words:

$$V_{\min} \leq V_i \leq V_{\max} \tag{1}$$

The existing National Electricity Rules in Bosnia and Herzegovina (BH) do not contain code which strictly specifies power factor (pf) requirements. This means that pf has to be determined based on the network parameters and operational requirements. The auxiliary services are not currently exercises in distribution networks in BH which means that DG cannot bill the reactive energy delivered to the network. However, DGs are regularly billed for the excess reactive power absorbed, which means that design, construction and appropriate operation of shunt reactive power sources might be an interesting option for DG owners.

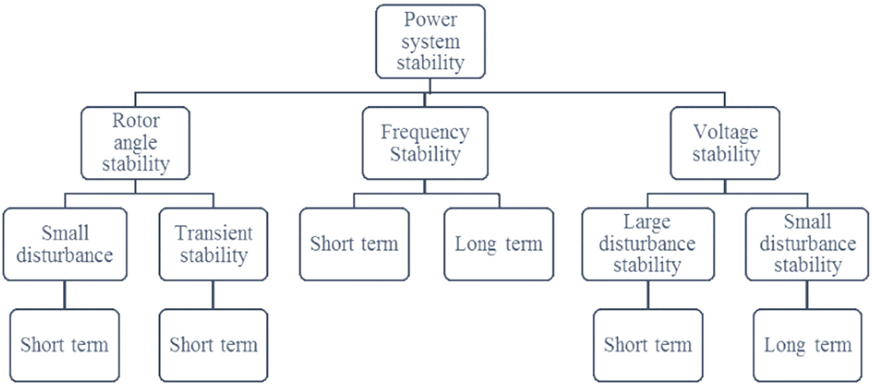

Fig. 1. Schematic representation of fuzzy inference system with three input and one output variable, based on [1]

2 Voltage and Reactive Power Relationship

Voltage profile developments in the power system greatly depend on the amounts of reactive power. This also means that DG can be used to control voltage development in the grid by absorbing or delivering reactive power. It can be expected that during heavy loads voltage will drop and during light load periods voltage will rise. DG can contribute to voltage control by implementing variable pf operation scheme. Figure 2. show a simple illustration of phasor diagram for voltage, current and impedance angle relations and how reactive power might influence it in the case of lagging (a) and leading (b) pf. The most suitable power factor is one that minimizes reactive power requirements while maintaining stable voltage levels throughout the network. One way of improving power factor is by adding shunt capacitors which deliver some reactive power to generators thus making more DG active power available. When capacitors are installed in parallel with the load they improve power factor and reduce load current and voltage drop. This is essential during high loads when costumer demand for reactive power increases. To achieve this, DG should be operated with lagging pf, i.e., DG delivers reactive power. The shunt capacitors improve the stability on the grid during high loads by preventing voltage drops. This is the reason why larger amount of reactive power is switched in during heavy loads when switchable shunt devices are available. The sending end voltage (V_s) which represent the network connection point, can also be reduced by shifting the current phase in front of the receiving end voltage (V_r). In the case of light load when the voltage increase is high, the static voltage increase on the grid is reduced and DG must be operated with leading pf. For this reason, a large portion of shunt devices is switched out of service during light loads, if possible. In conclusion, by manipulating phasors presented in Fig. 2. It is possible to control the voltage at the DG connection point and prevent it from rising too high or dropping too low. In this way, the ratio of active and reactive power is thus determined and assigned to a DG as an operational requirement.

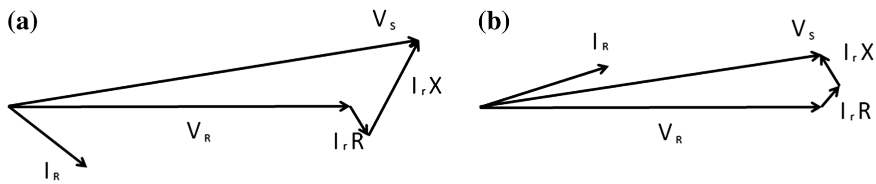

Fig. 2. Phasor diagram of V, I and Z for: **a** lagging pf **b** leading pf

3 Experimental Setup

The single line diagram of the test system is shown in Fig. 3. In total, there are three customer zone substations marked as SUB A, B and C, which are fed by a total of six aluminium conductor lines. L5 and L6 have the highest thermal and current rating and are used to (SUB A, B, C) to the source station. L2 is altered to accommodate DG connection and is divided in L2a and L2b. In SLD, this BB 10 is defined as swing bus and is used as reference point. Transformers are modelled with resistance and reactance of 0.005 and 0.1 p.u. respectively and all transformer MVA ratings are per winding base. At times of low demand, pf generally improves and gets closer to unity. This means that demand for reactive power decreases and some or all capacitors need to be switched off. This is important since reactive power has great influence on voltage development in power system. It therefore needs for to be determined when capacitors will be switched in and out of service. SUB a capacitor banks are VAr controlled and switch on and off automatically based on the amount of reactive load requirements. In fact there is one 6.8 MVAr capacitor bank with step switch resulting in two effective capacitor banks each of 3.4 MVAr. Controller settings result in stack 1 switching on at a feeder load of 2.0 MVAr and switching off at a load of −2.0 MVAr. Stack 2 switches on at a feeder load of 4.0 MVAr and off at a load of 0.0 MVAr. SUB B has two time clock controlled capacitor banks. Capacitor bank no.1 size is 2.5 MVAr and is daily switched on week days. Capacitor bank no.2 has is always on. SUB C does not have a zone substation capacitor bank. However line capacitor banks on the distribution feeders help to keep the power within an acceptable range and they can generally use a range of control modes from fixed (always on) to time clock, temperature controlled or even be VAr controlled.

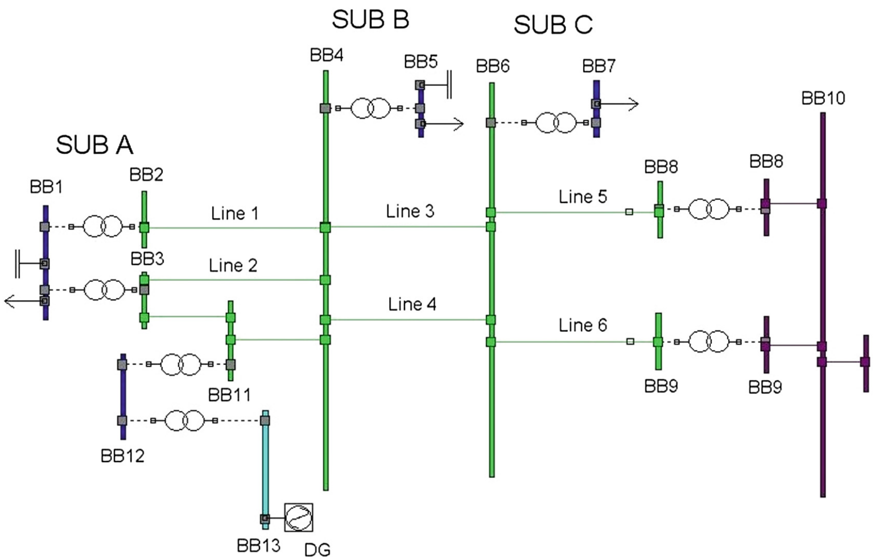

Fig. 3. Single line diagram of the test system

The first case to be analysed is the low load scenario for the unity pf which provides useful insight into system behaviour. At this point V_r and V_s are in phase and by plotting voltage developments against DG active power output, it is possible determine whether voltage is rising or falling and to provide indication in which direction current curve needs to be rotated. Generator's reactive power is limited to zero and in case of additional absorption capacitors banks are added to maintain unity power factor. This arrangement prevents reactive power interchange between grid and generators. The load flow simulations are performed for the various DG power output scenarios ranging from no load scenarios up to the DG rated output power. If the system voltage is determined to be out of the prescribed limits, load flow is continued for the range of non-unity pf scenarios, in order to determine the acceptable pf for each DG output level. Further, the identical analysis is repeated for the worst case single line outage contingency scenario. Finally, the same analysis is repeated for the high system load scenario. The data collected during the analysis using maximum and minimum load situations include the voltage assessment at each of the 13 bus bars of the test power system. Based on Eq. 1. it is necessary to ensure that voltages will be between 0.9 and 1.1 p.u. at all times. It would be desirable to reduce voltage oscillations further during simulations in order to allow for transient developments and voltage rise occurring within DG reticulation system. An extra 0.3 p.u. will be allowed for this and reactive power design at this stage is aimed at limiting maximum voltage at 1.07 p.u. (1.1 – 0.3) and similarly, minimum voltage to 0.93 p.u. The results are presented and discussed in following section.

4 Results and Discussion

This section of the paper presents the results and discussion of the obtained results from the simulations, which were carried out as described in previous sections.

4.1 Low Load Scenario

Figure 4 shows static voltage developments on all 13 buses during low load with all lines in service. It is immediately clear that this is a highly unstable operating in the

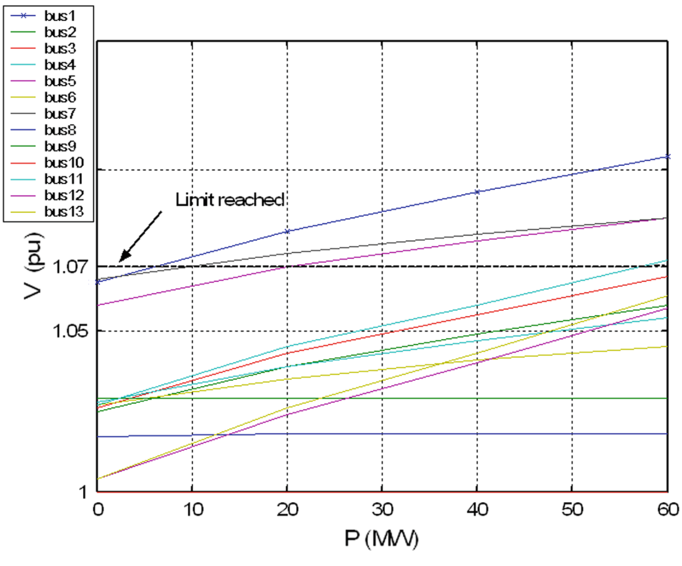

Fig. 4. Voltage Developments for unity pf-low load scenario, all lines in service

case of increased DG output since even relatively small generation output values cause large voltage fluctuations. The voltage needs to be decreased, which means that DG should be operated at a leading power factor.

Further, Fig. 4 also provides another important insight into system behaviour. It could have been assumed that BB11, which represents the point of common coupling would be the point with largest voltage value. However, it can be seen that costumer load buses are more critical. Namely, buses 1, 5 and 7 experience high voltage rises and cause instability. This would cause large disruptions of supply and needs to be avoided. For example, low voltage side at SUB A reaches over 11% of increase in full capacity and this can be even higher in reality. Bus11 is also exceeds 1.07 p.u. at maximum generation capacity. With reference to Fig. 4, voltage can be decreased if generators absorb reactive power and force pf to become leading. This is modelled in load flow software by inserting negative values in the generator Q field. Initial estimate is presented which is then being adjusted until acceptable voltage values are reached for all buses. The main objective of this simulation was to minimize the amount of Q absorbed, thus keeping pf as close to unity as possible while ensuring that minimum margin of voltage stability was reached. Figure 5 presents values of proposed pf (leading) for different values of generation for all lines in service during the low load scenario. This scenario counts for approximately 99% probability to occur during low load.

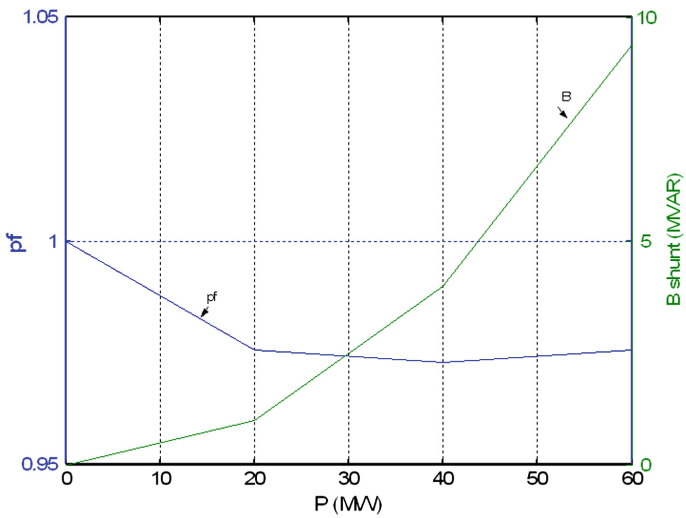

Fig. 5. Pf (Leading) and B shunt values yielding stability for low load all lines in service scenario

This is therefore the recommended mode of operation for normal condition at low load. Figure 5 also shows values of B shunt used in simulation to hold required levels of Q. The pf operational scheme presented in Fig. 5 ensures voltage static stability with minimum margin, thus minimizing the amounts of reactive power. The benefits of this pf analysis are presented in Fig. 6 which demonstrates that the voltage levels are within required limits. Load buses still have highest values, but do not exceed specified limits. It can therefore be concluded that in the case of low load with all lines in service, the system is statically stable when operated with leading pf schemes presented in Fig. 5.

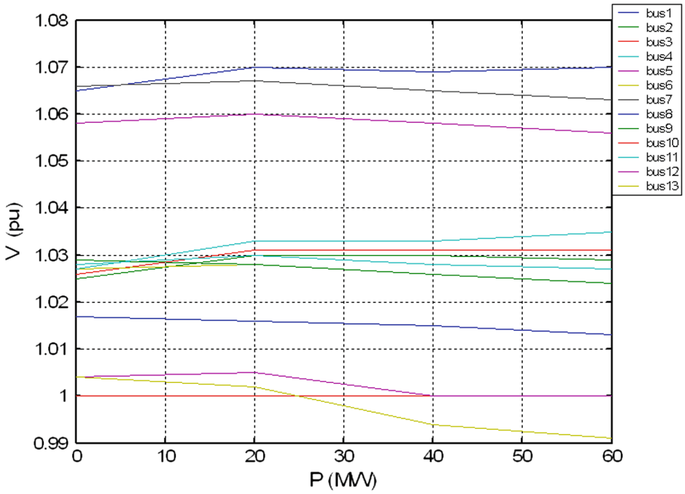

Fig. 6. Voltage developments versus Power for determined pf Value

The contingency conditions, such as single line outage represent an important operational scenario of the power system. It can be expected that for a number of reasons, any line could be out of service for approximately 1% of the times, which represents around 3.5 days a year. During this unwelcome operational scenario, additional steps need to be undertaken in order to avoid load supply interruptions and to protect various components of the power system. In this experiment, simulations are performed once more staring from the unity pf studying every single line outage. The worst case scenario was determined to be following L5 being placed out of service. During this time the highest voltage variations are noted. Figure 7 represents results of this analysis. The voltage at bus 1 for example, rises as high as 1.14 of its nominal p.u. value and this is not acceptable. It is also interesting to observe that voltage exceeds limits on total of 10 nodes throughout the network. This is regarded as the case of worst case disturbance. In order to use DG for voltage control purposes, the approach identical to that used in the previous section is used. The results are presented in Fig. 8. Once again, DG is to be operated with leading pf which means that it needs to absorb reactive power in order to decrease voltage. Values of B shunt are presented on the same graph with pf. Figure 9 shows stabilised voltage developments on all 13 buses for this outage case. Pf varies with level of DG output but voltage remains stable. In particular, pf improves with the increase in DG output. The other lines outage cases display less dramatic voltage increase when compared with L5 outage and DG could be operated with a range of pf defined for the case of L5 outage. However, this is not entirely true in the case of L2a outage. When the unity pf case was presented, it was observed that voltage kept rising with the increase in generation. It was found that at P levels beyond network capacity, voltage slowly starts to drop. In the case of L2a outage, this change of direction occurs before maximum rating has occurred. This is a realistic possibility and needs to be accounted for in the analysis even if it has a low probability to occur. This situation is presented in Fig. 10. At full capacity, 3 points in the network have voltage lower than allowable value. These are buses 5, 12 and 13.

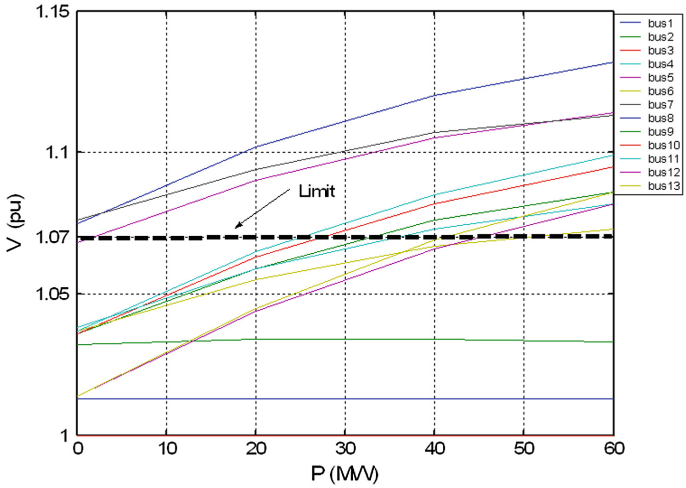

Fig. 7. Voltage versus Power for L5 out of service scenario, low load

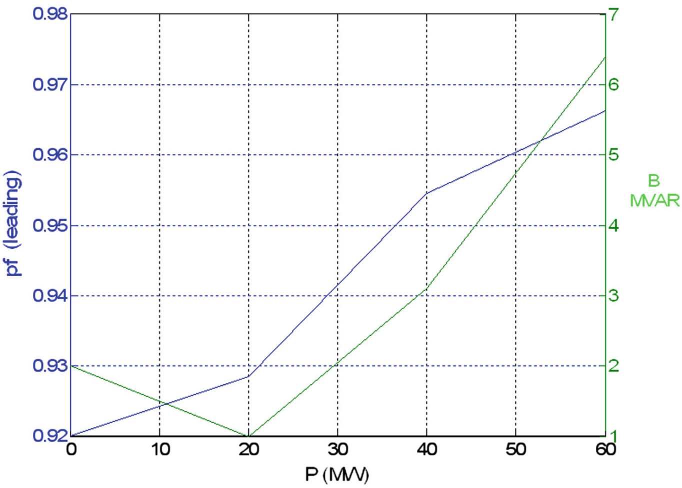

Fig. 8. pf and B Shunt versus DG power output values

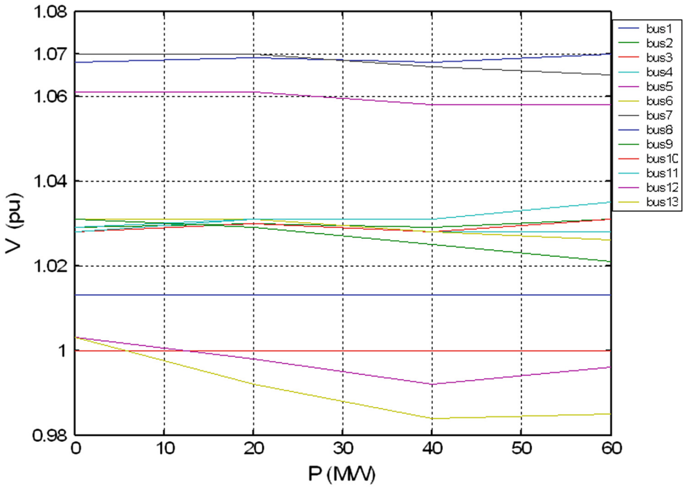

Fig. 9. Voltage developments versus Power for determined pf value

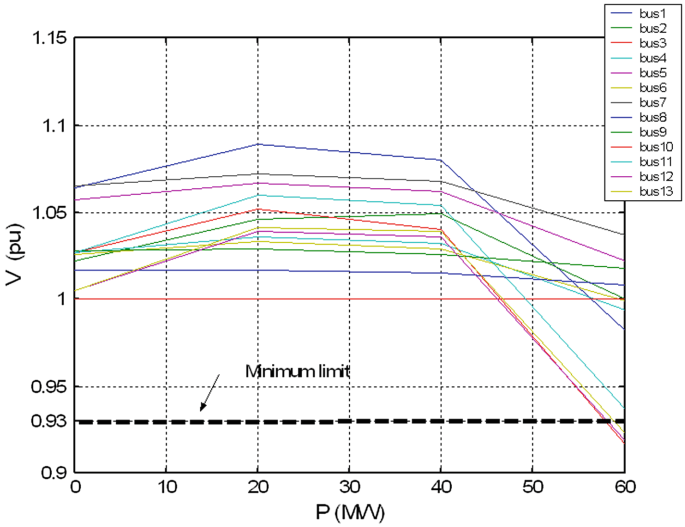

Fig. 10. Voltage versus DG output power for the Case of L2a outage during low load

This instability issue can be resolved by reversing the direction of phasor rotation and making the pf lagging when the voltage starts to drop. In other words, generator stars delivering reactive power which now has the same sign as active power from generator point of view. A summary of these results is presented in Fig. 11. together with values of B shunt used during simulations to maintain DG operation with desired power factor. If DG is operated with the range of power factors presented in Fig. 11, the network voltage will remain stable in the case of L2a outage for entire a range of generation. At this point it can be concluded that system can be operated in a stable and safe way in the case of low load under conditions of voltage control with appropriate values of pf by DG. Finally, it was determined that variable pf is more efficient from both stability and possibly a financial point of view. Finally, the range of variable DF pf was determined, ranging from 0.92 leading to 0.99 lagging. Each pf value is assigned to particular power system operational scenario.

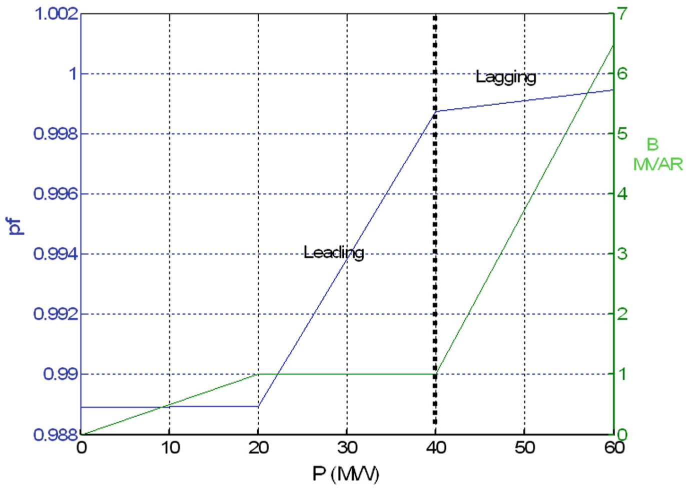

Fig. 11. Pf and B shunt versus P for the Case of L2a out, low load

4.2 High Load Scenario

In the case of high load scenario, the analysis demonstrated that in the case of normal operation, system can be operated with unity pf without compromising voltage values. This is desired result since it might provide financial benefit to the operator. The results of the load flow analysis have confirmed that voltage on all buses remains within stability limits and these results are presented in Fig. 12. Similar to the low load case, the contingency condition following single line outage for the high load scenario was also considered. It was determined that the worst case outage for high load occurs when L6 is placed out of service. In this case, the highest voltage drop is recorded in the network. Figure 13 shows results of the analysis with L6 out of service and it can be observed that there is a sharply and deep voltages drop which amounts to approximately 19%. This is not an acceptable operating condition and requires design of appropriate operational strategy in order to bring the voltage back to allowable limits.

This contingency condition causes voltage on all load buses fall below permitted values. The worst voltage drops are recorded on buses 13 and 12, both having the value of 0.813 p.u. In order to ensure system stability, the voltage throughout the network now need to be increased and this means that DG must be operated at lagging pf. The analysis demonstrated that all other outage cases are proven to be less dramatic, as they all display smaller voltage drops when compared to L6 outage. This means that pf

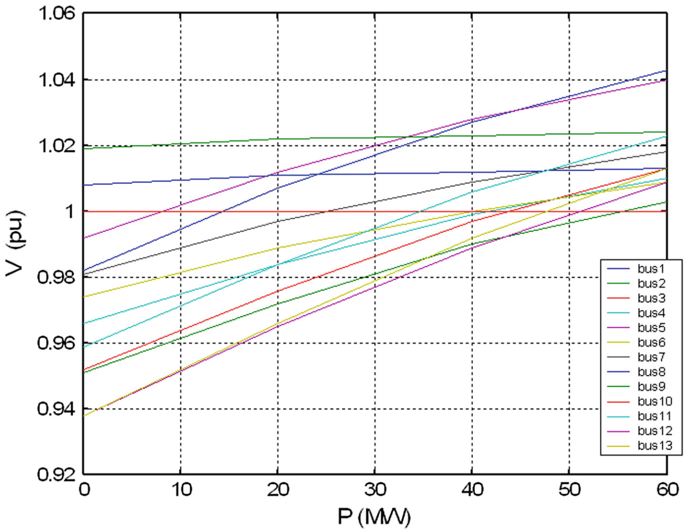

Fig. 12. V versus P for high load normal mode of operation, all line in service

designed in the case of L6 outage will stabilise the voltage in the case of any other single line outage. Figure 14 shows the range of variable pf recommended for running the DG as a function of generation output. B shunt values, used to maintain desired pf in software simulations are also presented. In the case of no generation, system is still unstable and 20 MVAR are needed to keep the voltage up in the prescribed range. Pf at 10 MW generation is 0.67 and it was more practical to assign this value to the case of

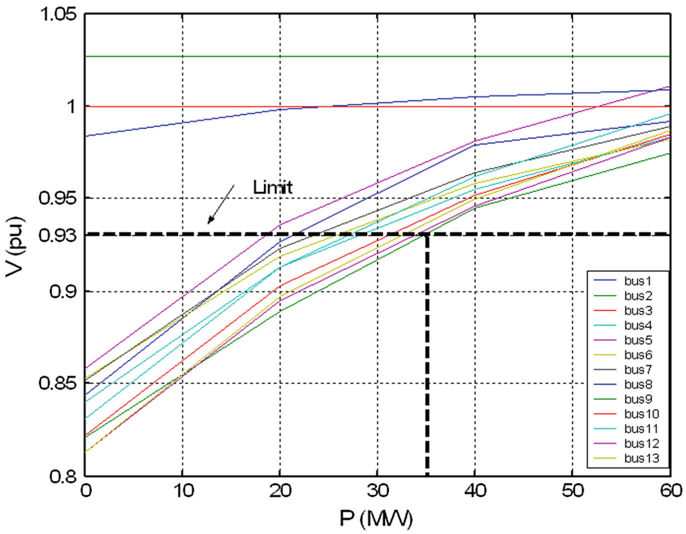

Fig. 13. Voltage developments versus DG power output for L5 out of service, high load

no generation, for the purposes of better illustration. This should not be confused to the actual zero pf DG displays in the case of no generation scenario. Figure 15 shows the final static voltage developments in the case of L6 outage during the high load when generators are operated according to pf defined in Fig. 14.

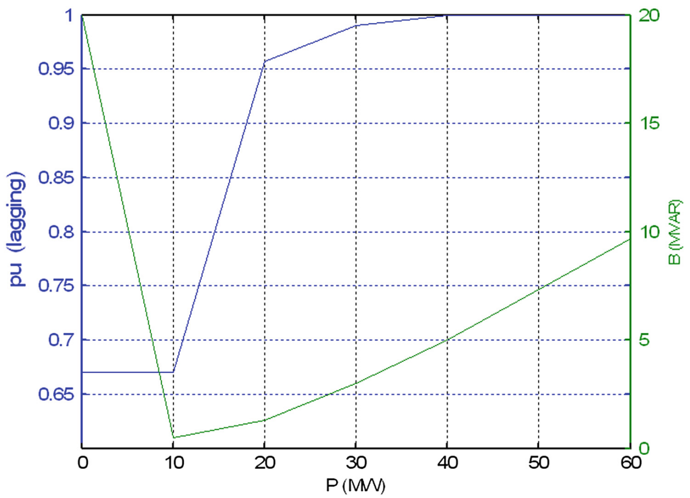

Fig. 14. Pf and required B Shunt values versus DG power output, L2a out of service, low load

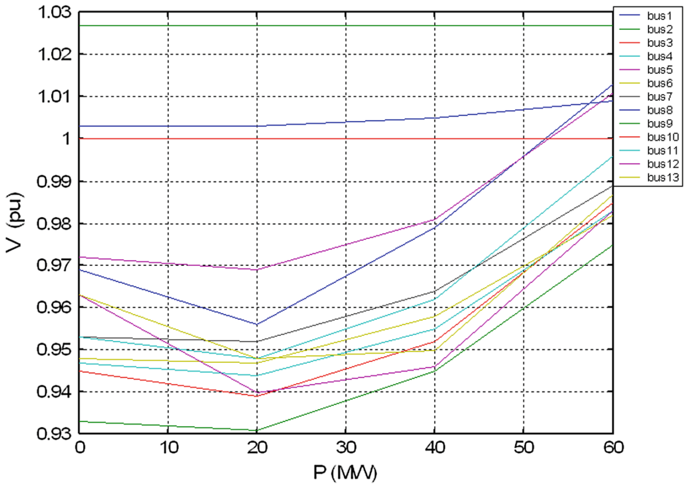

Fig. 15. Schematic representation of fuzzy inference system with three input and one output variable

5 Limitations and Future Work

The investigations presented in this paper present some of the most important aspect so power system analysis during the DG connection pre approval phases. The required parameters that need to be examined at this stage are by no means exhausted and need to be included in comprehensive pre connection approval report. Further, one of the most important future research direction proposed by the authors is practical confirmation of obtained results especially in terms of pf design for various operating conditions. Finally, design and experimental confirmation of dedicated voltage controllers should prove to be an interesting practical implication of research results presented in this paper.

6 Conclusion

This paper presented results of investigations related to voltage variations and reactive power requirement in power distribution system, considering DG. The results were obtained from a series of load flow simulations performed for the various DG power output scenarios ranging from no load scenarios up to the DG rated output power for all lines in service and for the worst case contingency scenario caused by a single line outage. Results indicated that DG connection has significant influence on voltage developments on the network which can be controlled by adoption of the appropriate voltage control strategy by DG operator. However, in deregulated markets, the interest of DG operator might be different from interest of system operator. Results further suggest that for larger DG units, construction of shunt reactive power sources might be necessary. Contingency scenarios such as single line outages require special operational strategies. Finally, important future research directions arising from the results of this paper were suggested.

References

1. Andersson, G.: Modelling and analysis of electric power systems. In: Lecture 227-0526-00, ITET ETH Zurich EEH—Power Systems Laboratory (Sept 2008)
2. Van Cutsem, Vournas, : Voltage Stability of Electric Power Systems, 1st edn. Springer, USA (1998)
3. Moradi, M.H., Abedini, M.: A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems. Int. J. Electr. Power Energy Syst. **34**(1), 66–74 (2012)
4. Pradeepa, H., Ananthapadmanabha, T., Sandhya Rani, D.N., Bandhavya, C.: Optimal allocation of combined DG and capacitor units for voltage stability enhancement. Procedia Technol. **21**, 216–223 (2015)
5. Poornazaryan, B., Karimyan, P., Gharehpetian, G.B., Abedi, Mehrdad: Optimal allocation and sizing of DG units considering voltage stability, losses and load variations. Int. J. Electr. Power Energy Syst. **7**, 42–52 (2016)

6. Castro, J.R., Saad, M., Lefebvre, S., Asber, D., Lenoir, L.: Optimal voltage control in distribution network in the presence of DGs. Int. J. Electr. Power Energy Syst. **78**, 239–247 (2016)
7. Liu, K.Y., Sheng, W., Hu, L., Liu, Y., Meng, X., Jia, D.: Simplified probabilistic voltage stability evaluation considering variable renewable distributed generation in distribution systems. IET Gener. Transm. Distrib. **9**(12), 1464–1473 (2015)