Project title: P1: Control methodologies of distributed generation for enhanced network stability and control – (UQ)
End of year report 2010

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Milestone-5: EOY report includes progress on methodologies and software being developed and any possible publications submitted for FY 2009

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Forward

Milestone 4 report was submitted by the end of December 2009. Milestone 4 was an interim report. However, we decided not to duplicate the content of milestone 4 in this report. Hence milestone 5 should be considered as two parts. Part A is the milestone 4 and Part B continues from milestone 4 report and which is completed in this report as the End of Year 2009-10.

List of publications during 2009 July to 2010 July:

1. Tareq Aziz, T.K. Saha, N. Mithulananthan, "Distributed Generators Placement for Loadability Enhancement Based on Reactive Power Margin," Proceedings of the 9th International Power and Energy Conference IPEC2010, 27 - 29 October 2010, Singapore.
2. Tareq Aziz, T.K. Saha, and N. Mithulananthan, "Identification of the Weakest Bus in a Distribution System with Load Uncertainties Using Reactive Power Margin, Proceedings of the 2010 Australasian Universities Power Engineering Conference, Christchurch, New Zealand, 5-8 December 2010.
3. S. Dahal, N. Mithulananthan, and T. K. Saha, "Investigation of Small Signal Stability of a Renewable Energy Based Electricity Distribution System," IEEE Power and Energy Society General Meeting, 2010, Minneapolis, USA, July 2010.
4. S. Dahal, N. Mithulananthan, T. Saha, " Enhancement of small signal stability of a renewable energy based electricity distribution system using shunt controllers", in proceedings of Australasian Universities Power Engineering Conference (AUPEC 2010), Dec 5 – 8, Christchurch, New Zealand.
5. Tareq Aziz, Sudarshan Dahal, N. Mithulananthan and Tapan K. Saha, "Impact of Widespread Penetrations of Renewable Generation on Distribution System Stability" 6th International Conference on Electrical & Computer Engineering 2010 (ICECE'10), December 18-20, 2010, Dhaka, Bangladesh.

Executive summary

Distributed Generation (DG) with renewable energy sources is one of the options, which has been extensively utilized to reduce emission of greenhouse gases (CO2, NOx, SOx etc.). In recent years, wind & solar based power generation has become very attractive alternatives to traditional power generation technologies. Countries such as Germany, Spain, Denmark and U.K. have successfully integrated large wind farms using existing infrastructures. As of mid 2010, Europe has commissioned 333 MW of off-shore wind turbines and has total installed capacity of 2.3 GW. On the other hand, the total installed capacity of solar energy systems has been reached in the tune of 22.9 GW. As a result of such high penetration level, the renewable sources of energy needs better control strategies & technologies that work in harmony with the existing infrastructure. In Australia, the penetration level of renewable energy to the national electricity grid is still very small. However, with 2020 vision of 20% renewable energy, future grid must be prepared for the consequences of intermittency and other technical issues.

Recent work carried out at the University of Queensland, which is presented in this report is divided into three sub-categories as follows:

1. Review of typical grid interconnection requirement, IEEE standards and literature for integration of DG into main grid.

2. Effect of component modelling strategies, interconnection requirements and their impact on location and size of reactive power compensation systems.
3. Effectiveness of various reactive power system compensation schemes (such as capacitor banks and SVC's) in improving small-signal stability.

Based on the analyses for a distribution system, following conclusions are drawn:

(a) Appropriate load model plays a significant role in the occurrence of voltage collapse and instability problems. Hence, development of appropriate load model is always a challenge to reflect the reality of a power system. So stability index, which can be used irrespective of load types, is required to identify the weakest bus and take protective measures. In this context, reactive power margin based index can be considered as a reliable stability index to identify critical node with all kind of load uncertainties in a typical distribution system.
(b) Shunt compensators are commonly used in a power system to support voltage stability. Distributed placement of reactive power compensators results in the same loadability improvement with reduced system loss when compared to a concentrated placement of compensator on the weakest bus. This study was conducted with constant power load model and DG with unity power factor operation without utilizing its limited reactive power generation capacity.
(c) Shunt compensators can sometimes be detrimental to oscillation damping. Integration of DG units into a distribution system obviously generates some oscillation modes,

which needs to be well damped. So, careful attention should be paid to locate shunt controllers to minimize the detrimental impact on oscillation damping. Location for which shunt compensator gives the least detrimental impact on oscillation damping is selected as the best location for small signal stability enhancement. For a static shunt compensator such as capacitor, the minimum eigenvalue shift may be used as an index while participation factor may be used as an index to locate a dynamic compensator such as SVC. SVC is a better choice for oscillation damping as compared to shunt capacitor of the same rating. SVC performances are better for transient responses of bus voltage and generator rotor angle. This suggests that additional SVC controller can be designed to enhance the dynamic performance of a distribution system with DG units, which is our ongoing work and will be reported in the final report.

Chapter 1 Control methodology and grid interconnection requirements -A literature review

1.1 Introduction

In the early 90s' distributed source of energy was treated by utility operators as a lump load for design, control and analysis. This treatment by utility operators began to change as the level of distributed generation penetration increased in the grid. Distributed Generators (DG) have significant impact on the system and equipment operation in terms of steady-state and dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. This impact may manifest either in positive or negative manner depending on the type of DG and its characteristics. The ever increasing levels of the penetration of DG requires a regulation that enables existing DG units connected to the grid without jeopardizing the system stability at the same time acting as an enabler for new technology development. The next section presents a brief review of various control methodologies reported in recent literature of DG integration. This section will be followed by a summary of IEEE grid interconnection requirements for seamless contribution of DG connected to the grid.

1.2 Literature review

The steady state voltage level at each load connection point is one of the most important parameters for maintaining the quality of supply. The technical regulations or specific contracts define the allowed voltage range that bounds the maximum permitted variation of every busbar voltage. In a conventional distribution system, the desired voltage is maintained by controlling voltage or reactive power flow that in turn controls voltage drop [1]. The equipment deployed for the voltage and reactive power control are switched shunt capacitors, on-load tap changer (OLTC) transformers, and steps voltage regulator [2]-[3]. SVC and/or STATCOM offer reactive power compensation for transient voltage stability improvement as well as steady state voltage regulation [4], [5]. Availability of Distribution STATic COMpensator (D-STATCOM) based on multilevel inverter results in distributed placement of dynamic compensation devices in a distribution system. This distributed approach suggests several SVC/STATCOM placement at primary i.e. MV distribution level (11kV and 22 kV) instead of placing bulk SVC at HV level (132kV and above) with a transformer [18], [19], [20]. Distributed compensators installed on distribution side of power delivery transformer can provide significant benefits over lumped compensation that has been traditionally on transmission and sub-transmission level. The benefits of the distributed compensators on the distribution side of substation have been found in [20], which include lower VAr requirement, better voltage regulation in load centres, lower rating transformer requirement and increased reliability. This methodology didn't count presence of DG's. All substation loads are assumed to have 90% power factor with constant PQ load and distribution transformer is not considered as OLTC. SVS is placed at every bus at 25kV level without considering any optimization process for the selection.

The conventional controllers discussed above are operated based on an assumption that both the real and reactive powers flow only in one direction, i.e. from the transmission system to the HV/MV substations to the distributions systems. This results in decrease in voltage along the feeder, from the substation to the feeder-end as no DG is present at the feeder-end. Due to, significant penetration of DG the power flow may become reversed and the distribution network becomes an active system with power flows and voltages determined by both generation as well as loads [21]. Based upon its type, DG gets connected to the grid. For a system with load and DG as shown in Figure 1.1, the voltage drop (in p.u.) of the feeder can be calculated by (1.1), where the notations are given in Fig 1.1.

$$\Delta U = \frac{R_{LN}(P_L - P_{DG}) + X_{LN}(Q_L - (\pm Q_{DG}))}{U_2} \tag{1.1}$$

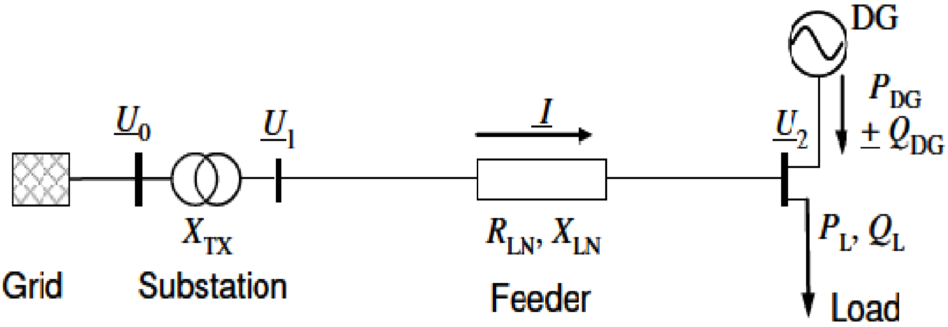


Figure 1.1: One line diagram for calculation of voltage drop in presence of DG [12].

This bi-directional power flow in turn results in significant changes for voltage control mechanism in the distribution network [22]-[23]. Next section summarizes how some DG included distribution systems utilize the reactive power compensators to maintain voltage throughout the system.

1.2.1 Localized voltage control

One of the most common power quality problem reported in practice is voltage fluctuation. At the point of common coupling of the distributed generator, this problem is sometimes inevitable because of the variable nature of renewable energy sources. This can be mitigated by a number of equipments but the fast response of the D-STATCOM makes it an ideal solution [24]. Optimum location and size of compensation device is required to mitigate power quality problems of consumers with the least capital cost. In [25], two case studies of D-STATCOM are presented, with and without presence of DG. The presence of DG reduces the size of the D-STATCOM. Molinas [26] addresses the gearbox issue (torque transients due to grid fault) for fixed speed wind turbine with the help of STATCOM.

Flicker management is an issue in case of wind turbine connected to grids, hence modelling of wind turbine and their control algorithms plays very important, Saad-Saoud [27], proposes a model for simple induction generator as set of first order differential equations and their integration for flicker analysis. Investigations into STATCOM and wind farm with fixed wind speed turbine have been carried out by Saad-Saoud et al. [28] in their paper in 1998. In [29], coordination between DG and switched capacitors are presented in order to ensure that the voltage rise caused by DG will not result in any overvoltage with energised capacitors. In few studies, DG reactive power capability has been utilized to mitigate the reactive power and voltage problem. Foster [30] utilize the reactive power of Doubly Fed Induction generator (DFIG) with capability chart to mitigate issues arises during voltage dip. The use of existing reactive power sources available in the wind turbine to maintain voltage at point of common coupling using off line optimization strategies has been the focus of research work by Keane[31]. Role of DFIG based wind turbine for stability improvements has been investigated by Nunes [32]. A typical wind farm consists of various reactive power controllers and based on the generation during any time of the day various controllers attempt to maintain the voltage such that wind turbine is free to generate maximum reactive power. The tap changers are key controllers in such voltage control exercise and ref [33] suggests a control strategy with DFIG and tap changer.

1.2.2. Coordinated control of reactive power devices for voltage control

Large integration of DG in a distribution system leads toward coordinated control. A coordination between OLTC and reactive power production of DG has been proposed by Caldon in [33]. Average network voltage is strictly related to the amount of P and Q (or P and power factor-cosφ) flowing through the primary substation transformer. The centralized controller monitors cosφ to satisfy the network active load demand. DG units are forced by their local regulators to inject power with a given reference cosφ determined by centralized controller (known as controlled by V_{mset}). Another parameter VI-set handled different loading conditions. A proper co-ordination among OLTC, substation switched capacitors and feeder switched capacitors in order to obtain optimum voltage and reactive power control has been proposed by F. Viawan and Conti [34], [35], [36], [37] as shown in Figure 1.2.

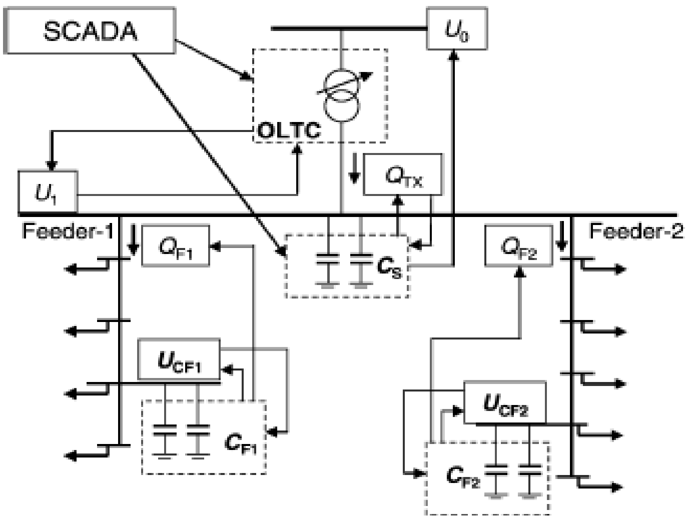


Figure 1.2: Coordinated control of voltage and reactive power with distributed generation [36].

With the proposed method, DG operating at constant voltage reduces OLTC operations per day and voltage fluctuation in the system. Yi Wang [39] suggests co-ordinated control strategy for DFIG and Fixed Speed Induction Generator (FSIG) turbines under the unbalance grid conditions. They also demonstrated the effectiveness of control strategy with simulation results. Li Wang [40] proposed line commutated back to back HVDC link to connect induction generator based wind turbine generation system to grid. This system allows user to comply with grid interconnection standards because of line commutated converter.

1.2.3 New system architecture and its control

Muyeen [41] presents a new operational strategy for a small scale wind farm, which is composed of both fixed and variable speed wind turbine generator systems (WTGS). Because of large dependency on reactive power, fixed speed wind generators suffer greatly from meeting the requirements of new wind farm grid code. A new wind farm topology, where series or parallel connected fixed speed WTGSs are installed with variable speed wind turbine (VSWT) driven permanent magnet synchronous generators (PMSG) has been proposed in this study. A fully controlled frequency converter for grid interfacing has been used and it has abilities to control its reactive power as well as to maximize real power output to grid. Front end converter of the PMSM based system does a dual role of delivering active power from the PMSM to the grid; along with supplying the reactive power during LVRT thus avoids extra STATCOM panel to meet grid interconnection requirement. Simulation results show the cost effectiveness of the proposed technique in details.

1.2.4 Energy storage placement sizing and its control to mitigate intermittency

Taking account of renewable energy intermittency problem, energy storage based control methodology has been developed by a number of researchers. Teleke [42], [43] deals with optimal control of battery based energy storage, which helps in making wind farm power output more predictable and thus allowing them to behave as conventional generator. Muyeen [44] presents an energy capacitor system (ECS) to smoothen the output power fluctuations of a variable speed wind farm. A suitable and economical topology of ECS composed of a current controlled voltage source inverter, dc-dc buck-boost converter and an electric double layer capacitor (EDLC) bank including control strategies has been developed in that study. In Muyeen’s study, the simulation results are described in light of the US grid code, set by Federal Energy Regulatory Commission (FERC) [45]. In recent years, several environmental and economic benefits have led large scale integration of renewable energy based distributed generators in the existing power system. Making renewable energy a dependable for source of energy despite their intermittent nature is a big challenge. Moreover, grid requirements and standards (put by various professional organizations such as IEEE/IEC) are working to shape the control strategies to allow flawless integration of DG in the main grid. Next section summarizes IEEE recommended standard for DG integration, which is considered for our control & placement methodology tool development.

1.3 Grid interconnection requirements and IEEE & AEMO standard(s)

The grid interconnection requirement forms a basis for data exchange between the equipment manufacture & utility/end user and control of power plant in general for interconnected power system. The IEEE has come up with a standard intended to facilitate the interoperability of distributed generation (DG) and help DG project stakeholders implement Monitoring, Information exchange, and Control (MIC) to support the technical and business operations of DR and transactions among the stakeholders. The requirements put forward by grid operator and/or by IEEE generally sub-divided into five sub categories as follows:

1. Voltage and reactive power requirements;
2. Frequency and Active power control requirements;
3. Fault ride through capability (LVRT) requirements;
4. Flicker, Harmonics requirements;

5. Data exchange requirements.

These requirements also change based on the size of DG. In case of Australia Electricity market Operator (AEMO), for a power plant having size of less than 30 MW it is expected that they deliver/operate at unity power factor under all operating conditions of frequency & voltage of a system to which it is connected. In the event of credible contingency it is expected that the voltage of supply at a connection point should not rise above its normal voltage as a function of time as shown in the Figure 1.3. For the quality of supply related issues for power generating units are required to comply with IEC 60034-1. Similar guidelines are in place for generator for frequency excursion, see AEMO website for further details (http://www.aemc.gov.au/Media/docs/Rule%20To%20Be%20Made-d63e6f1b-f171-434c-a0f3-cc9877c4d730-0.pdf).

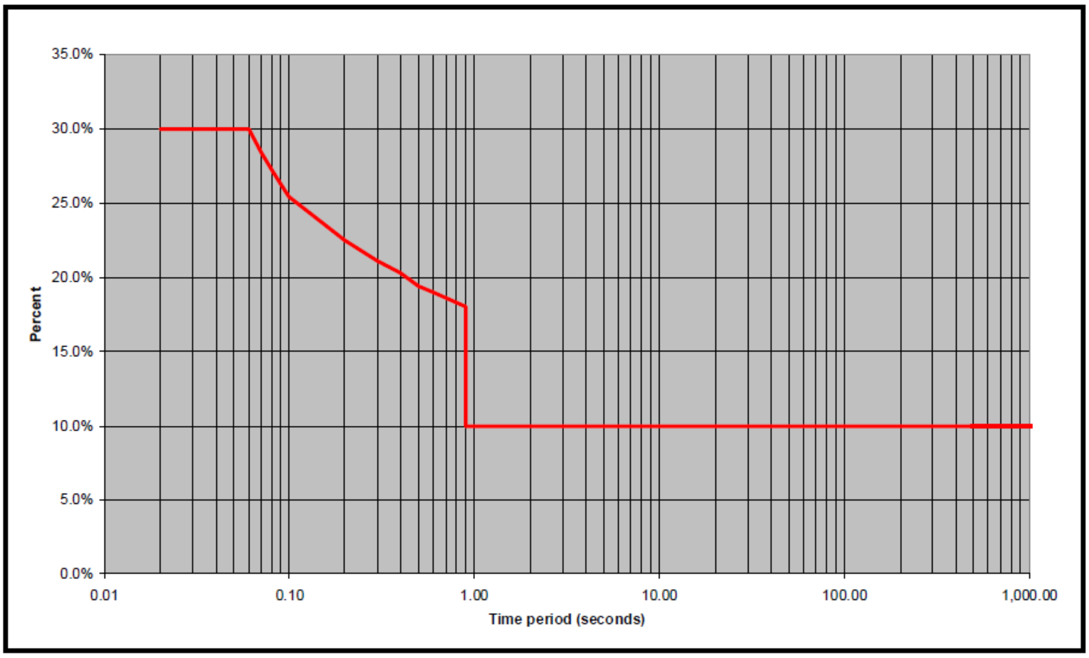


Figure 1.3: Acceptable percentage change in voltage due to credible contingency (***AEMO requirement***).

1.4 Summary

In this part of the report, a brief discussion of different voltage control methodologies in distribution system has been presented. Existing literature shows that, with an emergence of large scale penetration of renewable based distributed generation, the conventional control methodology needs to be redefined. The principal challenges in developing control algorithm for DG based distribution system have been identified as: intermittency of renewable energy sources, lack of sufficient reactive power, different load models and following the standard grid codes in all circumstances (particularly in low voltage ride through condition.The objective of grid interconnection requirement and standards such as IEEE for renewable energy does not only allow the seamless integration of wind and solar power but also set forward the realistic expectations in line with conventional power plants in a de-regulated environment. Current development of controller is heavily influenced by such requirements. In fact, certain grid interconnection requirements demands new technically challenging variable speed WTG to act as a synchronous machine aggregated at point of common coupling. These issues will be addressed in our studies extensively with a focus of building a robust control methodology counting the presence of all types of DG. Next chapter outlines the placement of compensator devices for voltage stability improvement with consideration of different load modelling uncertainties.

Chapter 2 Identification of effective voltage stability index for placement of reactive power compensator with load model uncertainties

2.1 Introduction

Voltage stability has become a concern and serious issue for power system planners and operators with the increased loading of transmission and distribution lines. Network configuration, R/X ratio of interconnections, load models, load directions, presence of generators and use of compensators are most influential factors of the strength of a bus in terms of voltage stability in a distribution system. In turn, identifying weak buses can give correct information for the optimal reactive power planning, that would decide which buses are the most severe and need to have new reactive power sources installed [60]. Ranking of bus based on strength has also been found useful in determining location for distributed generator to enhance loadability of the system [61].

Load modelling for power system stability studies has always been a challenge for a number of reasons. The actual load below sub-transmission level consists of large varieties of components like thermostatic loads, resistive and inductive loads, induction motors, and lighting loads. Furthermore, number and type of loads varies continuously through time as different load components are switched on or off in response to residential, commercial and industrial activities. Other factors like change in weather may also cause highly unpredictable and irregular variations in the nature and amount of load. This statistical nature of load makes it very difficult to establish a load model that is generically applicable for power system studies [62]. To correctly analyse the voltage stability of a power system, suitable dynamic models are usually required based on nonlinear differential and algebraic equations. However, in many cases, static analysis tools can be used to identify influencing factors for long term voltage stability [63].

The influence of load modelling on different voltage stability indices has been worked out in few studies and it has been shown that with an increasing percentage of constant impedance load, indices related to P-V nose curves fails to measure the strength of nodes under stressed condition [64], [65]. In this work, the impact of load uncertainties on reactive power margin as a voltage stability index has been comprehensively examined. Reactive power margins of load buses have been calculated for a primary distribution system to measure the strength of each bus with different compositions of load models. Results found in this study proves reactive power margin as a suitable index to identify the weakest bus irrespective of load pattern. Details of this work have been published in [66].

2.2 Static load model

Most of the power system loads are connected to low-voltage or medium voltage distribution systems. In transmission system, voltages are generally regulated by various control devices at the load/generator nodes. Therefore in load flow calculation, loads can be represented by using constant power load models. In distribution systems, however, voltages differ widely along system feeders due to non-availability of reactive power control devices. So in load flow studies of distribution system, V-I characteristics plays very crucial role [67]. Load models are divided into two wide categories: static and dynamic. In load flow studies Static load models are used. They are typically classified as constant impedance, constant current and constant power load model. In general, a static load model is expressed by following exponential equations:

$$P = P_0 \left(\frac{V}{V_0} \right)^{np} \quad (2.1)$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^{nq} \quad (2.2)$$

Here P_0 and Q_0 stand for real and reactive power consumed at a reference voltage V_0. The exponents np and nq depend on the load type. Table 2.1 shows typical values of np and nq used in power system analysis/studies [68], [69].

Along with exponential type as explained above, load can also be represented as polynomial load. Polynomial load model is a static load model that signifies the power-voltage relationship as a polynomial equation of voltage magnitude. It is usually referred as ZIP model as it is made up of different proportions of three types: constant impedance (Z), constant current (I) and constant power (P). The real and reactive power characteristics of the ZIP load model are given by

$$P = P_0 \left[a_p \left(\frac{V}{V_0} \right)^2 + b_p \left(\frac{V}{V_0} \right) + c_p \right] \quad (2.3)$$

$$Q = Q_0 \left[a_q \left(\frac{V}{V_0} \right)^2 + b_q \left(\frac{V}{V_0} \right) + c_q \right] \quad (2.4)$$

Table 2.1: Sample of load exponents

Load	**np**	**Nq**
Fluorescent lighting	1	3
Resistance space heater	2	0
Room air conditioner	0.5	2.50
Incandescent lamp	1.54	0
Small industrial motors	0.1	0.6
Large industrial motors	0.05	0.5

Where $a_p + b_p + c_p = a_q + b_q + c_q = 1$ and P_0 and Q_0 are the real and reactive power consumed at a reference voltage V_0 . In order to simulate various combinations of composite loads, the user can define the percentage co-efficient $a_p, b_p, c_p, a_q, b_q, c_q$ separately.

2.3 Test system and load composition

16-bus distribution system (see Figure 2.1) is used, in this study. This system consists of a total load of 28.7MW and 17.3MVAr, respectively and is a modified form in [70], where 3 feeder system has been converted to single feeder radial system with same amount of base case load. All the results presented in this work were simulated with DigSilent PowerFactory 14.0 [71], a commercial tool and also have been verified using research analytical tool PSAT

[72] and routines written in MATLAB. A wide variation of load composition is simulated through different sets of load model, which includes both extreme conditions and some intermediate conditions. In this work, three types of extreme load models have been considered along with 3 intermediate combinations represented by ZIP load model. These six cases of load compositions have been listed in Table 2.2. Here extreme ZIP cases involve total existence of only one type of load i.e. constant power, current and impedance.

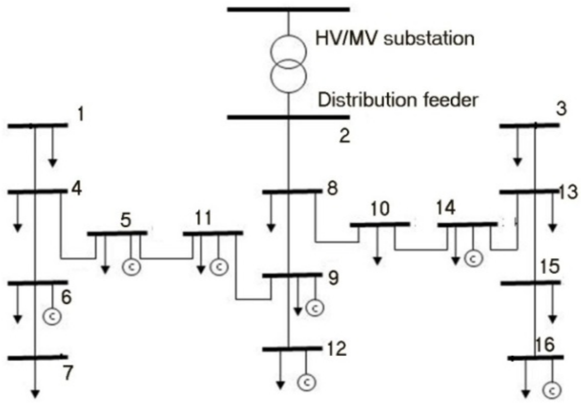


Figure 2.1: Single line diagram of test system

Table 2.2: Random load composition

Case	**ZIP composition of loads**		
	Z(%)	***I(%)***	***P(%)***
Extreme P	0	0	100
Extreme I	0	100	0
Extreme Z	100	0	0
Combination 1	0	50	50
Combination 2	30	20	50
Combination 3	80	20	0

Table 2.3: Typical load composition [3]

Load Class	**Load composition (%)**		
	Residential	***Commercial***	***Industrial***
Resistive	25	14	5
Small Motor	75	51	20
Large Motor	0	0	56
Discharge Lighting	0	35	19

This study has then been extended to practical scenarios. It is unlikely that a utility can easily divide customer loads directly into load components as mentioned in Table 2.1. Rather doing that, utilities break their load into 3 compositions with the presence of different percentages of loads. The breakdown typically used by the utilities has been shown in Table 2.3 [62]. Here motors with power rating greater then 100hp has been treated as large motors, which are principal loads in industrial feeder. Residential and commercial loads are dominated by small motors representing air conditioner and water-pumps. Fluorescent lighting comprises 35% of commercial feeder, whereas incandescent lights are the major illumination loads for residential feeder.

2.4 Simulation results and discussions

Along with reactive power margin (Q_{margin} in MVAr) [68], voltage sensitivity factor (V p.u. / MW) [73] and L-index [74] have also been measured to show the comparison in their performance with load type variation. Table 2.4 presents measured stability indices for three extreme types of loads. Table 2.5 shows the measured indices for 3 intermediate combinations with different proportions of loads as mentioned in Table 2.3. From the tabulated results, the lowest value of Q_{margin} and the highest value of VSF and L-index establish bus 7 as the weakest bus. For example, for constant power load models, lowest Q_{margin} 22.94 MVAr has been found with bus 7, which establishes it as the weakest bus. The finding is in complete agreement with VSF and L-index which have highest values at, 0.53 and 0.22 respectively, to prove bus 7 as the weakest bus. VSF is found to be equally sensitive as reactive power margin while L-index is less sensitive in identifying a weak bus. However, for constant impedance load VSF and L-index fails to provide any information on the strength of a bus because of failure of convergence [64].

Table 2.4: Weak bus detection for extreme load types

Rank	**Bus No.**	**Constant power**			**Constant current**			**Constant impedance**		
		$Q_{margin}(MVAr)$	***VSF***	***L-index***	$Q_{margin}(MVAr)$	***VSF***	***L-index***	$Q_{margin}(MVAr)$	***VSF***	***L-index***
1	Bus 7	22.94	0.53	0.22	26.36	0.071	0.49	28.25	-	-
2	Bus 6	24.41	0.50	0.22	28.16	0.062	0.44	30.19	-	-
3	Bus 4	32.54	0.34	0.19	38.07	0.029	0.28	40.93	-	-

Table 2.5: Weak bus detection for intermediate load types

Rank	**Bus No.**	**Combination 1**			**Combination 2**			**Combination 3**		
		$Q_{margin}(MVAr)$	***VSF***	***L-index***	$Q_{margin}(MVAr)$	***VSF***	***L-index***	$Q_{margin}(MVAr)$	***VSF***	***L-index***
1	Bus 7	24.7	0.51	0.22	25.31	0.93	0.26	27.88	-	-
2	Bus 6	26.35	0.48	0.22	27	0.87	0.26	29.79	-	-
3	Bus 4	35.42	0.30	0.19	36.34	0.55	0.20	40.37	-	-

Q-V curve studies of bus 7, the weakest bus, with three extreme load types has been shown in Fig. 2.2. It shows that highest reactive power margin 28.25MVAr occurs with constant Z type load whereas constant P type load offers the lowest reactive power margin i.e. 22.94MVAr. With intermediate loads, it has been observed that with increasing penetration of Z type load, reactive power margin improves resulting in an improved stability of the system.

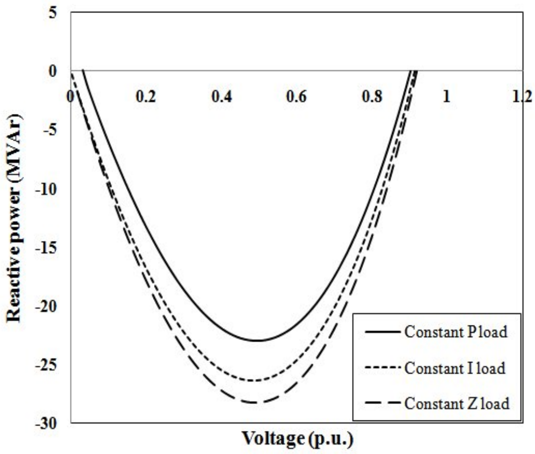


Figure 2.2: Q-V curves for extreme types of loads.

The work is extended to practical scenario where the system is supplying demand to one of the three usual load compositions: residential, commercial and industrial (data taken from Table 2.3). Bus 7 has again been identified as the weakest bus with lowest reactive power margin among all the buses, followed by buses 6 and 4. A comparison of Q_{margin} for different load composition has been shown in Fig. 2.3. It has been observed that, the same distribution system offers improved stability when treated as a commercial feeder compared to a residential or an industrial feeder. For example, bus 7 (the weakest bus as per finding) has Q_{margin} of 26MVAr with commercial load, which is higher than with residential or industrial load. This observation is more explicable with loadability study. The test system offers highest loadability of 4.3p.u. with commercial load composition. Residential and industrial both load compositions offer loadability of 3.5p.u. From all the measured data, it can be observed that constant P type load offers the lowest loadability and reactive power margin among all the compositions taken into account. But whatever the load composition is, reactive power margin index works as a reliable index in identifying weakest bus in a system.

Identification of the weakest bus of a system helps in proper placement of compensating devices for loadability enhancement. For a distribution system operator to optimize their resources and their profits maximizing loadability has always been a good choice. Detail study with reactive power compensator has been presented in the next section.

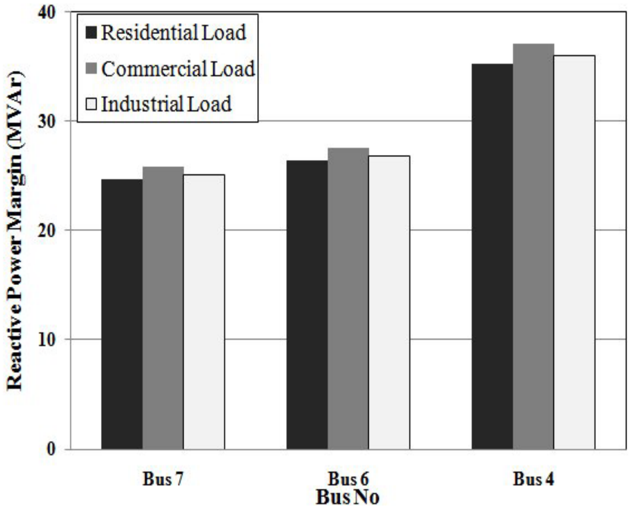


Figure 2.3: Reactive power margin with typical load composition

2.5 Summary

Recently, establishing a reliable index to assess voltage stability condition of a stressed multi-node power transmission and distribution system has got lot of attention. With the integration of renewable energy in power system the subject of voltage stability in distribution system is getting more interest. In several studies it has been observed that performance of stability indices in detection of weak nodes is largely influenced by load models. Though load model plays significant role in occurrence of voltage collapse and instability problems, development of appropriate load model under sub-transmission level is always a challenge to reflect the reality of a power system. So stability index, which can be used irrespective of load types, is required to identify the weakest bus and take protective measures.

In this study, reactive power margin has been used as a stability index to determine the weakest node in a 16 bus primary distribution system and its performance has been compared with two other widely used indices: VSF and L-index. Results show that reactive power margin can be utilized as a reliable index to determine critical or weak node while considering the influence of load uncertainties. Effectiveness of reactive power margin index has been proved using a modified 16 bus primary distribution system with various set of feeders and realistic load models. Identification of weak nodes leads to the optimal reactive power planning that would decide the candidate buses to have new reactive power sources installed.

Chapter 3 Selecting location and size of reactive power compensator for DG integrated distribution system

3.1 Introduction

Static voltage stability margin can be enhanced using adequate reactive power support and appropriate bus/node and hence, postpone the point of collapse. Various reactive compensation devices used by the utilities for this purpose, each of which has its own characteristics and limitations. However, the distribution utility is interested in achieving this goal with the most beneficial compensation device [75], [4]. Historically, synchronous condensers, connected at the sub-transmission and transmission buses, have been used to supply the continuously adjustable capacitive or inductive currents to support the voltages at the load centres. Because of the precedence set by synchronous condensers, the SVS, which have largely supplanted them, still tend to be situated at the sub-transmission and transmission buses. With the availability of STATCOMs or SVCs (cheaper) which can be connected at distribution level voltages without the need of transformers, it has been proved in [18] that small sized SVS directly connected to distribution buses offers a number of advantages over the traditional single bulk SVS placement at transmission or sub-transmission level. SVC placement on distribution buses offers reliable operation for (N-1) contingency operation along with savings in MVARs and transformer MVA. As more and more renewable based DG units get connected to the distribution system, compensation of reactive power becomes a major concern for power engineers. Our present work is solely concentrated in DG integrated distribution system. In this section, we present some simulation results considering SVC as the reactive compensation device. All these SVCs are connected to a primary distribution system through a transformer. This work investigates the proper placement and size of SVC in a DG integrated distribution system. IEEE 1547 has been followed all throughout this study.

3.2 System description

The 16 bus 23 kV 100MVA primary distribution system (as used earlier) is shown in Figure 3.1 with DG integration.

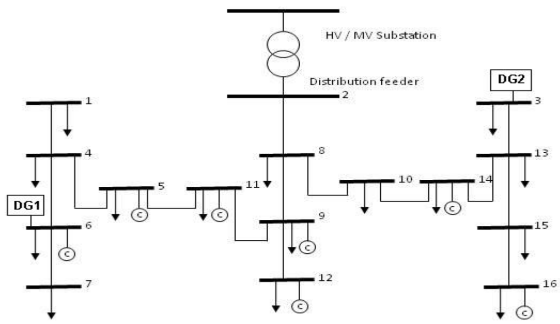


Figure 3.1: 16 bus system with DG integration.

Two distributed generator have been integrated in this system with specifications mentioned in Table 3.1. In general, a DG unit can be connected to a distribution network by one of three interfaces, including asynchronous generators, synchronous generators and electronic converters. In our study, FERC 661A standard has been followed to fix the power factor of the integrated DG units [45]. According to the standard, power factor of DG at point of common coupling can vary in between 0.95 lag to 0.95 lead determined by site specific study. DG should not actively regulate the voltage at the PCC [38]. With base case generation present (according to Table 3.1), the total amount of real power coming through feeder has been calculated as 12.08MW along with 2.60MVAr reactive power.

Table 3.1: Generation details

Generation type	Electric Machine	Machine Rating	Location
DG1	DFIG (WECC type 3) / Wind-variable speed full converter (WECC type 4)	S= 1.5 MVA Pf=1	Bus 6
DG2	Solar PV/ Solar Thermal plant	S=1.5 MVA Pf=1	Bus 3

3.3 Realistic loadability

Loadability limit has been defined as the point where the load demand reaches a maximum value and beyond that limit the power flow solution fails to converge and the system can no longer operate [1]. If the load is considered as constant power the loadability limit relates to the maximum deliverable power to a bus or a set of buses in a system [69]. So maximizing loadability has been a good choice for the distribution system operator who wants to optimize their resources and maximize their profit. But in presence of DG, the concept of loadability needs to be redefined in terms of grid code, which is found to be dictated by voltage limits at PCC. The voltage limits at the PCC, where the utility is connected with a local distributed generator, are specified in ANSI C84.1 range A. This specification narrowly defines normal operating conditions at the PCC [38]. According to that requirement, distributed resources shall cease to energize the utility grid when the voltage range is out of 88% and 110% of nominal voltage. In our study, we have taken realistic loadability as the ultimate loading margin at which voltage at the PCC goes below 0.88 p.u. of nominal value. However, this customary does allow occasional voltage excursions outside of these limits.

3.4 Ranking of nodes/buses

Buses with lack of adequate reactive power have always been a good choice for placing compensation devices as mentioned in the previous section. But with the inclusion of DG in the existing system, bus strength calculation needs an update. For the present study we are using constant power load model which allows using both reactive power margin and VSF as indices to measure bus strength. Figure 3.2 shows reactive power margin value and VSF for all buses in the 16 bus system in presence of DGs at the realistic loading margin. As can be seen from the figure, bus 7 is the bus with the highest VSF of 0.0073 V p.u. /MW (and obviously the lowest reactive power margin of 23.75MVAr) resulting in the weakest bus at a loading margin of 1.2 p.u. After closely examining this plot we can make a ranking of buses based on their strengths. Here, Table 3.2 represents the first four weak buses along with first four strong buses in terms of VSF as well as reactive power margin. For example, in Table 3.2, bus no. 7 stands out as the weakest bus with the highest sensitivity factor (0.0073 V p.u. /MW) and lowest reactive power margin of 23.75MVAr. On the contrary, bus no. 8 appears as the strongest bus with the lowest VSF (0.0013 V p.u./MW) and highest reactive power margin (157.34MVAr).

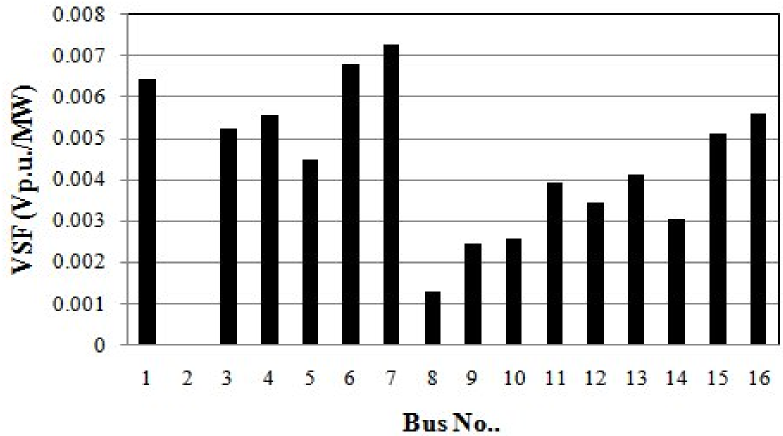


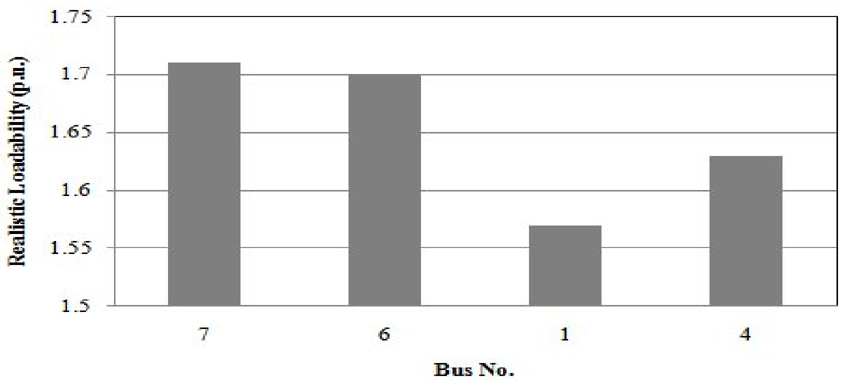
Figure 3.2: VSF for 16 bus system with DG integration.

Table 3.2: Bus ranking in presence of DG

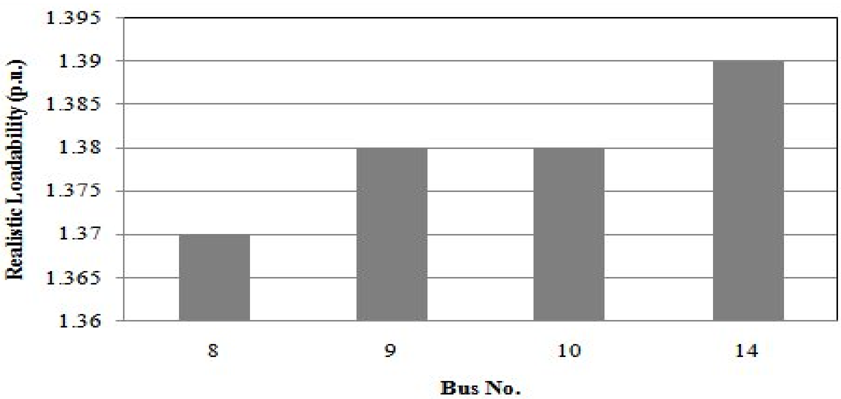
Weak Bus			**Strong Bus**		
Bus No.	***Reactive Power Margin (MVAr)***	***VSF (Voltage p.u./MW)***	***Bus No.***	***Reactive Power Margin (MVAr)***	***VSF (Voltage p.u./ MW)***
7	23.75	0.0073	8	157.34	0.0013
6	25.26	0.0068	9	79.16	0.0024
1	28.63	0.0064	10	78.34	0.0026
4/16	33.66	0.0056	14	67.41	0.0031

3.5 Loadability improvement with SVC placement

Among two popular configurations of SVC, Fixed Capacitor Thyristor Controlled Reactor (FC-TCR) and Thyristor Switched Capacitor and Thyristor Controlled Reactor (TSC-TCR), our present study focuses on the use of TSC-TCR type of SVC in the test 16 bus distribution system. Our study first focuses on finding the suitable sites for placing SVC. To start with, we take a rough estimate of reactive power support needed at the weakest bus by following procedure given in [75]. A synchronous compensator with no limit on reactive power has been used at the weakest bus at realistic loading margin (i.e. 1.2 p.u.). The amount of reactive power generated at this point from synchronous compensator was found as 14.52 MVAr. This is the starting size of SVC that will be used for finding the best location with an objective of realistic loadability improvement. Figure 3.3 depicts the improvement in loadability with inclusion of bulk SVC on the specific single bus. For example placing an SVC of capacity 14.52 MVAr at bus 7 (the weakest bus according to VSF result) results in a realistic loadability of 1.71 p.u (see Figure 3.3 (a)). Again, as shown in Figure 3.3 (b) placing SVC of same size on a strong bus for example bus 8 will result in less improvement in loading margin which turns out to be 1.37 p.u. So from the study, it can be pointed out that placing SVC on weak buses result in better improvement in realistic loading margin compared to their placement at strong buses.



(a)



(b)

Figure 3.3: Improvement in realistic loadability with bulk SVC placement

Table 3.3 shows realistic loadability results for distributed placement of SVC among weak buses. Earlier, total MVAr value for bulk placement on a single bus was taken as 14.52MVAr. Now for distributed placement, the total MVAr is divided equally among the weak buses. For example, SVC of 4.84 MVAr has been chosen to place on each of the buses when we select first three weak buses from table 3.2. Analysing the results it can be stated that, for distributed SVC placement loadability improvement is almost the same as bulked placement of SVC on the weakest bus. But as we distribute it among the weak buses grid loss tends to decrease up-to 1.39MW, which has been found 1.61MW with bulk placement of SVC. Bulk placement of SVC requires only one transformer at a time in operation which reduces cost to some extent though it does not support (N-1) contingency reliability. So ultimately decision of choosing distributed or bulk SVC has to be taken considering a number of issues as mentioned: grid loss, reliability and cost.

Table 3.3: Distributed placement of SVC

Case	Bus No.	SVC size					Realistic Loadability (p.u.)	Grid loss
		Bus 7	Bus 6	Bus 1	Bus 4	Total		
1	7,6	7.26	7.26			14.52	1.707	1.52
2	7,6,1	4.84	4.84	4.84		14.52	1.707	1.43
3	7,6,1,4	3.63	3.63	3.63	3.63	14.52	1.707	1.39

Figure 3.4 plots the variation of realistic loadability with the variation in size of SVC on the weakest bus i.e. bus 7. Minimum size of SVC has been taken as 14.52 as stated earlier. It has been found that as the capacity of SVC increases to 30MVAr, loadability reaches a value of 2.02 pu, beyond this capacity there is no improvement in loading margin.

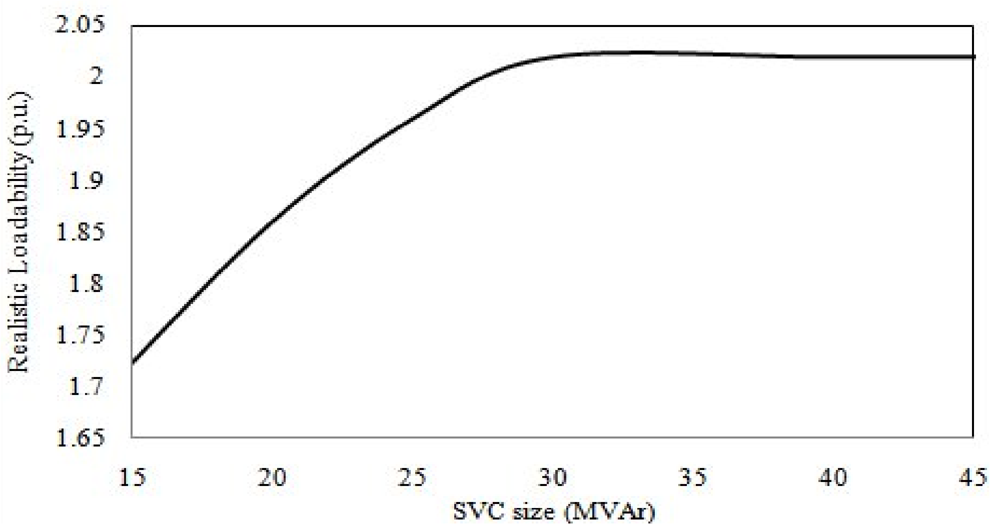


Figure 3.4: Realistic loadability vs. SVC size.

3.6 Summary

According to most of the present grid codes including IEEE 1547 [38], distributed generators of bellow certain size are required to maintain unity power factor at point of common coupling. With an increase in penetration of renewable based DG units in a distribution system, compensation of reactive power is becoming a major concern for power engineers. Sufficient reactive power supply at the suitable location enhances realistic loadability and hence, can defer or delay the point of collapse. Our present work is concentrated in DG integrated distribution system. In this chapter, we have presented some simulation results considering SVC as the reactive compensation device. This work investigates proper placement and size of SVC in a DG integrated 16 bus primary distribution systems. Results show that distributed placement of VAR compensator results in same loadability improvement as concentrated placement of compensator on the weakest bus except reduced amount of losses in the first case. It has also been found that with the increase of capacity of SVC, loadability improves up-to certain maximum value, beyond which, there is no improvement. In this comparative study load model has been taken as constant power load. DG has been considered with unity power factor operation. Our future analysis will consider both these issues with support of the results derived in this section.

Chapter 4 Stability enhancement using shunt FACTS controllers

4.1 Introduction

This part of the report explains the control methodologies of a distribution system to improve voltage and damping of system oscillation. One of the major issues of control is the appropriate location of the controllers. The modes of oscillation in a power system may be effectively damped by appropriate location of shunt controllers. Conventional distribution systems are highly compensated with shunt capacitors for voltage stability improvement. In the recent years, Flexible AC Transmission System (FACTS) controllers such as SVCs and DSTATCOM are also used to achieve the efficient voltage and power quality control. It is well known that application of shunt compensators enhances the voltage stability of a power system as demonstrated in pervious chapter. However, they have been reported to degrade the small signal stability in some cases by contributing negative damping to the system oscillation. On the other hand, controllable device such as SVC can support the small signal stability if primary controller parameter is carefully selected. So, careful attention should be given to minimize the detrimental impact on the small signal stability while selecting a control methodology for voltage stability improvement. This report mainly focuses on determining the appropriate location of shunt controllers such as capacitors and SVC to enhance stability of the system. A comparison of performance of shunt capacitors and SVC application is also presented.

4.2 System modelling

4.2.1 Dynamic model of distribution system

The power system behaviour can be represented by a set of differential and algebraic equations.

$$\left.\begin{aligned} \dot{X} &= f(X,Y,p) \\ 0 &= g(X,Y,p) \end{aligned}\right\} \tag{4.1}$$

Here, X is a vector of state variables related to dynamics of DG units and associated controllers, $Y = [\delta \quad V]'$ is a vector of algebraic variables associated with angle and bus voltage magnitudes and $p = [P \quad Q]'$ is a vector of uncontrollable parameters such as variations of active and reactive powers at a bus. Linearization of (5.1) around an operating point (X_o, Y_o, p_o) would give,

$$\left.\begin{aligned} \Delta\dot{X} &= (\partial f/\partial X)\Delta X + (\partial f/\partial Y)\Delta Y + (\partial f/\partial p)\Delta p \\ 0 &= (\partial g/\partial X)\Delta X + (\partial g/\partial Y)\Delta Y + (\partial g/\partial p)\Delta p \end{aligned}\right\} \tag{4.2}$$

Vectors ΔY and Δp are related algebraically by power flow Jacobian matrix[76].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \underbrace{\begin{bmatrix} P_\theta & P_V \\ Q_\theta & Q_V \end{bmatrix}}_{J} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{4.3}$$

Where J is power-flow Jacobian matrix and $P_\theta = \partial P / \partial \theta$, $P_V = \partial P / \partial V$, $Q_\theta = \partial Q / \partial \theta$ $Q_V = \partial Q / \partial V$.

Now, for a given values of p, the linearization of DAEs at equilibrium point (x_o, y_o) gives

$$\begin{bmatrix} \Delta \dot{X} \\ 0 \end{bmatrix} = \begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y \end{bmatrix} \tag{4.4}$$

Where, $f_x = \partial f / \partial X \mid_o$, $f_y = \partial f / \partial Y \mid_o$, $g_x = \partial g / \partial X \mid_o$, and $g_y = \partial g / \partial Y \mid_o$. If g_y is a non singular matrix, (5.4) can be reduced as

$$\Delta \dot{X} = A_{DG} \Delta X \tag{4.5}$$

Where, $A_{DG} = (f_x - f_y g_y^{-1} g_x)$ represents the system state matrix of the distribution system with DG units. In this case, the DAE system is reduced to a set of Ordinary Differential Equations. The eigenvalues of system state matrix A_{DG} gives the information on small signal stability of the system. The complex eigenvalues of A_{DG} represent the oscillatory modes of the system. The real part and imaginary part of the complex eigenvalues give the information on damping and frequency of the oscillatory modes, respectively. The low damped and low frequency modes are critical modes, which need to be handled carefully to enhance the small signal stability of the system.

4.2.2 SVC

SVC is a shunt connected compensating device whose impedance is adjusted to control reactive power flow in the line. A thyristor controlled reactor is connected in parallel to a fixed capacitor to control the effective reactance of the capacitor[76]. The block diagram of SVC is shown in Fig. 4.1. Here, V_t and V_{ref} are the voltage magnitude at SVC terminal and voltage to be maintained by SVC, respectively. K is the gain of controller, T_n and T_d are used for gain adjustments and T_r is the thyristor time constant. $B_{\max}$ and $B_{\min}$ specify the range of SVC compensation and B_{SVC} is the effective susceptance of SVC.

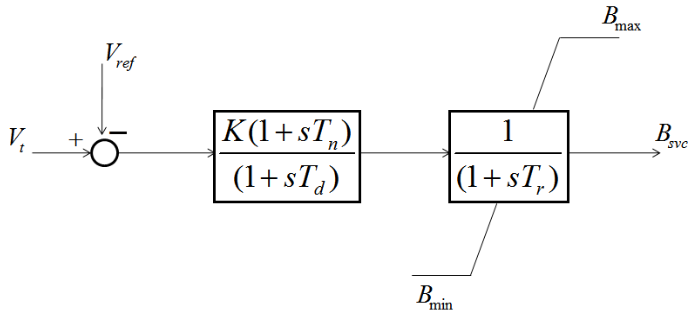


Figure 4.1: Block diagram of SVC control.

4.3 Location of shunt controllers

4.3.1 Selection of significant buses

At a particular operating point, shunt controllers may absorb or inject ΔQ to control a bus voltage while keeping P constant. So, $\Delta P = 0$ in (4.3) gives

$$\Delta Q = J_{\mathrm{Red}} \Delta V \tag{4.6}$$

Where, $J_{\mathrm{Red}} = [Q_V - Q_\theta P_\theta^{-1} P_V]$ (4.7)

J_{Red} is called the reduced Jacobian matrix of the system. It relates the bus voltage magnitude and the bus reactive power injection. The system is said to be stable if all the eigenvalues of J_{Red} are positive[77]. If any of the eigenvalues are zero, the system is at critical point of the voltage stability. Negative eigenvalues mean that the system is voltage unstable. The eigenvalues, which have lower magnitude, refer to the modes of possible voltage instabilities. Then, the bus participation of bus k to instability mode i is defined as

$$\Pi_{ki} = \xi_{ki} \eta_{ik} \tag{4.8}$$

Where, ξ_{ki}: k_{th} entry of right eigenvector ξ_i

η_{ik}: k_{th} entry of left eigenvector η_i

The bus participation indicates the contribution of the i^{th} mode to the $V-Q$ sensitivity at the bus k [77]. For all the small eigenvalues, the bus participation factor determines the area close to voltage instability similar to VSF and reactive power margin method explained in previous chapters. In this paper, the buses which show highest participation to the voltage instability mode of interest are selected as the candidate buses for SVC placement.

4.3.2 System state matrix with SVC

After connecting the dynamic SVC model to the system, the system state matrix A_{sys} needs to be updated. The linearized distribution system model with DG units and SVC may be written as

$$\begin{bmatrix} \Delta\dot{X}_{DG} \\ \Delta\dot{X}_{SVC} \end{bmatrix} = \begin{bmatrix} A_{DG} & 0 \\ 0 & A_{SVC} \end{bmatrix} \begin{bmatrix} \Delta X_{DG} \\ \Delta X_{SVC} \end{bmatrix} + \begin{bmatrix} C_{DG} & 0 \\ 0 & C_{SVC} \end{bmatrix} \begin{bmatrix} \Delta V_{DG} \\ \Delta V_{SVC} \end{bmatrix} \tag{4.9}$$

Where, V_{DG} and V_{SVC} are the terminal voltage vectors of DG units and SVC, respectively, X_{DG} and X_{SVC} are state vectors of DG units and SVC, respectively. The matrices A_{DG}, C_{DG}, A_{SVC} and C_{SVC} are block diagonal numerically depending upon system operating point and machine parameters. The linear representation of coupling characteristics between the system dynamic devices and network can be written as

$$\begin{bmatrix} \Delta I_{DG} \\ \Delta I_{L} \end{bmatrix} = \begin{bmatrix} W_{DG} & 0 \\ 0 & W_{SVC} \end{bmatrix} \begin{bmatrix} \Delta X_{DG} \\ \Delta X_{SVC} \end{bmatrix} + \begin{bmatrix} N_{DG} & 0 \\ 0 & N_{L} \end{bmatrix} \begin{bmatrix} \Delta V_{DG} \\ \Delta V_{SVC} \end{bmatrix} \tag{4.10}$$

Where, I_{DG} is currents injected from DG units and I_L is current injection from all the load buses including SVCs. The matrices W_{DG} and W_{SVC} represent the dependence of DG units and SVCs with the corresponding state vectors. N_{DG} and N_{SVC} represent matrices of DG units and SVC, respectively.

A complete distribution network may be represented as

$$\begin{bmatrix} \Delta I_{G} \\ \Delta I_{L} \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} \Delta V_{G} \\ \Delta V_{L} \end{bmatrix} \tag{4.11}$$

Where, Y_{GG} , Y_{GL} ,Y_{LG} and Y_{LL} are the matrices derived from system admittance matrix. Using (9), (10) and (11) the overall system state matrix with SVC can be derived as

$$A = \begin{bmatrix} A_{DG} & 0 \\ 0 & A_{SVC} \end{bmatrix} + \begin{bmatrix} C_{DG} & 0 \\ 0 & C_{SVC} \end{bmatrix} \times \left(\begin{bmatrix} Y_{GG} - N_{DG} & Y_{GL} \\ Y_{LG} & Y_{LL} - N_{L} \end{bmatrix} \right)^{-1} \times \begin{bmatrix} W_{DG} & 0 \\ 0 & W_{SVC} \end{bmatrix} \tag{4.12}$$

4.3.4 Participation of SVC on system modes

The contributions of states on oscillation modes can be observed by evaluating the participation factors (PFs) of each state on a particular mode. Participation factor gives the relationship among the states and eigenmode in a dynamic system. The participation of k_{th} state in the i_{th} eigenmode is given by

$$p_{ki} = \phi_{ki}\psi_{ik} \tag{4.13}$$

Where,

ϕ_{ki} : k_{th} Entry of right eigenvector ϕ_i

ψ_{ik} : k_{th} Entry of left eigenvector ψ_i

4.4 Results and analysis

4.4.1 Test system

The simulation was carried out on a radial distribution system similar to the systems used in Chapters 2 and 3 with DG, which is shown in Figure 4.2. It is a 16 bus system with total load of 28.7 MW and 17.3 MVAR [78]. A synchronous generator supplying 4 MW and operating in voltage control mode is connected at Bus 2. Another synchronous generator operating in power factor control mode is connected at Bus 3, supplying 5 MW at unity power factor. Both synchronous generators are modelled by sixth order model [76- 79]. A wind generator supplying 2 MW is connected at Bus 6 and modelled by third order induction machine model [79],[80]. A photovoltaic (PV) generator is connected at Bus 7, supplying 1 MW to the system. As PV generators are static devices supplying active power to the system, they are modelled by constant current source[78],[81]. The system loads are modelled by constant impedance load models. The distribution network is modelled by π-model similar to that of transmission system model.

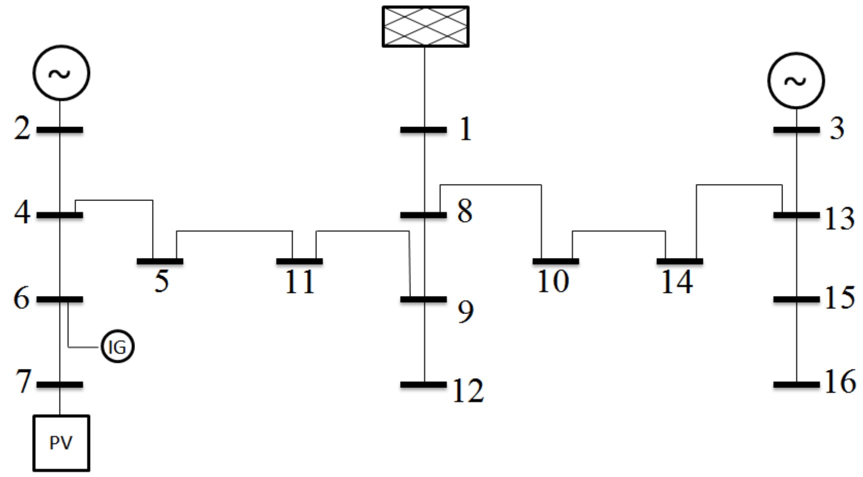


Figure 4.2: Single line diagram of the test distribution system.

There are three pairs of complex eigenvalues as given in Table 4.1, which represent the oscillatory modes that exist in the distribution system in the base case. The oscillatory modes are better damped as compared to those of high voltage transmission systems.

Table 4.1: The oscillatory modes of the distribution system

Modes	**Real Part (1/s)**	**Imaginary Part (rad/sec)**	**Damping Ratio**	**Frequency (Hz)**
1, 2	-5.57	20.64	0.26	3.28
3, 4	-4.23	18.15	0.23	2.89
5, 6	-9.81	17.72	0.48	2.82

4.4.2 Identification of significant buses

The modes of voltage instability were calculated using modal analysis and given in Figure 4.3. The weakest mode to the voltage stability was found to Mode 12, which has a magnitude of 0.4932.

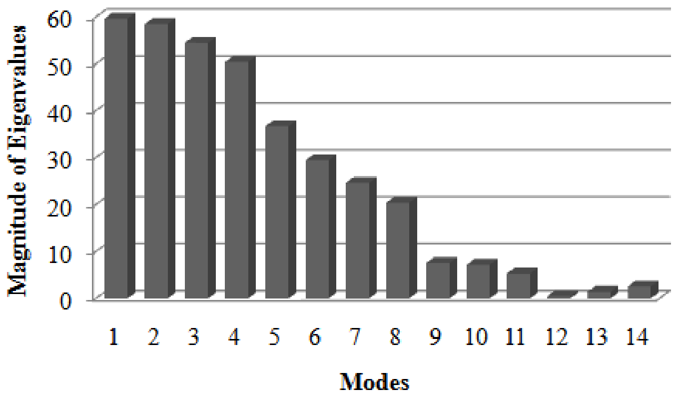


Figure 4.3: Modes of voltage stability.

Bus participations to the weakest mode are given in Table 4.2. It can be observed that Bus 16 has the highest bus participation factor for Mode 12. Hence, Bus 16 is the most appropriate location of shunt compensator for voltage stability improvement. The ranking of candidate buses are 16, 15, 3, 13, and 14. These buses are the possible location of shunt controller for small signal stability enhancement.

Table 4.2: Bus participation

Bus#	**Bus participation**	**Normalized participation**
3	0.1848	0.8391
4	0.0016	0.0073
5	0.0058	0.0262
6	0.0025	0.0114
7	0.0026	0.0119
8	0.0157	0.0714
9	0.0128	0.0582
10	0.0656	0.2979
11	0.0076	0.0345
12	0.0143	0.065

13	0.1658	0.7525
14	0.089	0.4038
15	0.2116	0.9603
16	0.2203	1

4.4.3 Impact of capacitor placement

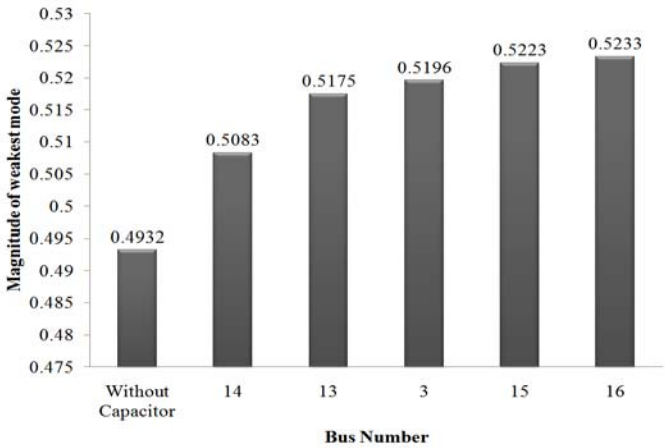


Figure 4.4: Magnitudes of the weakest modes with different capacitor locations.

Shunt capacitor of 5 MVAR was placed at the candidate buses identified in section 4.4. First, impact of capacitor placement on the weakest mode of voltage stability is presented in Figure 4.4. It can be observed that the magnitude of weakest mode increases as shunt capacitor is placed in the system. This means the voltage stability of the system increases [77],[76]. Furthermore, the magnitude of weakest mode increases as the capacitor is moved from lower to higher ranked buses. This supports the bus ranking result obtained in section 4.4.

Next, impact of capacitor placement on small signal stability was studied by placing the capacitor at Bus 16, which is the highest ranked bus. The result is presented in Figure 4.5. It can be observed that the placement of capacitors push the system eigenvalues towards the right side in the complex plane. As a result, the damping of oscillatory modes is weakened. The reason behind this phenomenon is the negative damping imposed by shunt compensators on synchronizing and damping torques of the system oscillations.

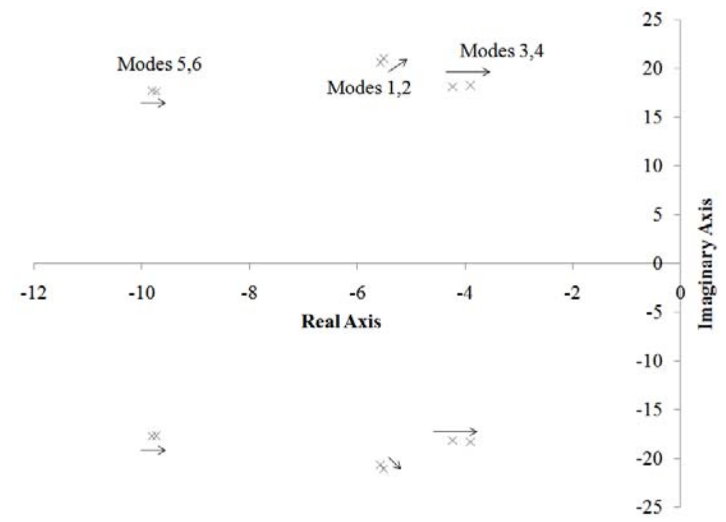


Figure 4.5: Oscillatory modes with and without capacitor at Bus 3.

Placement of shunt capacitors at different buses of a distribution system has different impact on oscillatory modes. However, the primary objective of a shunt capacitor in a distribution system is voltage control. So, the best location of a shunt capacitor would be the one among the candidate buses identified in Section 4.4 which has the least detrimental impact on damping of oscillatory modes. This means the location which gives the least shift of eigenvalues towards the right side of the complex plane would be the best location. The difference of real part of eigenvalues with and without the additional shunt capacitors is taken as the shift of eigenvalues. The shifts of oscillatory modes when shunt capacitors are placed at different candidate buses are shown in Figure 4.6.

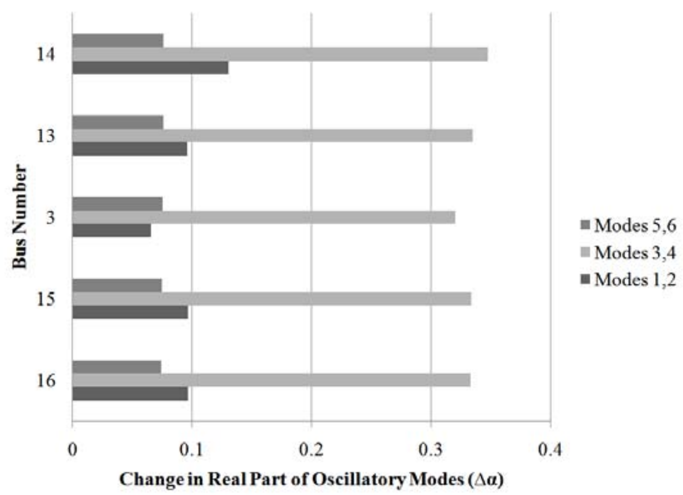


Figure 4.6: Change in real part of oscillatory modes with different capacitor placements.

It can be observed that placement of capacitor at Bus 3 results in the least shift of Modes

3,4 by 0.319 towards right direction on the complex plane. So, Bus 3 would be the best location of shunt capacitor for the least detrimental impact on system modes. With capacitor at Bus 3, the shifts of Modes 1, 2 and Modes 5, 6 are 0.065 and 0.075 respectively. The shifts of Modes 1, 2 and Modes 5, 6 are not significant with different locations of shunt capacitor.

4.4.4 Placement of SVC

The primary controller of SVC may support damping of electromechanical oscillations of a power system [82]. In other words, it is able to reduce possible negative damping effect caused by shunt capacitor. Fig. 4.1 suggests that SVC controller can add a pole, which would effectively reduce weakening of oscillatory modes due to capacitor. As a dynamic component, SVC adds a state variable to the state space representation of the system. The influence of SVC state variable to the system oscillation modes can be observed by evaluating the participation factor. In this paper, participation factor is used as an index to determine the best location of SVC. The location for which the SVC state has the maximum value of participation factor to the system oscillatory modes is selected as the best location of SVC to support small signal stability of the system. For a particular value of T_r, SVC participation depends on its location.

The participation factors of SVC states on these modes are shown in Figure 4.7. The model of SVC as shown in Figure 4.1 has been used. The gain and thyristor time constants are assumed to be 1 and 0.02 seconds respectively [76]. The gain adjustment may be discarded to see the effectiveness of SVC on system damping [83]. It can be observed that locating SVC at Bus 3 results in the highest participation of SVC state on Modes 1,2 and Modes 3,4. The participation on Modes 5, 6 is 0.0013, which is relatively very small but still is the highest among all the SVC locations. So, Bus 3 is a suitable place for installing SVC to support the small signal stability of the system. It is important to note that the best location of SVC is the same as the location of capacitor, which would have the least detrimental impact on system modes as explained in Section 4.4

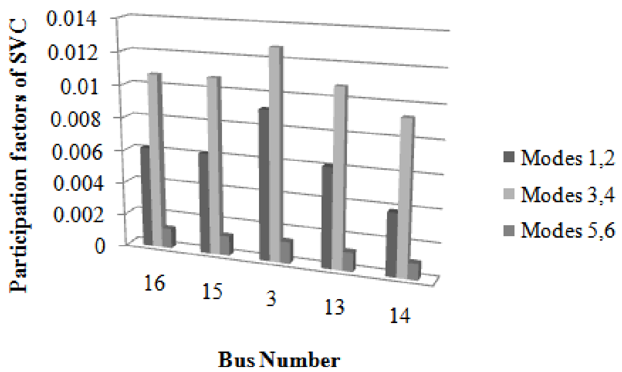


Figure 4.7: Participation factors of SVC states on system modes with different locations of SVC.

4.4.5 Comparison of SVC and shunt capacitor placement

The negative damping effect of shunt compensators can be minimized by properly designed primary controller of SVC. The effectiveness of SVC can be observed by comparing the shifts of real part of modes with respect to the base case for SVC and capacitor placements. The size of both capacitor and SVC were taken as 5 MVAR. The gain and thyristor time constants are again 1 and 0.02 seconds, respectively. The effectiveness may be improved by proper setting of the gains and time constants of SVC. Here, SVC and capacitor were placed at Bus 3 and corresponding shift of oscillatory modes were observed. The result is shown in Figure 4.8.

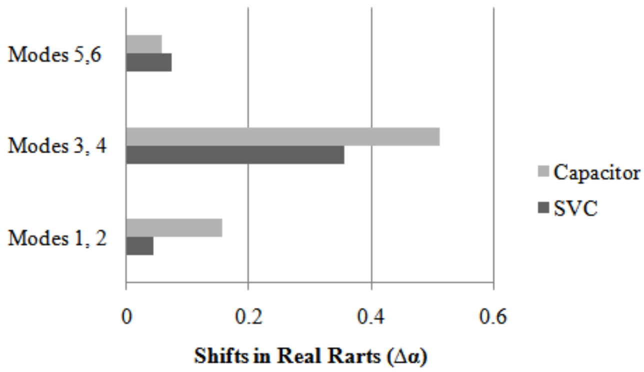


Figure 4.8: Comparison of real part shift with shunt capacitor and SVC at Bus 3.

It can be observed that placement of SVC results in smaller shifts of real part of the modes 1, 2 and Modes 3, 4 towards the right of the complex plane as compared to placement of capacitor. The shifts of Modes 5, 6 are very small in both cases and that indicates that shunt controllers have negligible contribution to these modes. It is important to note that placement of SVC also deteriorates the stability of oscillation modes in the same way as capacitor does. For this reason, some additional controllers are suggested for SVC to improve the stability of oscillatory modes in addition to voltage stability[82],[15]. This work is concerned on the best location of SVC without an additional controller, which can serve for enhancing voltage stability as well as minimizing negative damping effect of shunt capacitor.

Now effectiveness of SVC and capacitor for improving the time domain response of the distribution system were observed. The sudden increase in wind power output by 10% was taken as a disturbance to the system. The responses of voltage at Bus 3 and rotor speed of synchronous generator at Bus 3 were observed. The results are shown in Figures 4.9 and 4.10. It can be observed that the response of voltage is slightly less damped with capacitor than without any controller at Bus 3. Also, damping of oscillations in bus voltage and generator rotor speed has been improved with SVC placement compared to capacitor placement. This is because of the primary controller of SVC, which adjust its total susceptance to generate required reactive power to maintain the voltage magnitude.

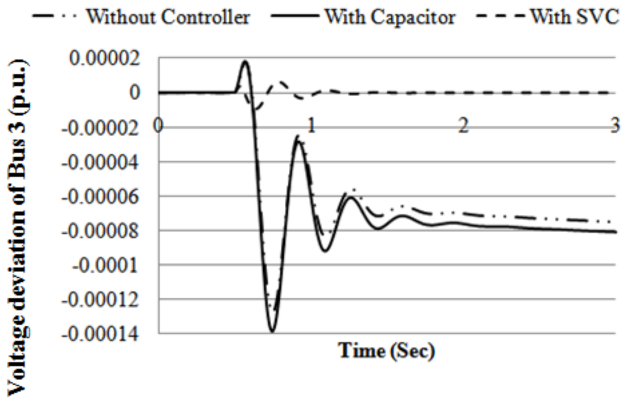


Figure 4.9: Comparison of response of voltage at bus 3 with and without shunt controller.

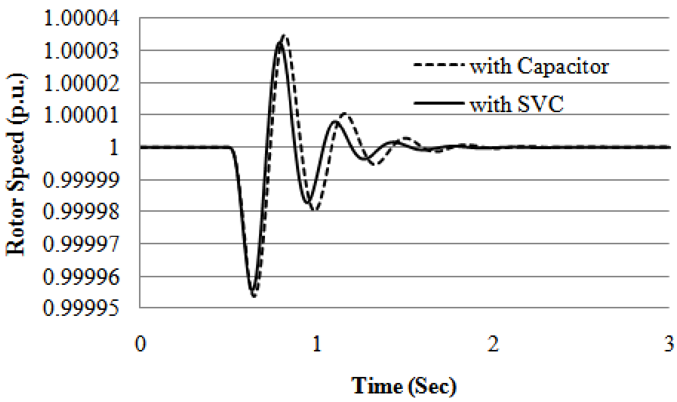


Figure 4.10: Comparison of response of rotor speed of generator at Bus 3 with shunt capacitor and SVC.

4.5 Summary

Shunt compensators are commonly used in a power system to support voltage stability. However, shunt compensators can sometimes be detrimental to oscillation damping. Integration of DG units into a distribution system obviously generates some oscillation modes, which need to be well damped. On the other hand, distribution systems are usually highly compensated to enhance voltage regulation. So, careful attention should be paid to locate shunt controllers to minimize the detrimental impact on oscillation damping. The results are published in [84]. In this work, an approach to locate shunt controllers to enhance the stability of distribution system with DG units is presented. First, buses were ranked for best locations of shunt controller for static voltage stability enhancement. Then, the location for which shunt compensator gives the least detrimental impact on oscillation damping is selected as the best location for small signal stability enhancement. For a static shunt compensator such as capacitor, the minimum eigenvalue shift may be used as an index while participation factor may be used as an index to locate a dynamic compensator such as SVC. SVC is a better choice for oscillation damping as compared to shunt capacitor of the same rating. SVC performances are better for transient responses of bus voltage and generator rotor angle. This suggests that SVC controller can be designed to enhance the dynamic performance of a distribution system with DG units. The design aspects will be addressed in our future works.

Chapter 5 Conclusion and Summary

5.1 Conclusions

Based on the analyses presented in chapter 2, 3 and 4 following conclusions are drawn:

1. Reactive power margin based index can be considered as a reliable stability index to identify critical node with all kind of load uncertainties of a typical distribution system.
2. Distributed placement of VAR compensator among weak buses results in reduced amount of loss compared to concentrated placement of VAR source on the weakest bus.
3. A controller location suitable for voltage stability may not necessarily be suitable for small signal stability.
4. Damping of oscillatory modes is weakened by both shunt capacitor and SVC without any additional damping controller. However, the weakening effect by an appropriately located SVC is less than the shunt capacitor of same rating.

5.2 Future work

Based on the conclusion from chapter 2, 3 and 4 it can be said that comprehensive additional control methodology needs to be developed to enhance the availability of DG in pre-fault as well as post fault conditions maintaining grid interconnection requirement. To achieve this goal, future work will focus on following issues:

1. Development of unified placement methodology for various reactive power devices (Capacitor banks as well as STATCOMs) in the network to improve the static and dynamic loadability of the system & to maintain post-and during fault voltage profiles, as stipulated by IEEE/Grid interconnection requirements for DG.

2. Verification/validation of the proposed methodology in view of IEEE standard and grid code using simulation platform developed in DIGISILENT.

As of now, impacts of different controllers on oscillatory stability of a distribution system have been investigated under the assumptions that they are already placed in network for small signal stability enhancement, which is a rare case. Future work will be on the design of dedicated controllers to improve small signal stability of a distribution system with emphasis on following points:

1. Design of an additional controller for SVC to improve damping of oscillatory modes.

2. Investigation on impacts of various DG units on oscillatory modes through appropriate analytical framework.

Appendix I: List of publications (embedded files)

1. Tareq Aziz, T.K. Saha, N. Mithulananthan, "Distributed Generators Placement for Loadability Enhancement Based on Reactive Power Margin," Proceedings of the 9th International Power and Energy Conference IPEC2010, 27 - 29 October 2010, Singapore.

2. Tareq Aziz, T.K. Saha, and N. Mithulananthan, "Identification of the Weakest Bus in a Distribution System with Load Uncertainties Using Reactive Power Margin, Proceedings of the 2010 Australasian Universities Power Engineering Conference, Christchurch, New Zealand, 5-8 December 2010.

3. S. Dahal, N. Mithulananthan, and T. K. Saha, "Investigation of Small Signal Stability of a Renewable Energy Based Electricity Distribution System," IEEE Power and Energy Society General Meeting, 2010, Minneapolis, USA, July 2010.

4. S. Dahal, N. Mithulananthan, T. Saha, " Enhancement of small signal stability of a renewable energy based electricity distribution system using shunt controllers", in proceedings of Australasian Universities Power Engineering Conference (AUPEC 2010), Dec 5 – 8, Christchurch, New Zealand.

5. Tareq Aziz, Sudarshan Dahal, N. Mithulananthan and Tapan K. Saha, "Impact of Widespread Penetrations of Renewable Generation on Distribution System Stability" 6th International Conference on Electrical & Computer Engineering 2010 (ICECE'10), December 18-20, 2010, Dhaka, Bangladesh.

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