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Ramaprasad Panda
Silicon Institute of Technology, Bhubaneswar, India, rp_panda@sify.com

PRASANTA KUMAR SATPATHY Dr.
Biju Pattnaik University of Technology, Rourkela, Orissa, India, satpathy.pks@gmail.com

Subrata Paul
Jadavpur University, Kolkata, India, speejupow@yahoo.co.in

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Application of SVC to mitigate voltage instability in a Wind system connected with GRID

Ramaprasad Panda[1], Prasant kumar Satpathy[2], Subrata Paul[3]
Silicon Institute of Technology[1], Bhubaneswar, India
Biju Pattnaik University of Technology[2], Rourkela, Orissa, India
Jadavpur University[3], Kolkata, India
Email ID: rp_panda@sify.com[1], satpathy.pks@gmail.com[2], speejupow@yahoo.co.in[2]

***Abstract*: This paper presents an approach for enhancement of voltage stability of an interconnected power system employing distributed generators (DG) along with conventional generators. When the DG is from wind then voltage instability in the system is of great concern. In this paper a 28 bus test system is considered where the wind penetration varies from 10% to 99% over the day. This causes a large variation at different bus voltages violating the grid code. A shunt FACT device (SVC) is used to mitigate this problem at the buses connected to wind generators. Thereafter, suitable locations for the SVC placement are identified to enhance the voltage stability and reduce system power loss. The simulation study is carried out on the system using the software program developed in Matpower-4. The same is verified by using the software MiPower®.**

***Keywords*— Include at least 5 keywords or phrases**

I. INTRODUCTION

Recently wind power generation has been experiencing a rapid development in a global scale. The size of wind turbines and wind farms are increasing quickly; a large amount of wind power is integrated into the power system. As the wind power penetration into the grid increases quickly, the influence of wind turbines on the power quality and voltage stability is becoming more and more important. It is well known that a huge penetration of wind energy in a power system may cause important problems due to the random nature of the wind and the characteristics of the wind generators. In large wind farms connected to the transmission network (110 kV – 220 kV) the main technical constraint to take into account is the power system transient stability that could be lost when, for example, a voltage dip causes the switch off of a large number of wind generators.

Induction machines are used extensively in the power system as induction motors but are not widely used as generators. Despite their simplicity in construction, they are not preferred as much as synchronous generators. This is mainly due to the defined relationship between the export of P and absorption of Q.

Connecting a wind generation scheme to a network will affect the operation and performance of the network depending on the scheme and rating of the generator itself. The impacts are as follows:

- Power Flows
- Voltage stability
- Fault Analysis
- Impact of Wind Turbines on the Networks

In this paper the issue of voltage instability is discussed in a 28 bus system with wind penetration at various buses along with conventional generators. A system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude after a disturbance, increase in load demand or change in operating condition. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power. Under normal operating conditions, the bus voltage magnitude (V) increases as reactive power (Q) injected at the same bus is increased. However, when voltage of any bus decreases with the increase in reactive power, for that same bus, the system is said to be unstable. Although the voltage instability is a localized problem, its impact on the system can be wide spread as it depends on the relationship between transmitted P, injected Q and receiving end V. These relationships play an important role in the stability analysis and can be displayed graphically [1].

Induction machines consume reactive power and consequently, it is present practice to provide power factor correction capacitors at each wind turbine. These are typically rated at around 30 per cent of the wind farm capacity. Hence wind systems are considered as active power generator only. This limitation causes voltage instability problem in the system when the wind output varies over a large range. This is because the existing conventional generators are unable to compensate this large variation in requirement of reactive power in the system due to their rated MVA constrains.

Use of fixed capacitor/reactor in the system is one of the solutions. But dynamic nature of wind generation restricts the use of fixed compensation. Use of suitable FACTs at suitable places devices can give a robust solution to this problem.

II. FLEXIBLE AC TRANSMISSION

FACTs is an acronym which stands for Flexible AC Transmission System. FACTs is an evolving technology based solution envisioned to help the utility industry to deal with changes in the power delivery business. The potential benefits of FACTs equipment are now widely recognized by the power systems engineering and T&D communities. The philosophy of FACTs is to use power electronic controlled devices to control power flows in a transmission network, thereby allowing transmission line plant to be loaded to its full capability. FACT devices are broadly classified in to two categories based on the type of power switches employed. They can be

1. **Thyristor-Based FACTs Controllers**
2. **GTO-Based FACTS**

Developments in the field of high voltage power electronics have made possible the practical realization of FACTs controllers. By the 1970s, the voltage and current rating of GTOs had been increased significantly making them suitable for applications in high voltage power systems [2]. This made construction of modern Static VAR Compensators (SVCs), Thyristor Controlled Series Capacitors (TCSCs), Thyristor Controlled Phase Angle Regulators (TCPARs), and many other FACTS controllers possible. A fundamental feature of the thyristor based switching controllers is that the speed of response of passive power system components such as a capacitor or a reactor is enhanced, but their compensation capacity is still solely determined by the size of the reactive component.

Series capacitors are connected in series with transmission lines to compensate for the inductive reactance of the line, increasing the maximum transmittable power and reducing the effective reactive power loss. Power transfer control can be done continuously and rather fast using the Thyristor Controlled Series Capacitors (TCSCs), making it very useful to dynamically control power oscillations in power systems [3]

A normal thyristor, which is basically a one-way switch, can block high voltages in the off-state and carry large currents in the on-state with only small on-state voltage drop. The thyristor, having no current interruption capability, changes from onstate to off-state when the current drops below the holding current and, therefore, has a serious deficiency that prevents its use in switched mode applications. With the development of the high voltage, high current Gate Turn-Off thyristors (GTOs), it became possible to overcome this deficiency. Like the normal thyristor, a gate current pulse can turn on the GTO thyristor, while to turn it off, a negative gate-cathode voltage can be applied at any time. This feature and the improved ratings of GTOs made possible the use of Voltage-Sourced Converters (VSC) in power system applications.

If a VSC is connected to the transmission system via a shunt transformer, it can generate or absorb reactive power from the bus to which it is connected. Such a controller is called Synchronous Static Compensator or STATCOM and is used for voltage control in transmission systems [4]. The major advantage of a STATCOM, as compared to a SVC, is its reduced size, sometimes even to less than 50 %, and a potential cost reduction achieved from the elimination of capacitor and reactor banks as well as other passive components required by the SVC.

If a VSC is employed as a series device by connecting it to the transmission line via a series transformer, it is called a Static Synchronous Series Compensator or simply SSSC. This controller can also generate or absorb reactive power from the line to which is connected and in that way change the series impedance of the line. It is convenient to think of the SSSC as being comparable to a continuously variable series capacitor or inductor, and, therefore, can be used to control the power flow in the transmission line [5]

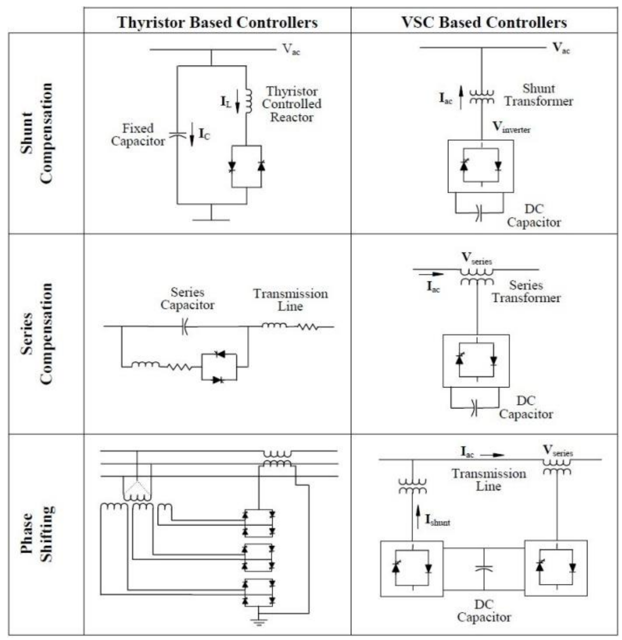

Figure: 1 Summary of different FACT controllers

A Unified Power Flow Controller (UPFC) can control transmission line impedance, voltage and phase angle. It has the capability of controlling with two-degrees of freedom, i.e. it can control inverter output voltage magnitude and phase angle and only the current rating of the device limits its output capabilities [6]. This new device offers utilities the ability to control voltage magnitude in the system, control power flows, both steady-state and dynamic, on predefined corridors, allowing secure loading of transmission lines up to their full thermal capability. A summary of different FACTs controllers is given in Fig.1

Shunt-connected FACTs devices such as SVC are adopted to control the bus voltage magnitude or the reactive power injected at the bus. SVC is installed to improve the voltage regulation and voltage stability at various buses in an interconnected system.

III. MODELING OF SVC

The Static VAR Compensator (SVC) equipment is composed by capacitors, thyristors and inductances [7]. There are mainly three existing SVC models in load flow calculations, e.g. the generator-fixed susceptance model, the total susceptance model and the firing angle model.

The generator model represents the slope by connecting the SVC to an auxiliary bus separated from the high voltage bus by a reactance equal to the per unit slope. The generator model of a SVC with and without a step-down transformer is shown in Fig.2(b) & 2(c). The generator model can be directly used in a conventional load flow program. However, the generator model is valid only when the SVC is operating within the regulated limits. The SVC model has to be changed to a fixed capacitor or inductor model depending on the operating limit. The generator model needs 2 or 3 nodes (depending on without or with a step-down transformer) in a load flow program; whereas the fixed impedance model only needs 1 node. When the SVC is changing from the generator model to the fixed susceptance model, the load flow input data matrices need to be modified and the corresponding Jacobian matrix is re-dimensioned and reordered. In other words, a new load flow calculation is needed. The necessity to continuously check whether or not the SVC is changing between the generator model and the fixed-susceptance model also makes the method inefficient and troublesome. In this paper the generator model is connected where the SVC operates with in the regulated limits without considering the SVC transformer. Transformer.

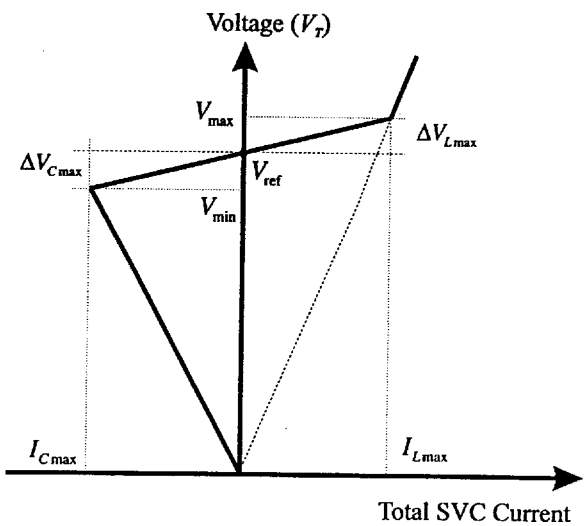

Fig.2(a) SVC Characteristics

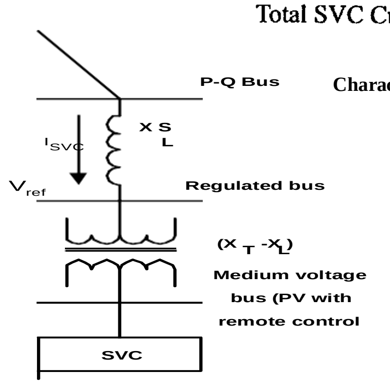

Fig.2(b) SVC models with slope representation using conventional power flow *PV* busses

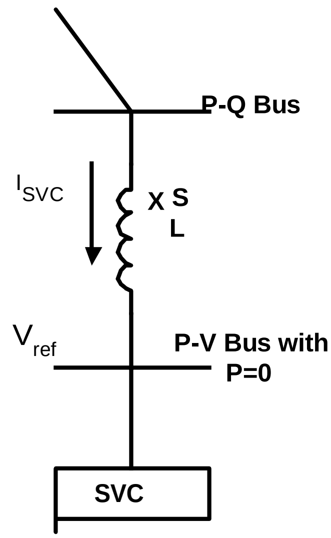

Fig.2(c) include the SVC Transformer

IV. Simulation Studies:

System under Study

In this study, the various issues arising out of the integration of wind energy is analyzed with a practical system. An equivalent model of the network is derived from the practical system with 28 bus system shown in Fig.5. Here four number of wind farms are connected at bus 41 to 44 with the capacity of 147 MW, 50 MW, 25 MW and 110 MWs respectively at 33 kV level. One thermal generator of 50 MW is also connected at bus 23 on 132 kV level. The grid interconnection is at 400 kV as shown with an equivalent generator. The distance between wind farms and the grid for 147 MW, 50 MW, 25 MW and 110 MW wind farms are 326 km, 296 km, 255 km and 329 km respectively. All the wind farms are connected through 220 kV and 132 kV single circuit lines, except the 147 MW wind farm, which is connected with a double circuit line for a short distance of 30 kms. The present system has a unique problem in which with 70% of wind generation, the voltage at some buses going beyond 1.1 PU though the loading on the network are within the limits. Further, the voltage drops down to below 0.9 PU when wind generation increases to 95% and it has not been possible for generation beyond this level even though full generation was possible with very good wind potential, leading to the disconnection of some wind turbines. Hence in order to understand the issues detailed measurements were undertaken at buses 10, 22 and 24. The details of system considered for the study and measurement are given in system data.

System Data: The single line diagram of the equivalent electrical network is shown in Fig.5. Bus 1 is the grid bus at 400 kV level, buses 2 to 11 are at 220 kV level, buses 21 to 33 are at 132 kV level and the wind farms are connected to the buses 41 to 44 at 33 kV level. The transmission lines of 220 kV level are of zebra conductors with thermal rating of over 200 MVA and that of 132 kV level are the panther conductors with the thermal rating of over 90 MVA. The equivalent loads at different busses are given in Table 1.

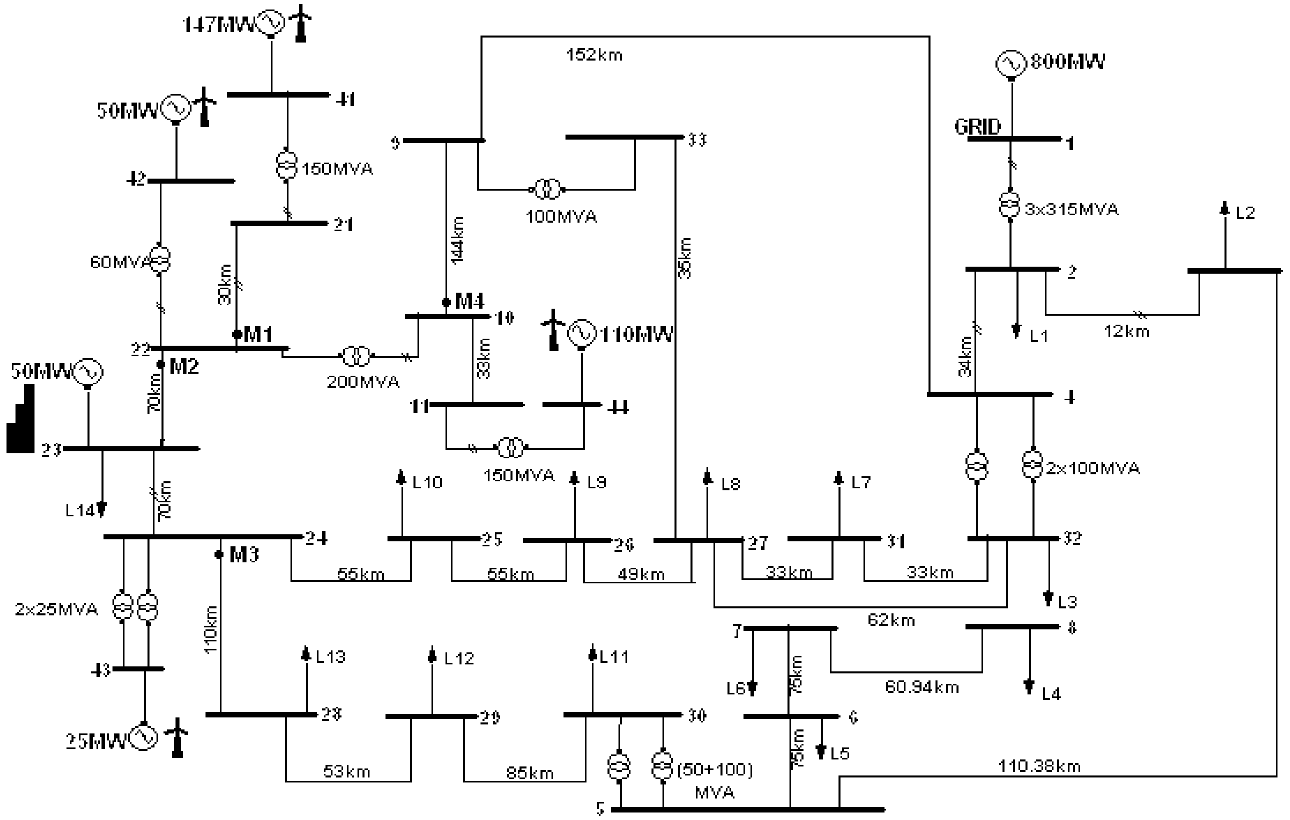

Fig.3 Layout of the 28 bus wing system

Table 1: Load Details

Sl no	Load no	Connection at bus	Load details (MW+jMVAR)
1	L1	2	43.96+j0.47
2	L2	3	91.85+j55.79
3	L3	32	11.64+ j3.1
4	L4	8	108.54+j20.8
5	L5	6	16.56+j0.37
6	L6	7	-102.03+j0.249
7	L7	31	4.9+j3.83
8	L8	27	0.65+j0.4
9	L9	26	0.6+j0.35
10	L10	25	0.5+j0.3
11	L11	30	34.82+j12.43
12	L12	29	19.96+j9.36
13	L13	28	9.25+j6.97
14	L14	23	1.81+j1.21

Simulation studies were carried out using Matpower-4 to determine the adequacy of the existing system and hence to determine the wind power evacuation possible with the existing infrastructure. In the simulation, the conventional generation sources are treated as PV buses as the generator would maintain the voltage by varying its reactive power generation. However, Wind turbine generators are typically induction generators without internal excitation source. Hence, these machines absorb reactive power from the system and do not generate any reactive power. In order to reduce the reactive power charges, shunt capacitor banks at the terminals of the wind turbine generator are installed which is a fixed compensation, so that effective drawl of reactive power is nearly zero. Hence the wind generator buses are treated as PQ buses. The load flow was carried out for the system represented in Fig.5, for varying wind generating conditions. The installed wind power generation capacity at buses 41, 42, 43, and 44 are to an extent of 147, 50, 25 and 110 MW's respectively. The power generation is varied in steps of 10%

from no generation to full generation. The voltage in per unit at the wind farm buses and at buses 10, 21, 28 and 29 (which are in the vicinity of wind farms and at distant from the wind farms) for various generation conditions are tabulated in table 2. It is seen from the table 2, that there is an increase in voltage at buses near wind farms much beyond the limits and at buses far away from the wind farms (buses 28 and 29), the voltage drops to a very low value as the wind generation exceeds 70 % of the installed capacity which is beyond the grid code limits. Further, the result shows, it is not possible to evacuate full capacity of wind generation even if full generation is possible.

Table 2: Change in voltages at important buses with change in wind generation

% wind	bus 10	bus 21	bus 28	bus 29	bus 41	bus 42	bus 43	bus 44
10	1.06	1.061	0.982	0.966	1.061	1.059	1.034	1.061
20	1.065	1.069	0.981	0.965	1.069	1.065	1.036	1.067
30	1.066	1.072	0.977	0.961	1.072	1.066	1.035	1.069
40	1.063	1.07	0.97	0.954	1.071	1.063	1.029	1.066
50	1.054	1.063	0.958	0.943	1.064	1.055	1.018	1.058
60	1.038	1.049	0.941	0.929	1.05	1.039	1.001	1.042
70	1.02	1.033	0.924	0.913	1.034	1.022	0.985	1.025
80	1.01	1.027	0.916	0.905	1.028	1.014	0.981	1.015
90	0.998	1.017	0.907	0.895	1.019	1.003	0.977	1.003
100	0.881	0.903	0.816	0.818	0.904	0.886	0.875	0.886

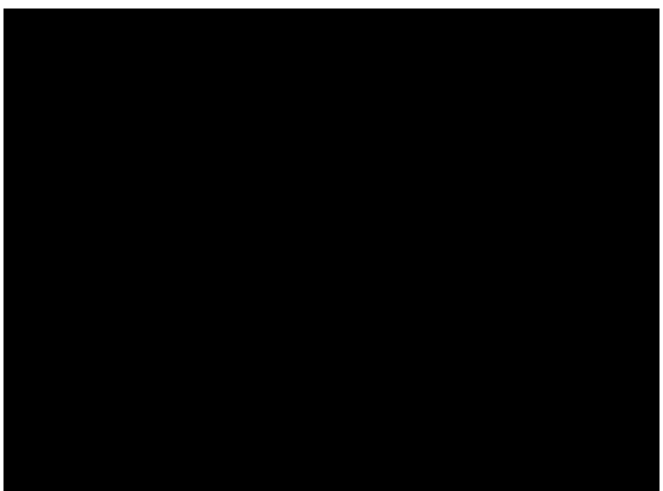

fig 4 Voltage drop at various at impotant buses

The reduction of voltage may be explained as the inability of the power system to supply the reactive power or by an excessive absorption of reactive power by the system itself. Also it is observed that the line loss increases squarely with respect to wind generation. Through voltage instability analysis L index [8] at various buses are calculated with peak wind generation which is given at table: 3.

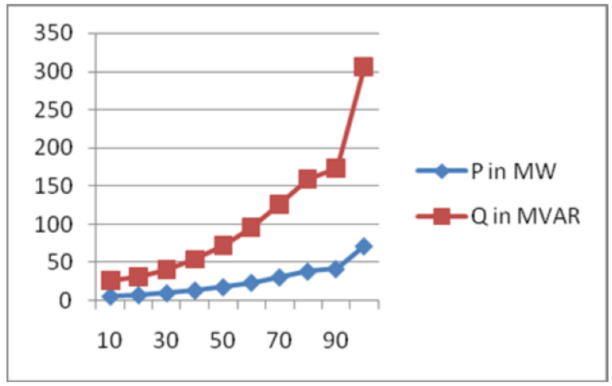

Fig. 5 P & Q losses with respect to increase in wind generation

L-Index at bus 41 increases from 0.015 to 0.529, as wind generation increases from zero to maximum. A similar observation is made at buses 42, 44, 21 and 11. The L-index values clearly show that, as the wind generation increases, the system become more unstable. This demonstrates the need for suitable reactive power compensation in order to improve the voltage stability of the network. The largest values of L-index are at buses 41, 42, 44, 21, and bus 11 are 0.529, 0.481, 0.476, 0.420 and0.391 respectively. Buses 41, 42 and 44 are the wind farm buses at 33 kV level, bus 21 is at 132 kV level and bus 11 is at 220 kV level.

Simulation studies were carried out for all these buses with placement of a SVC alternatively with following parameters
Maximum capacitive compensation50 MVAR
Maximum Inductive Compensation 50 MVAR
Characteristics' Slope =0.1
The results show varying levels of compensation requirement to maintain the required voltage level, line losses & no of buses violating required voltage level in the system at various level of wind generation i.e. at 10%, 70% & 100% of their installed capacity in each case. The readings are available in table:4

Table 3: L- index at various buses

	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 21	Bus 22	Bus 24
L-index at 0% wind	0.037	0.046	0.038	0.12	0.146	0.163	0.224	0.031	0.02	0.02	0.015	0.015	0.028
L- index at 99% wind	0.039	0.05	0.046	0.145	0.18	0.207	0.282	0.167	0.356	0.391	0.42	0.365	0.036
	Bus 25	**Bus 26**	**Bus 27**	**Bus 28**	**Bus 29**	**Bus 30**	**Bus 31**	**Bus 32**	**Bus 33**	**Bus 41**	**Bus 42**	**Bus 43**	**Bus 44**
L-index at 0% wind	0.032	0.036	0.04	0.114	0.143	0.145	0.044	0.043	0.036	0.015	0.015	0.028	0.02

L- index at 99% wind	0.05	0.065	0.078	0.152	0.191	0.181	0.071	0.062	0.113	0.529	0.481	0.081	0.476

Table 4: Variation of bus voltages and line losses with SVCs at critical buses

Wind Gen	SVC Bus	Bus 10	Bus 21	Bus 28	Bus 29	Bus 41	Bus 42	Bus 43	Bus 44	P loss	Q loss	SVC Inject	No of buses *
10%	Without	1.06	1.061	0.982	0.966	1.061	1.059	1.034	1.061	5.67	26.14	NA	7
70%	Without	1.02	1.033	0.924	0.913	1.034	1.022	0.985	1.025	30.783	126.37	NA	7
100%	Without	0.881	0.903	0.816	0.818	0.904	0.886	0.875	0.886	71.674	306.86	NA	25
10%	41	1.041	1.037	0.971	0.958	1.034	1.038	1.021	1.043	5.597	26.09	-6.82	1
70%	41	1.025	1.04	0.925	0.914	1.043	1.027	0.986	1.03	30.622	125.56	4.73	6
100%	41	0.994	1.023	0.895	0.884	1.03	1.003	0.97	0.999	57.283	240.42	14.33	7
10%	42	1.043	1.043	0.931	0.959	1.043	1.033	1.022	1.045	5.595	26.08	-8.5	1
70%	42	1.031	1.045	0.929	0.917	1.046	1.04	0.99	1.035	30.336	124.28	6.99	6
100%	42	1	1.024	0.898	0.886	1.026	1.025	0.973	1.005	56.78	238.43	1.4	7
10%	44	1.031	1.034	0.968	0.955	1.034	1.032	1.016	1.021	5.586	26.28	-13.94	1
70%	44	1.03	1.043	0.928	0.916	1.044	1.031	0.989	1.04	30.389	124.54	6.67	7
100%	44	1.004	1.024	0.899	0.887	1.025	1.008	0.974	1.024	56.513	237.16	18.15	7
10%	11	1.038	1.04	0.971	0.957	1.04	1.038	1.02	1.036	5.58	26.02	-10.97	1
70%	11	1.033	1.046	0.929	0.917	1.047	1.034	0.991	1.04	30.244	123.9	7.84	6
100%	11	1.009	1.028	0.899	0.887	1.029	1.012	0.974	1.02	56.192	235.96	22.13	7
10%	21	1.04	1.035	0.971	0.957	1.036	1.037	1.02	1.041	5.595	26.09	-10.44	1
70%	21	1.027	1.042	0.926	0.915	1.044	1.029	0.987	1.031	30.534	125.15	5.39	7
100%	21	0.998	1.028	0.898	0.886	1.029	1.007	0.973	1.003	56.865	238.55	15.59	7

***Voltage Outside (0.95-1.05 p.u.) range**

From the above table, it is seen that the appropriate location would be at bus 41 and 42 which had the maximum value of L-index of the system. The detailed analysis clearly shows that L-index technique provides an optimal solution in locating the dynamic compensator where the compensation level required is also most optimum and appropriate. The above analysis clearly indicates the necessity of a dynamic compensation in order to evacuate full generation. SVC is the most cost economic solution compared to other dynamic compensator considering the time of action, voltage variation and the ease of operation.

V. CONCLUSION

In this paper the voltage instability problems in a wind generation system with grid connectivity is discussed. It was found that variation in wind generation creates severe voltage variations in the grid inviting the possibility of a system blackout. As the amount of wind generation is dynamic in nature over the day, reactive compensation for the system should be dynamic in nature. An SVC at the most critical bus is a better option for maintain voltage stability in the system without overloading the lines.

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