A Novel Scheme for Placement and Sizing of SVCs to Improve Voltage Stability of Wind-Integrated Power Systems

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Received: 28.01.2015 Accepted:03.04.2015

Abstract-On the grid front, issues concerning voltage instability worsen further as and when large wind farms are integrated at multiple locations in an existing network. Since the wind power is fluctuating in nature, it largely affects the reactive power mismatch and prevents the grid operators from injection of wind power to the grid even though it is available abundantly. Dynamic compensation of reactive power at multiple locations of the network could be an effective means for addressing such problems. This paper presents a novel method for suitable placement and sizing of Static VAR Compensators at desired locations, such that smooth evacuation of wind power can occur under various operating conditions, while maintaining voltage stability, simultaneously. The authors have studied the adverse impacts of wind penetration under various system conditions and implemented the scheme in order to improve voltage sensitivity index. The results obtained from the case studies conducted on the standard IEEE 30-bus and practical Indian 28-bus test systems validate the proposed scheme.

Keywords: Voltage stability; L-index; Wind Integration; SVC; Grid Code.

1. Introduction

Voltage instability is still a visible problem to many matured utilities in the power sector [1-3]. This problem may surface in any system, whenever the VAR demand shoots up the margin of available VAR supply in that system at that point of time. The VAR mismatch in the system is governed by various factors, namely the distance between generating stations with respect to major load centers, mode of their connectivity, characteristics of the loads, and availability of reactive power support in the system [4]. Wind power plants often provide a better alternative for supplementing the deficit power requirements of the grids as compared to large scale generating units, e.g. hydro electric and thermal units [5]. These units are preferably situated in regions having higher potential for wind energy, regardless of where the major load centers in the system are located. Therefore, commissioning of wind farms in the existing grid might lead to generic problems such as power congestion, violation of bus voltages beyond the stipulated grid code, abnormal system losses and voltage instability, thus creating further problems for evacuation of power injected by these farms [6]. In view of this, the authors have conducted a thorough study in order to identify the bottlenecks which restrict smooth evacuation of wind power to the grids, and to find a suitable solution as regards sizing and placement of SVCs to overcome the said limitations.

In this paper, the authors have focused on two major aspect of wind integration. Firstly, the study is conducted to identify the effect of wind power integration in the existing power system, which is followed by evaluation of the critical buses in the system based on voltage stability index (L-index) and the margin of voltage deviation at the load buses for two scenarios (before and after wind farm integration). Such critical buses need additional VAR support for the improvement of voltage profile in the system. However, arbitrary selection of the location and random selection of the magnitude of VAR support may be uneconomical. Therefore, in the next part of the study, an attempt is made to find suitable locations for placing the appropriate size of SVCs in order to maintain a standard voltage profile in the system during possible variations in operating conditions. This paper is organized in the following manner. Section 2 highlights the scope of wind power plants along with the basis for performing the impact analysis. Section 3 describes the criteria considered for evaluation and assessment of voltage stability indices. In Section 4, the modeling aspect of SVCs for steady-state analysis is described. Section 5 describes the procedure for the implementation and simulation of the proposed approach along with the analysis of the case study. The case study includes two test systems, namely modified IEEE 30-bus and practical Indian 28-bus test system. The results of simulation are obtained with the support from the MATLAB based Matpower platform while accommodating the modifications proposed by the authors. These results clearly indicate that the location of critical buses and margin of voltage deviation at these buses do change while moving from the pre-integration period to the post-integration period of wind power penetration. This change justifies the adverse impact of wind power integration in existing grids. The authors have demonstrated that the criticality of the load buses is quite curable by means of installing appropriate size of SVCs at suitable locations. The study justifies that placement of SVCs at suitable locations ensures smooth penetration of wind power into the grid during various loading conditions and level of wind penetration in the range of 0% to 100% of installed capacity, while maintaining the bus voltages within the grid code limit.

2. Scope of Wind Energy

From a global perspective, solar and wind energy dominate the energy market in the category of inexhaustible sources of energy. Since growth of solar power penetration is restricted by availability of land (1 MW solar panel needs approximately 5 acres of cleared land), wind energy is considered as a leading contender. Though wind power still bears an image of a plaything in the view of some environmentalists, it is emerging as a serious alternative for most of the researchers and utilities involved in seeking a clean, green alternative. This is true not only in developed countries of the world but in developing countries like India and China as well. Therefore, the need for continuous research exists in most of the countries who are avidly seeking alternative energy sources.

Traditional wind generation units consisting of Simply Fed Induction Generators (SFIG) do not support reactive power generation, but on the contrary are reactive power consumers. Therefore, SFIG wind parks are typically equipped with external sources of reactive power. Static sources like shunt capacitors are relatively inexpensive compared to dynamic resources such as SVCs [4]. In contrast, newer wind parks consisting of Doubly Fed Induction Generators (DFIGs) having reactive power capability, are preferred [7]. The presence of power electronic controls in DFIGs makes the system a fast acting dynamic reactive resource as compared to direct grid connected synchronous generators used in conventional power plants [8]. This allows for voltage control and reactive power regulation of the wind park. However, in the literature it is reported that the limiting factor for reactive power production in DFIGs is typically the rotor current limit, and for the reactive power absorption the limiting factor is the stator current limit [9].

Further, the rotor voltage exhibits a limiting effect at high positive and negative slips, whereas the reactive power capability is very sensitive to small changes in the slip near the limiting zone. As such, the voltage control capability of DFIGs does not match that of the synchronous generators, due to the limited capacity of the pulse width modulated (PWM) converters. Therefore, when the voltage control requirement for the overall system goes beyond the capability of the DFIGs, the voltage stability of the grid is seriously affected. These limitations create difficulty in maintaining steady power generation of wind generators. Further, in the absence of dedicated transmission corridors, generated wind power may not be smoothly evacuated to the far end load centers. This causes other problems like voltage instability and line congestion. A single line diagram illustrating wind power integration in an existing power system is shown in Figure 1.

In this Figure, ‘VC’ represents the voltage of the power grid bus extending connection for the wind power plant, ‘VW’ represents the voltage of the local bus at the wind power plant end, ‘Z’ represents the impedance of the connecting line including cables and transformers, ‘PW’ and ‘QW’ represent the respective real and reactive powers supplied by the wind power plant. The complex power ‘SC’ injected to the grid at the connecting bus is calculated as per Equation (1).

$$S_C = {(V_C)^2}/{Z^*} \tag{1}$$

Where, ‘Z*’ is the complex conjugate of the line impedance ‘Z’. It could also be observed from Figure 1 that ‘PW’ and ‘QW’ are the differential active and reactive powers at the local wind bus, as expressed in Equations (2) and (3).

$$P_W = P_G - P_L \quad (2)$$

$$Q_W = Q_G - Q_L \quad (3)$$

Where PG and QG represent the active and reactive power generated at the wind park while PL and QL represents the loads at the local wind bus.

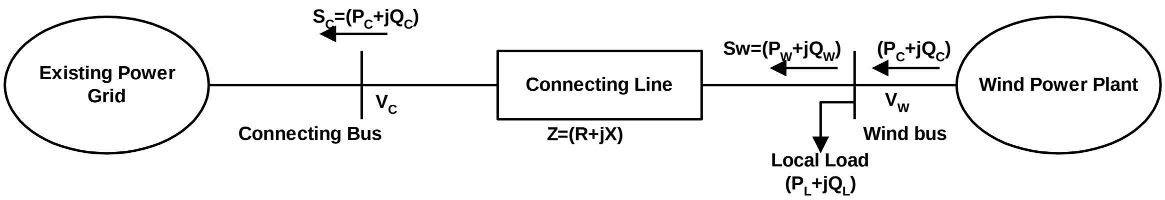


Fig. 1. Schematic of wind power integration in existing grid

In the event that such wind farms remain geographically far away from major load centers and have relatively weak connectivity with the existing grids, the line impedance becomes large enough to limit the power injected to the grid. Such limitations may amount to serious operational concerns for voltage stability of the system due to a wide departure of ‘VW’ as depicted in Equation (4).

$$V_W = \sqrt{\left[\left(\left\{2\alpha - V_C^2\right\}/_3\right)^2 - \left\{\alpha^2 + \beta^2\right\}\right]^{\frac{1}{2}} + \left(V_C^2/_2\right) - \alpha} \quad (4)$$

Where,

$$\alpha = -(RP_W + XQ_W) \quad (5)$$

$$\beta = -(XP_W - RQ_W) \quad (6)$$

Further, wind farms equipped with fixed speed wind turbines and simple induction generators also play an important role. These induction generators often behave as induction motors by consuming reactive power, thereby significantly affecting the local grid voltage during system contingency. These factors genuinely force the grid operator to restrict the wind farms from injecting power to the grid, even in steady state.

3. Voltage Stability Assessment in Wind-Integrated Grids

Voltage instability has been given much attention by power system researchers and planners in recent years, and is being regarded as one of the major sources of power system insecurity. Voltage instability phenomena are the ones in which the receiving end voltage decreases well below its normal value. While trying to regain normalcy with the support of restoring mechanisms, it may continue to oscillate further due to lack of enough damping against the disturbances. Voltage collapse is the process by which the voltage falls to a low, unacceptable value as a result of an avalanche of events accompanying voltage instability.

Developing countries like India and China are faced with a sharp increase for energy demand in recent years. The government is also offering incentives to entrepreneurs to come-up with large wind farms at potential wind sites. It is often observed in practice that majority of large wind farms in China and India are geographically far away from load centers being connected to the grid through relatively weak transmission networks. These two factors raise serious concerns about system security and stability. As a result of wind power integration, the focus is getting gradually shifted from the power quality issues to the ensuing voltage stability problems.

It is always desirable that the voltage profile in power system operations be maintained within acceptable limits to ensure stability, security and reliability of power systems. A sudden imbalance between reactive power demand and reactive power supply may be responsible for the violation of voltage profile beyond the stipulated grid code. Hence, an adequate reserve of reactive power and a quick dynamic supply are among the successful remedial actions needed to avoid voltage collapse occurrences. However, determination of the optimal location and size of compensation becomes very important in preventing voltage collapse/operating a power system in the most economical way. The compensation is usually addressed at vulnerable locations in the system, which may be identified through various voltage sensitive indices.

Several methods were developed over the past two decades to conduct static voltage stability analysis. The line index method is a method which uses system’s impedance matrix as the study parameter in order to characterize the critical bus bars in a system by assigning a suitable L-index [10-11]. This method is derived from the power flow solution of the system. Using the load bus self admittance matrix and the mutual admittance matrix between the generator and load buses, a complex gain matrix of the power system is obtained.

Consider a system where n is the total number of buses with g generator buses, and remaining (n-g) load buses. For a given system operating condition, using the load-flow (state-estimation) results, the voltage-stability L index is computed as shown in Equation (7).

$$L_j = \left|1 - \sum_{i=1}^{g} F_{ji}\left(V_i/V_j\right)\right| \tag{7}$$

Where j=g+1...n and all the terms within the sigma on the right-hand side of (1) are complex quantities. The values of Fji are complex and are obtained from the network Y-bus matrix. For a given operating condition,

$$\begin{vmatrix} I_G \\ I_L \end{vmatrix} = \begin{vmatrix} Y^{GG} & Y^{GL} \\ Y^{LG} & Y^{LL} \end{vmatrix} \begin{vmatrix} V_G \\ V_L \end{vmatrix} \tag{8}$$

Where IG, IL and VG, VL represent complex current and voltage vectors at the generator nodes and load nodes. [YGG], [YGL], [YLL] and [YLG] are corresponding partitioned portions of the network Y-bus matrix. Rearranging equation 8, we obtain

$$\begin{vmatrix} V_L \\ I_G \end{vmatrix} = \begin{vmatrix} Z^{LL} & F^{LG} \\ K^{GL} & Y^{GG} \end{vmatrix} \begin{vmatrix} I_L \\ V_G \end{vmatrix} \tag{9}$$

Where

$$|F^{LG}| = -|Y^{LL}|^{-1}|Y^{LG}| \tag{10}$$

The L-index is a good indicator of the critical buses in a system in terms of their proximity to voltage collapse. This index varies in the range of zero and unity. The load buses having higher values of L-indices are considered to be more critical. The authors have used the L-index for determining the critical ranking of the buses because of its reliability and robustness.

FACT devices [12-16] are increasingly being utilized in many electric power systems to enhance voltage control and system dynamic performance. Among the existing devices, SVCs are more suitable for improvement of voltage regulation and enhancement of voltage stability margins. In most cases of SVC applications, reactive power is locally controlled to maintain the required voltage at the connected bus.

SVCs are shunt connected static devices, which can generate and/or absorb reactive power as per the specific requirements of the power system [17-18]. Out of several SVC models available in the literature [19-20], the authors have used the practical model in this work as indicated in Figure 2.

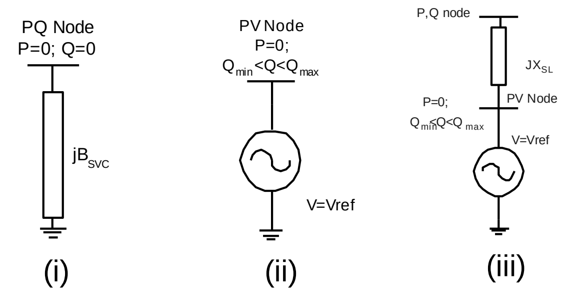
In the active model the SVC is treated as a nodal power injection device [21]. It uses active sources in the equivalent circuit, which can be easily incorporated in all power flow calculations. Generally, the active model uses the reactive power injection/consumption by the SVC as the state variable (Qs). The operational technical limits for this variable are:

$$Q_{\min} \le Q_{svc} \le Q_{\max} \tag{11}$$

$$Q_{\max} = B_{ind} \times V_{ref}^2 \tag{12}$$

$$Q_{\min} = B_{cap} \times V_{ref}^2 \tag{13}$$

Where Bind and Bcap are inductive and capacitive susceptance and Vref is the reference for the bus voltage.



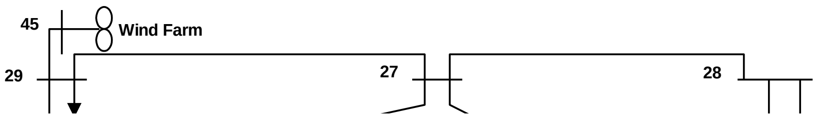


Table 1. Wind Integration details in IEEE 30-bus system

Connecting Line No.	From Grid bus	To wind bus	Installed wind capacity (MW)	Line Parameters (p.u.)		
				R	X	B
42	30	31	56	0.0159	0.0725	0.0306
43	26	32	21	0.0165	0.12574	0.0255
44	24	33	14	0.0343	0.11098	0.0714
45	29	34	49	0.0183	0.09539	0.03366

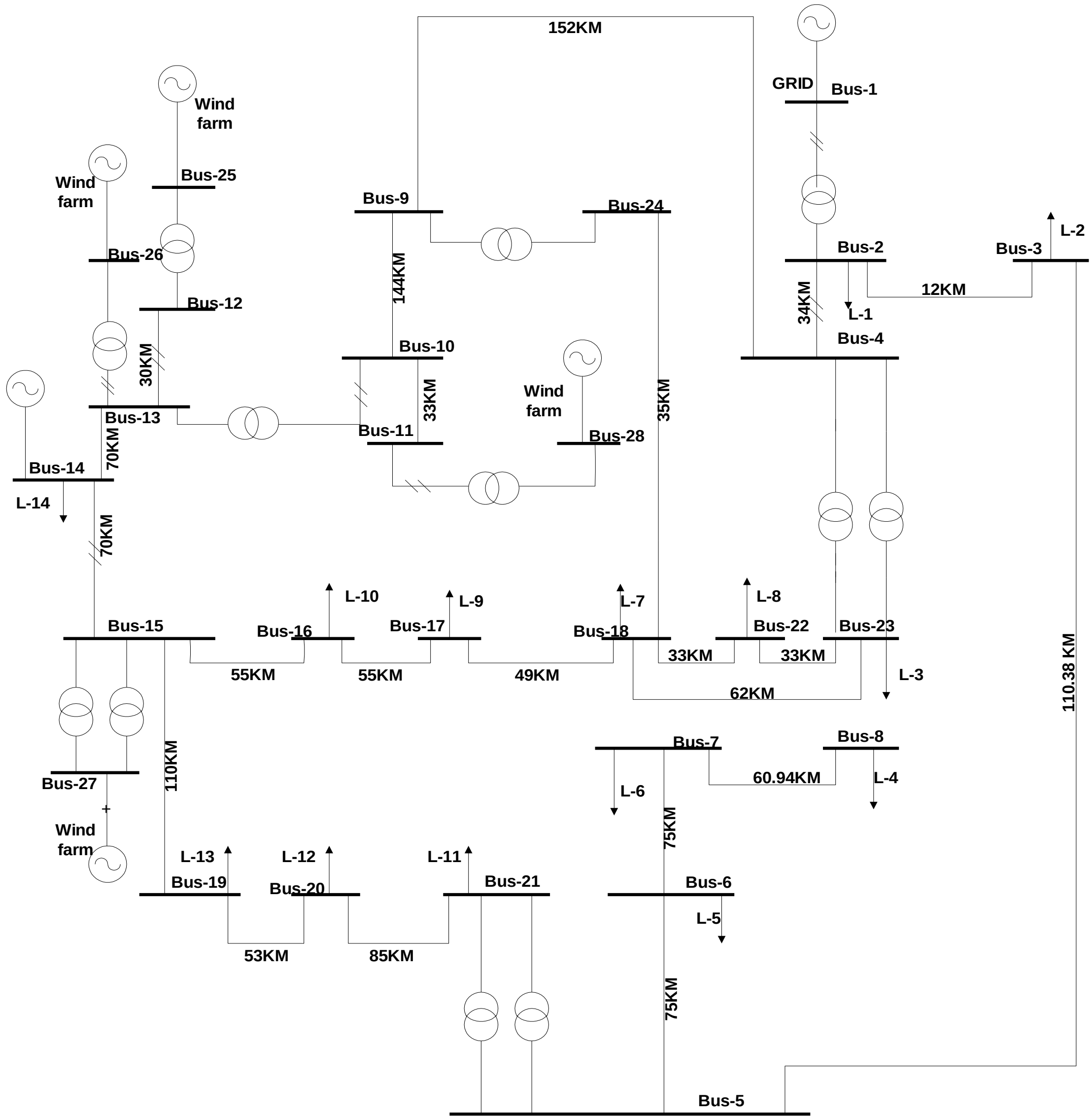


Fig. 2. Various SVC models (i) Passive (ii) Active and (iii) Practical model

Fig. 4. Schematic of 28 bus practical Indian system

In various applications, if the SVC parameters are within the range Imin < Isvc < Imax and Vmin < V <Vmax, it is represented as a PV/generator node at an auxiliary bus with P=0, V=Vref. A reactance of (XSL) equivalent to the slope of the V-I characteristic, shown in Figure 3 is added between the auxiliary node and the node of coupling to the system. The node at the point of common coupling remains as a PQ node.

4. Problem Formulation, Implementation and Analysis

In order to examine the adverse impacts of wind integration on voltage stability and hence to mitigate it through placement of multiple SVCs, the authors have considered the IEEE 30-bus test system and the practical 28-bus Indian test system. The original IEEE 30-bus system has been modified to accommodate four wind farms as shown in Figure 3. Each wind generator is connected to the system through an external link consisting of a transformer and a line. The system data for IEEE 30-bus test system is taken from the literature [22]. The line parameters of the external links are given in Table 1. All the PV bus voltages are set to 1.05 per unit (p.u). The transformation ratio of each transformer is set to unity for keeping the load bus voltages within the grid code range with given load (base case). The layout of practical Indian 28-bus test system is shown in Figure 4.

The system data for 28-bus system consisting of four wind farms is given in Annexure I. The objective of the study is fulfilled in this paper through the following steps.

Step-1: Firstly, various operating conditions are formulated by simulating different loading conditions, level of wind penetration and contingencies. For each operating condition, the load buses which violate the grid code are identified. Out of all such operating conditions, the one having maximum number of grid code violation at load buses is identified as the severest condition, which is presented for the next step in order to find suitable size and location for placement of SVCs. The details of this step are presented in the form of a flowchart as shown in Figure 5.

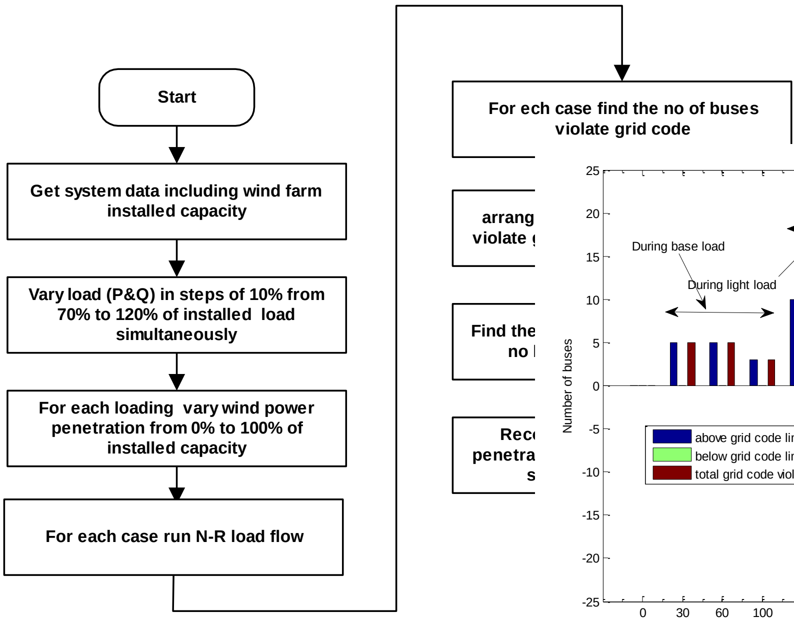


Fig. 5. Algorithm for determining the most c

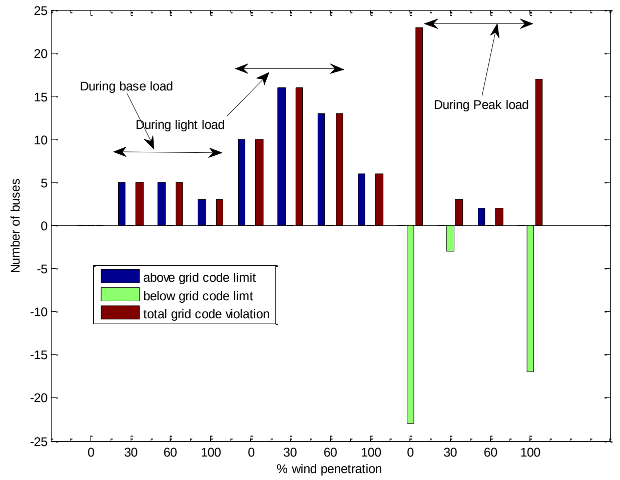
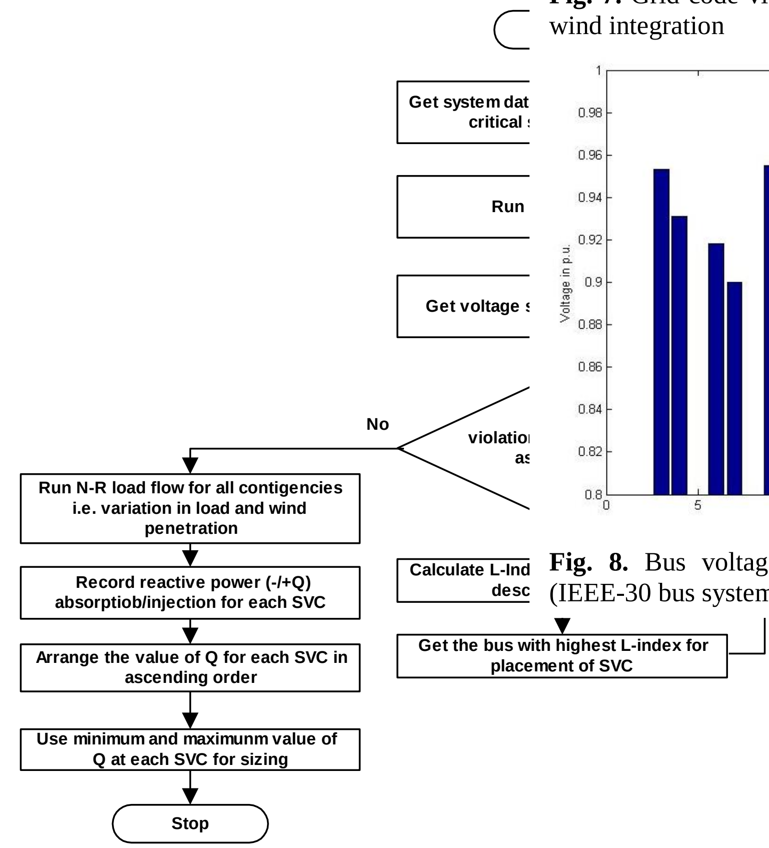


Fig. 7. Grid code violation for IEEE-30 bus system with wind integration



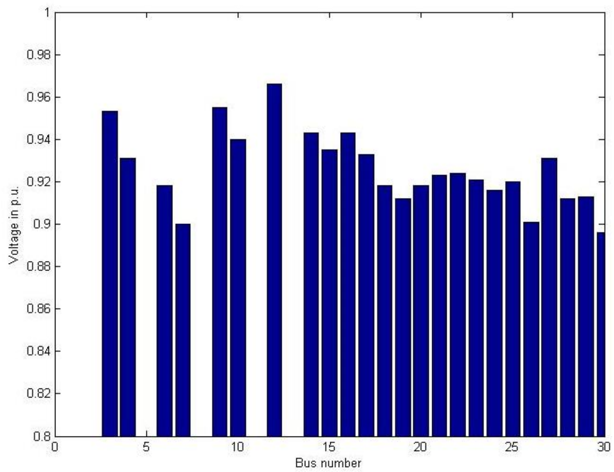


Fig. 8. Bus voltage during most critical contingency (IEEE-30 bus system without SVCs)

Fig. 6. Algorithm for the placement of SVCs

Step-2: In this step, the level of wind penetration and level of loading at the local buses corresponding to the severest condition obtained from Step-1 are used for critical ranking of the load buses based on L-Index. An SVC is placed at the most critical bus and N-R load flow is performed for ensuring that no bus voltage is violating the specified grid code. If the violation persists, then another SVC is placed at the most critical bus obtained from the later step and the loop continues, till no bus voltage violates the grid code.

Step-3: After identifying the number of SVCs and their locations from Step-2, the size of the SVCs is determined in this step. The N-R load flow is again carried out with all SVCs available at the selected locations for all system operating conditions. For each operating conditions VAR injection/absorption at each SVC is calculated for sizing of the SVCs. The algorithm shown in the flow chart (Figure 6) is applied for most suitable placement of SVCs and their VAR limits.

Table 2 presents most critical buses in terms of highest L-Index and number of buses violating voltage deviations beyond grid code limit (±5%) for possible system conditions in the IEEE 30-bus test case. The possible system scenario is achieved by varying the load in the local grid from light to peak demand in steps (70% to 130% of base load) and wind penetration in the grid is varied from 0 to 100% of installed capacity for each loading condition.

Figure 7 shows the number of buses violating grid code limit in voltage deviation for all possible scenarios for IEEE 30-bus test system. It also shows that the voltage deviation takes place on either side of the stipulated grid code limits justifying the need for reactive power support. It can be seen that a record number of twenty three buses out of thirty get affected by voltage deviation during peak demand while there is no wind power generation. Figure 8 shows the load bus voltage profile of IEEE 30-bus system during the most critical system condition mentioned above.

Table 2. Grid Code violation for IEEE-30 bus System (Without SVC)

Loading Condition of the system	Wind Penetration as % of installed capacity	Number of buses violating grid code	Most Critical Bus with its L-index	
			Bus No.	L index
Base Load	0%	0	30	0.145
	30%	5	19	0.092
	60%	5	30	0.236
	100%	3	30	0.493
Light Load (70%)	0%	10	30	0.092
	30%	16	30	0.094
	60%	13	30	0.253
	100%	6	30	0.494
Peak Load (130%)	**0%**	**23**	**30**	**0.241**
	30%	3	19	0.141
	60%	2	30	0.232
	100%	17	30	0.598

A similar study is also done for the 28- bus Indian system, results of which are presented in Table 3, Figure 9, and Figure 10. The study shows that the system becomes most critical in terms of voltage deviations when the system is under base load with 100% wind penetration in the network.

In order to maintain all load bus voltages within the grid code limit, SVCs have been placed at selective locations/buses based on the logic of Step-2 and VAR limits of these SVCs are calculated with the principle mentioned in Step-3.

Table 3. Grid Code violation for 28-Bus Indian System (Without SVC)

Loading Condition of the system	Wind Penetration as % of installed capacity	Number of buses having grid code violation	Most Critical Bus with its L-index	
			Bus No.	L index
Light Load (70%)	0%	11	8	0.09
	30%	11	25	0.097
	60%	7	25	0.21
	100%	3	25	0.407
Base load	0%	1	8	0.236
	30%	8	8	0.233
	60%	8	8	0.241
	100%	**22**	**25**	**0.456**
Peak loading (120%)	0%	7	8	0.385
	30%	10	8	0.384
	60%	7	8	0.401
	100%	11	8	0.433

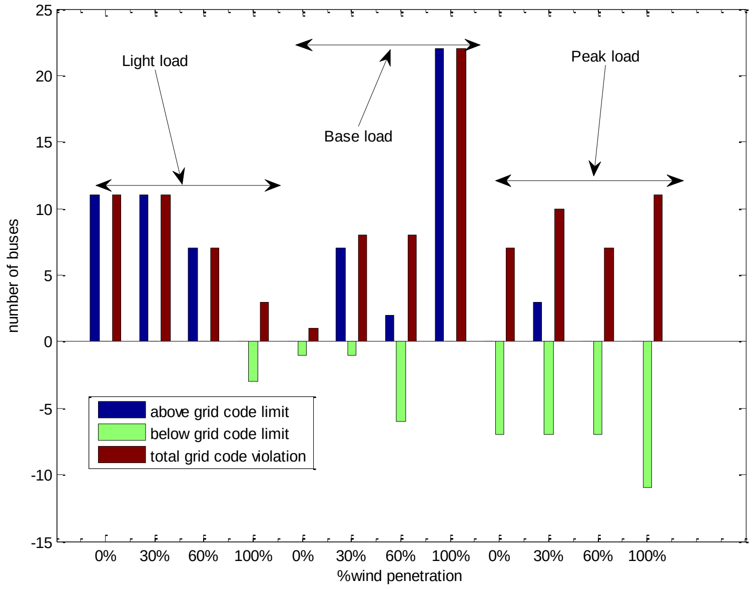


Fig. 9. Grid code violation for 28-bus Indian system with wind integration

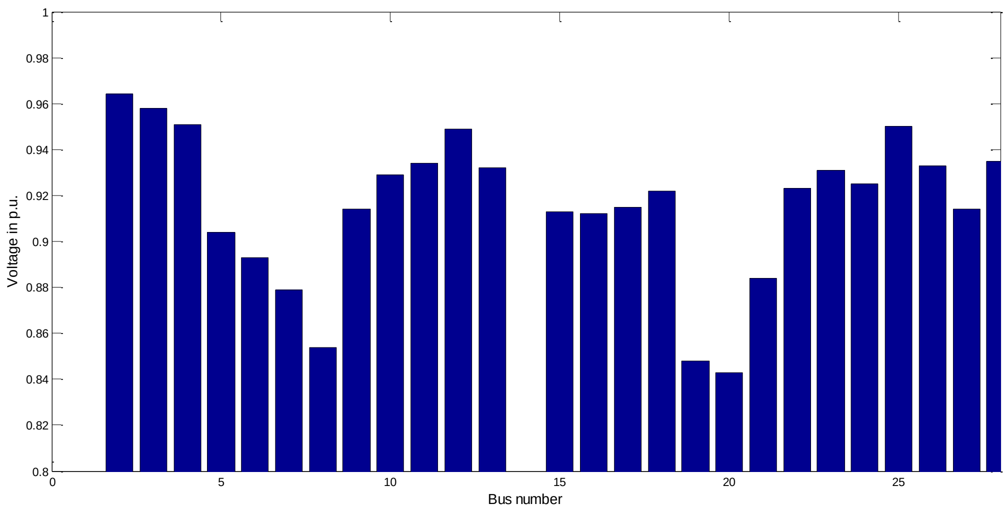


Fig. 10. Bus voltage during most critical condition (28-bus Indian system without SVCs)

The result shows that three SVCs are necessary to be placed at buses 30, 26 and 19 so that all bus voltages are maintained within the stipulated grid code limit for wind integrated IEEE 30-bus system. This is depicted in Table 4 and Figure 11.

Similarly, the proposed scheme is tested for 28-bus Indian system where it needs four number of SVCs at buses 25, 8, 28 and 20 so that smooth evacuation of wind power can be done through the local grid without violation of stipulated voltage limit for all system operating conditions. The results are shown in Table 5 and Figure12.

5. Conclusions

This paper has focused on two broad accepts related to a wind integrated power system. In the first part of the work, the adverse impact on the local grid through which the wind power is to be evacuated is studied. It is found that there is an

Table 4. Location and Size of SVCs for wind integrated IEEE 30-bus system

Most critical Bus for SVC placement	Qsvc (MVAR) For most critical contingency	Number of Buses violating Grid Code	Most Critical Bus after SVC placement	L-Index of that Bus	Remarks on Grid Code Violation	Extreme Q limits for all operating conditions For sizing	
						Q_{max}	Q_{min}
30	12.17	13	26	0.172	Exists	NA	NA
30 26	8.54 7.55	6	19	0.158	Exists	NA	NA
30 26 19	5.98 4.32 17.82	0	29	0.162	Nil	-16.17 -6.96 -11.37	5.98 4.32 22.77

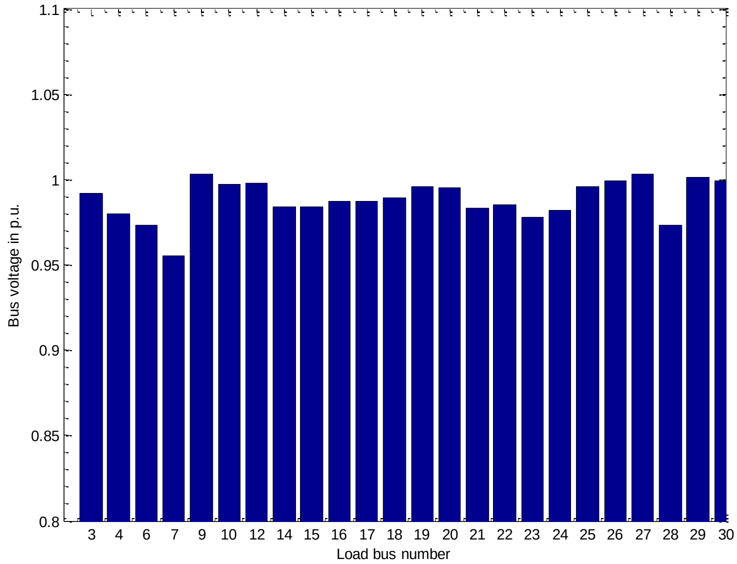


Fig. 11. Bus voltage during the most critical contingency (IEEE 30-bus system with SVCs)

Table 5. Location for SVCs for the most critical condition in the 28-bus system

Most critical Bus for SVC placement	Qsvc (MVAR) For most critical contingency	Number of Buses violating Grid Code	Most Critical Bus after SVC placement	L-Index of that Bus	Remarks on Grid Code Violation	Extreme Q limits for all operating conditions For sizing	
						Q_{max}	Q_{min}
25	6.62	14	8	0.27	Exists	NA	
25 8	-0.31 36.58	4	28	0.175	Exists	NA	
25 8 28	-6.96 35.99 37.63	3	20	0.101	Exists	NA	
25 8 28 20	-9.97 24.79 37.03 41.73	0	26	0.084	Nil	-8.93 -0.57 -16.1 2.79	-13.61 38.49 6.41 50.0

issue related to voltage instability at the local buses in terms

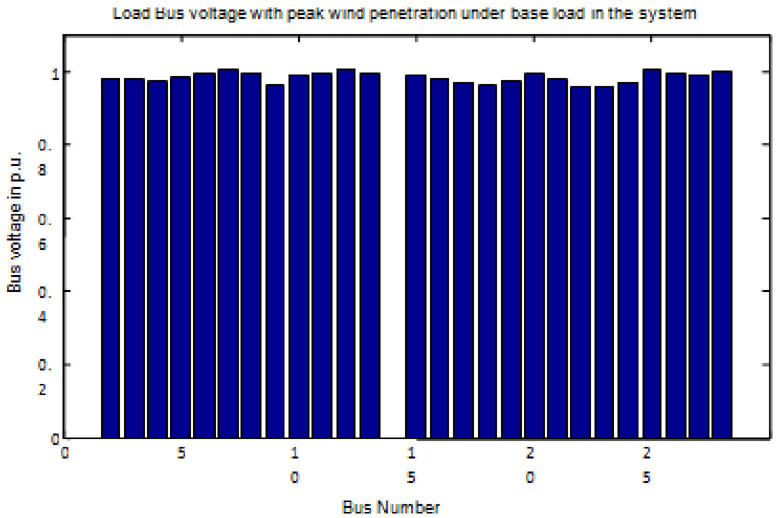


Fig. 12. Bus voltage during most critical condition (28-bus Indian system with SVCs)

of shifting of the criticality as the operating conditions change in the system. Since the wind power is highly erratic in nature, the voltage instability issue becomes further worse that needs fast and dynamic reactive power compensation at multiple locations. In the second part of the work suitable placement of SVCs is determined by a novel method based on improved voltage sensitivity index. The osbjective of this work is to restrict the violation of voltage at local buses within stipulated grid code limits under all operating conditions. The proposed method satisfies this objective, which is presented through case study on IEEE 30-bus test system and 28-bus Indian practical system.

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