Voltage stability improvement by using a newly designed STATCOM controller in case of high wind penetration cases

Kadir ABACI[1], Volkan YAMAÇLI[1], Zhe CHEN[2]
[1]Electrical-Electronics Department, Faculty of Engineering, Mersin University, Mersin, Turkey
[2]Energy Technology Department, Faculty of Engineering and Science, Aalborg University, Aalborg, Denmark

Abstract- **In this study, the penetration effect of wind generation on voltage stability in a weak multi machine power system has been investigated. In terms of static and dynamic voltage stability, the most critical bus of IEEE 10-machine 39-bus system has been determined by using sensitivity analysis. The comparison has been made for various wind power penetration levels. It is shown if a large amount of wind power is integrated into power system, the system stability will be deteriorated. In the paper, a static synchronous compensators (STATCOM) is proposed to improve the stability. The calculations and simulations have been conducted by DIgSILENT Power Factory 15.0. Comparative simulation results show that the STATCOM can effectively increase voltage stability margin of the AC system which was considerably decreased due to wind power's penetration.**

I. INTRODUCTION

Among the renewable energy sources, the wind energy has the fastest growing development [1, 2]. As the capacity of wind farms continue to increase, it is clear that the level of wind penetration will increase further. But a power system may have difficulty to absorb the available wind energy and maintain the system reliability and stability, which may be reduced as the wind penetration increases [3]. The close relationship between reactive power and voltage magnitude is known widely in the literature. Several studies have addressed the impact of increased penetration of wind power on the reactive power requirement of power system and voltage stability problem [4-8]. By connecting wind farms into power systems, the reactive power reserve and thus voltage stability of AC system will decrease. The reactive power support can be provided discretely by mechanically switched shunt capacitors and dynamically by synchronous condenser [9], Static Var Compensator (SVC) [10-11], or STATCOM [12-15] to ensure both steady state and transient stability during and after a disturbance [16]. In [10-11], the reactive power control by using SVC in the power system with high wind power generation and its effect on static and dynamic has been presented. During disturbance and heavy loading, the FACTS devices are very effective to maintain the voltage stability. The STATCOM improves voltage stability by reactive power regulation. In [12], a new STATCOM controller design is achieved in order to improve voltage stability of a weak AC system after integrating wind power system. In another study [13], steady-state stability is improved in a wind farm by using STATCOM device. In [14], in order to improve the transient and voltage stability of a power system Artificial Neural Network (ANN) based STATCOM is suggested with a Squirrel Cage Induction Generator based wind tribune (SCIGs). [15] shows how dynamic reactive support with a STATCOM improves the voltage quality and the extent to which low voltage ride through could be achieved.

The aim of this study is to presents the performance of STATCOM device which is installed on the most sensitive bus in a power system integrated with a wind power system. The critical bus of the 39-bus New England test is determined by the sensitivity analysis under various level of wind power penetration. STATCOM device's positive effects on voltage stability are shown by carrying out the long-term and transient voltage stability analysis.

II. CONFIGURATION OF THE SYSTEM

The Permanent Magnet Synchronous Generator (PMSG) based wind farm system consists of the transformers, the VSCs, the phase reactors, and the DC links as shown in Fig 1. The PMSG based wind farm and STATCOM are connected to the most critical bus in the weakest area of multi-machine power system. The wind power is connected to bus 10 of the New England system. In addition a new STATCOM has been installed to the most critical bus of the power system. Synchronous generators are modelled using sixth-order models. PMSG based wind farm and STATCOM devices controller models have been designed by using DIgSILENT Simulation Language (DSL). The model details are discussed in the following sections.

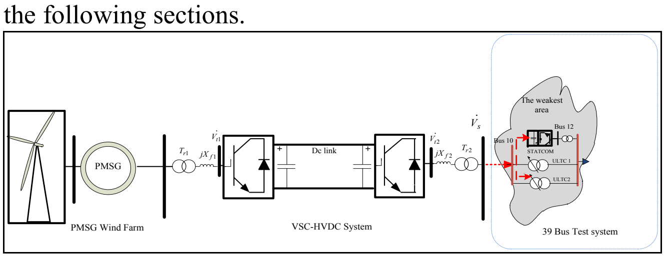

Fig. 1.Simplified representation of the PMSG based wind farm and to connected grid.

A. *Wind Turbine Model*

In this study because of less reactive power demand, PMSG based wind turbine instead of DFIG has been preferred. Because in the PMSG based wind farm by the self

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excitation capability, low excitation and high torque density losses providing more reactive power. The PMSG is connected to the grid through a back-to-back full-scale pulse with modulation (PWM) voltage source converter.

The wind turbine model consist of the wind speed model, the aerodynamic model of the wind turbine, the mechanical model of the drive train and models of the transmission system and the electrical components, namely the PMSG, PWM voltage-source converters, transformer, and the control and supervisory system.

Wind simulation plays an important role in the wind turbine modeling, particularly for dynamic interaction analysis between wind farms and the power system to which they are connected. A wind model applied in this paper has been developed [17]. The wind model provides an equivalent wind speed for each wind turbine, which is conveniently used as an input to a simplified aerodynamic model of the wind turbine. Equation(1) represents the wind speed

$$v_{eq} = v_a + v_{tu} + v_{3p} = v_a + v_{tu} + v_{eqws} + v_{eqts} \quad (1)$$

Where v_a is the average wind speed at hub height, $v_{tu}$is the stochastic wind speed mainly representing the wind turbulence [18] and the $3p$ wind speed v_{3p}, which is the combination of two equivalent wind speed components (the wind shear effect v_{eqws} and the tower shadow effect v_{eqts}) the relation between the wind speed and aerodynamic torque the can be write by the following equation

$$T_w = \frac{1}{2}\rho\pi R^3 v_{eq}^2 \frac{C_p(\theta,\lambda)}{\lambda} \quad (2)$$

where T_w is the aerodynamic torque extracted from the wind (in newtons meter), ρ is the air density (in kilograms per cubic meter), R is the wind turbine rotor radius (in meters), θ is the pitch angle of the rotor (in degrees), $\lambda= \omega R/v_{eq}$ is the tip speed ratio, ω is the wind turbine rotor speed (in radians per second), and C_p is the aerodynamic efficiency of the rotor. More detailed description of the WT model can be found in [19].

Wind Turbine Controller

As a variable speed WT, under low and moderate wind speed conditions, the electromagnetic torque is controlled to modify the turbine rotation speed in order to realize maximum power point tracking [20], whereas under high wind speed conditions, a pitch angle controller is activated to maintain the output power at the rated value. The vector control schemes [21] are implemented for the generator-side and grid-side PWM converters, as illustrated Figs. 2 and 3. More detailed description of these control schemes can be found in [22].

STATCOM Model

The STATCOM, previously referred to as Static Synchronous Condenser (STATCON), produces reactive power in the capacitive and inductive range by using self-commutating converters. It has advantages when compared to the SVC, e.g., current injection independent of system voltage, faster control and less space requirement.

The STATCOMs main components are voltage source converter (VSC), the transformer and the controller. The controller has a coupling transformer and a dc capacitor.

The instantaneous three phase variables of the STATCOM can be described in state-space form by -*dq* components using Park's transformation. The active and reactive powers injected into the electricity system by the STATCOM are

$$P= v_d.i_d+v_q.i_q \quad (3)$$

$$Q=v_q.i_d-v_d.i_q \quad (4)$$

STATCOM can supply both capacitive and inductive compensation and is able to control its output current within the rated maximum capacitive and inductive range independently of the ac system voltage.

Fig. 4 shows single line diagram of the STATCOM connected a load bus. A more detailed control scheme can be seen in Fig.5. The control systems keep the voltage of load bus in desirable value. Fig.4 shows the controller consists of two main part basically. DC controller keeps the DC voltage at the desired reference voltage value, and then the voltage error (e) is passed through a PI block. the AC Voltage error is passed voltage–droop characteristics with a desired slope (K_s). The secondary voltage is filtered with a low pass filter before input to the STATCOM V_{ref}.

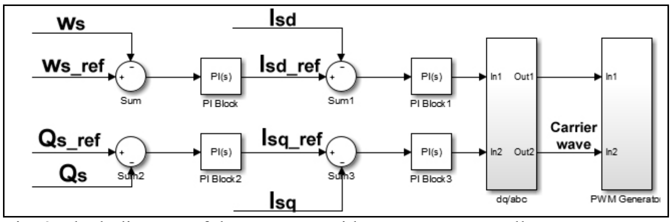

Fig. 2.Block diagram of the generator-side convertor controller.

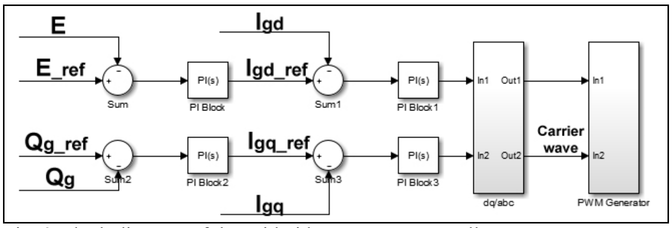

Fig. 3.Block diagram of the grid-side convertor controller.

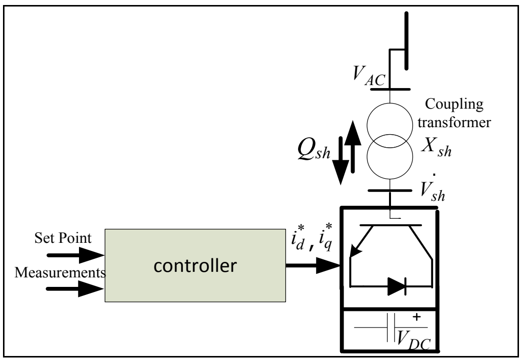

Fig. 4.Simplified representation of STATCOM connected to load bus.

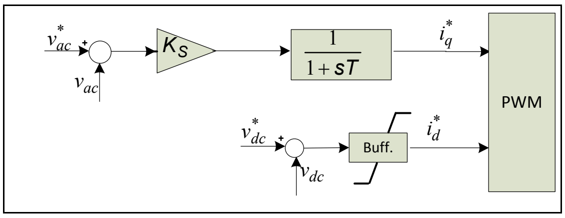

Fig. 5.Detailed scheme of the STATCOM controller.

III. Stability Analysis Of The System

A. Test System Configuration

The system configuration used in this study is explained below. The test system consists of three areas. The wind power is connected to the weakest AC area of the IEEE 10 machine 39 bus test system [23] through an AC link. The 650 MW rated power of generator (G_3), is nearest to the bus 12 which is the most sensitive to voltage instability. Through an HVAC, the active power injected into the AC system is assumed at two different value, 650 MW and 325 MW, which is 100% and 50% of the rated power of G3 respectively. A new STATCOM has been installed to the critical bus. The STATCOM tries to keep the bus voltage at the set value of 1.0 p.u. In following subsections, the models for the steady-state and electromechanical analysis are presented.

B. Sensitivity Analysis

The sensitivity analysis is applied to the power system for determining which bus is most sensitive to the change in reactive power in order to determine the best location for STATCOM. Shunt compensation is effective in improving voltage stability and V-Q sensitivity analysis is required to specify the location of STATCOM devices in order to achieve the best efficiency.

The Jacobian matrix of the power system is used in sensitivity analysis . The Newton-Raphson method solves the partitioned matrix equation

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{Vmatrix} \Delta\delta \\ \Delta V \end{Vmatrix} \tag{5}$$

By letting $\Delta P = 0$, we can write

$$\Delta V = J_R^{-1} \Delta Q \tag{6}$$

where $J_R = [J_4 - J_3.J_1^{-1}.J_2]$ is the reduced Jacobian matrix of the system. The diagonal elements of the matrix represent the steady state stability indices while the diagonal elements of the inverse reduced Jacobian matrix represent the sensitivities of the bus voltages. Sensitivity analysis is applied to load buses. The differentiation of voltage value is described as an equation of the J matrix and the variation of the reactive power. If $\frac{\partial Q}{\partial V}$ approaches to zero starts instability [24].

i^{th} diagonal element of J_R^{-1} is the V-Q sensitivity of bus i . The slope of the V-Q curve indicates the stiffness of the i^{th} bus (the ΔV for a ΔQ). According to, the more a stability system is the smaller sensitivity. Therefore the most sensitivity bus is the smallest diagonal element of $\frac{\partial Q}{\partial V}$ [25].

Application of the sensitivity analysis

To determined the most critical bus of the test system, sensitivity analysis method was used. The sensitivity analysis results are presented in Table I. The results show that Bus 12 has the highest sensitivity value and Area 1 is the weakest area of AC system. Thus in this study, bus 12 was chosen for the installation of STATCOM device.

C. P-V Curves

Under varying loading conditions, a simple method namely P-V Curve is used to analyze the limitation and margins of frequency and voltage stability. Voltage stability analysis and loadability analysis are examples of the application of this curve in power system analysis. For voltage steady-state stability, the basic indices of the voltage sensitivity at the operating point are derived from the calculation. In power flow studies of obtaining the corresponding P-V curves, the loads are typically represented as PQ loads with constant power factor, and increased according to

$$P_d = P_{d0}(1+\lambda) \tag{7}$$

$$Q_d = Q_{d0}(1+\lambda) \tag{8}$$

where P_{d0} and Q_{d0} are the initial real and reactive power respectively and λ is a p.u. loading factor, which represents a slow varying parameter typically used in voltage stability studies [26].

TABLE I
THE SENSITIVITY ANALYSIS RESULTS OF THE TEST SYSTEM

Bus no	J_R	J_R^{-1}
12	**44.7941**	**0.0330**
28	90.7959	0.0215
27	129.6402	0.0175
9	68.9053	0.0169
1	66.5807	0.0161
26	141.4650	0.0156
7	328.4265	0.0146
8	328.4625	0.0146
15	153.3162	0.0138
18	203.1263	0.0135
21	148.5103	0.0128
29	148.2132	0.0126
14	225.7369	0.0125
4	202.2042	0.0124
24	206.1864	0.0122
13	361.0083	0.0119
3	193.9692	0.0113
17	302.0382	0.0112
11	384.0988	0.0112
5	558.7410	0.0110
20	124.4286	0.0106
10	518.8049	0.0103
6	658.8054	0.0102
23	175.1652	0.0100
25	195.5722	0.0090
16	529.2298	0.0087
22	253.2083	0.0081
19	185.0704	0.0080
2	266.1438	0.0074

For the bus number 12 of the test system, P-V curves was obtained at three different wind power penetration levels in 39 Bus New England test system where bus 12 is fed by the generator of 650 MW. At bus 12, active and reactive power loads increase 5% from the initial load up to 60 seconds of the simulation. Fig.6 (a) shows the penetrated active power levels by the wind turbine. The penetration levels are0 MW, 325 MW and 650 MW which are 0%, 50% and 100% of the rated power of the generator G_3. Fig.6 (b) shows the injected reactive power by STATCOM at bus 12 for each penetration levels. It can be clearly seen that the reactive power injected by STATCOM increases significantly along with the penetration level and maximum penetration level so as to improve the system voltage stability. The results show that the voltage stability margin decreases as the wind penetration level increases.

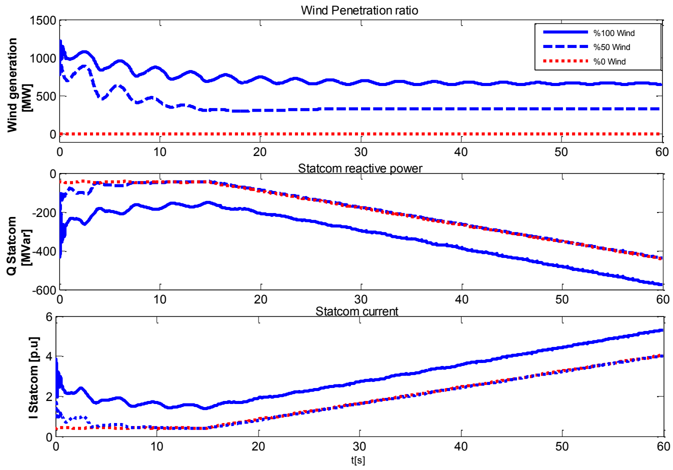

Fig. 6 . At the different penetration levels from top to bottom. Penetrated active power to Bus 10 – İnjected STATCOM reactive power –injected STATCOM current.

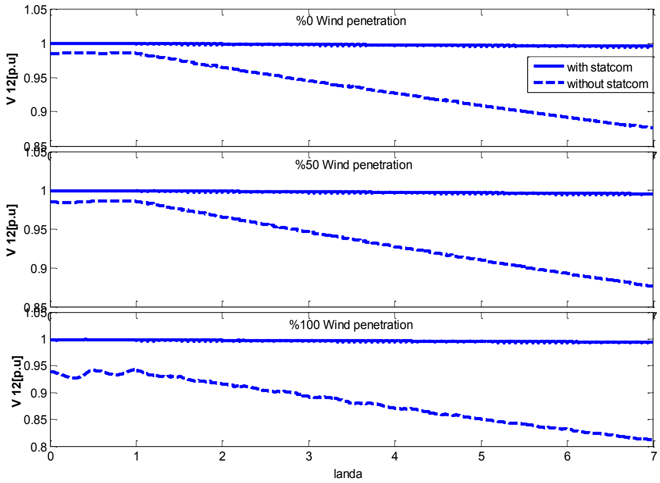

Fig. 7. At different penetration levels compare P-V curves

Table II lists the voltage ratings and STATCOM parameters at the different penetration levels. It can be seen that the installed STATCOM device improves the voltage profile and thus stability of the power system. Increased wind penetration caused the PMSG based wind farm voltage source converters to demand more reactive power from the AC system. As a result, the margin of stability has been decreased. For example, voltage of bus 12 is 0.8127 at %100 penetration while it is 0.8763 at %0 penetration level.

Fig. 7 shows the P-V curves of the bus 12 at the various penetration levels with STATCOM and without STATCOM.

TABLE II
COMPARE PARAMETERS OF THE STUDIED SYSTEM

Penetration Levels	System	V12 [p.u]	I STATCOM (p.u)	Q STATCOM [MVAR]
0%	With STATCOM	0.9955	4.0047	436.3
	Without STATCOM	0.8763	0	0
50%	With STATCOM	0.9956	4.016	439.6
	Without STATCOM	0.877	0	0
100%	With STATCOM	0.9941	5.291	573.9
	Without STATCOM	0.8127	0	0

Transient Voltage Stability Analysis

In order to ascertain the improvement on transient voltage stability, two different scenario, one three-phase short circuit fault case and one line outage case are studied. The short-circuit fault is located at bus 12, starts at t = 20 seconds and is cleared after 0.1 seconds. Fig. 8 shows the comparative transient responses of the most critical bus (Bus 12) at the different wind penetration levels with STATCOM and without STATCOM. It can be clearly seen from Fig. 8 that the STATCOM can effectively improve the voltage at bus 12 and provide damping of the system. Furthermore, the transient voltage stability has been studied by opening one of the parallel lines (line 13-12) which is connected to the critical bus of the 39 bus New England test system [22], at t=20 seconds.

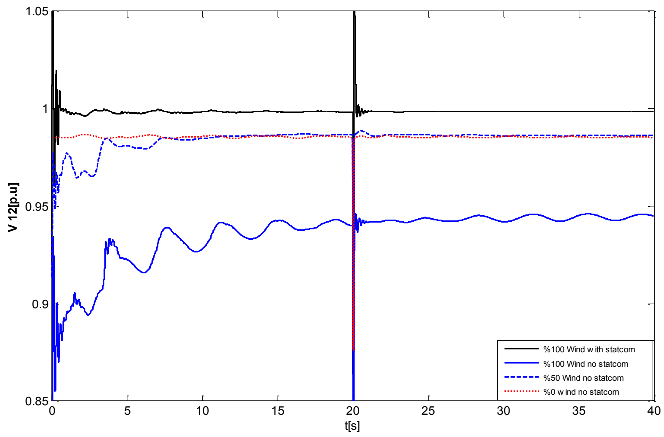

Fig. 8. At three phase short circuit fault at different penetration levels voltages of Bus 12.

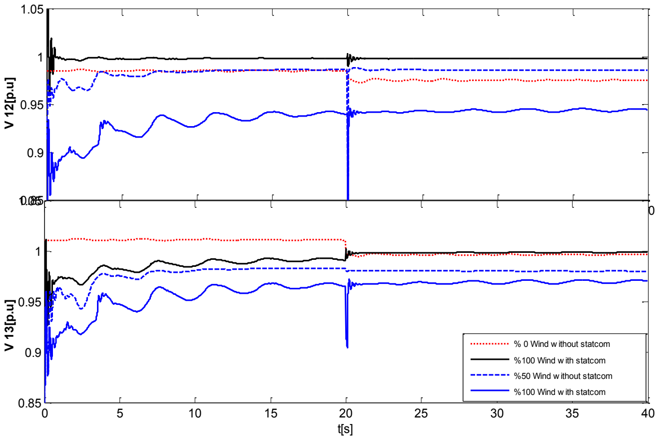

Fig. 9. At line outage fault for different penetration levels voltages of Bus 12 and Bus 13

Figure 9 shows the voltage of buses 12 and 13 after the given fault, it can be seen that the STATCOM device can improve the bus voltage at desired value in a short time.

IV CONCLUSIONS

In this paper, static and dynamic voltage stability has been studied under different wind penetration levels in power systems. As the wind penetration level increases, the voltage stability margin of the studied critical bus decreases which is not desired for security and stability reasons. By increasing the loading of the critical bus and using the P-V curves obtained for the current system, static voltage stability analysis is performed. In addition, at the different wind penetration levels the time-domain simulations under a three-phase short-circuit fault and a line outage have been performed in order to compare the effectiveness of the proposed STATCOM.

The results demonstrated that the proposed method of installing STATCOM device at the most critical bus can effectively improves voltage stability margin even at high wind farms penetration level.

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