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Design and Analysis of Statcom To Enhance Stability of Doubly Fed Induction Generator Based Wind Farm Fed To A Multi Machine System

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Abstract

This paper deals with the role of the Static Synchronous Compensator (STATCOM) in enhancing stability of the power system combined with Doubly Fed Induction Generator (DFIG) based off-shore wind farm. The STATCOM is employed to maintain stable voltage and also to improve the power quality. The use of STATCOM is recommended in systems with large loads, where the reactive power consumption from the grid could cause serious effects on the connected loads. In this work, design of suitable controllers is proposed to improve the stability of the overall system. A Proportional Integral Derivative (PID) Controller and the Fuzzy Logic Controller (FLC) are designed for the purpose of controlling the operation of the STATCOM and vary the reactive power supply according to the voltage level at the PCC. Simulation work of the proposed scheme is carried out using MATLAB/Simulink. It is observed from the obtained results that the STATCOM with FLC has the improved characteristics to enhance the operation of a multi machine system fed by a DFIG based Offshore Wind farm.

Keywords: Doubly Fed Induction Generator, Fuzzy Logic Controller, PID Controller, Point of Common Coupling (PCC), STATCOM.

Introduction

Modern power system experiences severe power quality issues that are caused because of the increased usage of non linear loads and increase in demand. These challenges are caused due to the increasing complexity in the operation of the power grid and their structure. One of the major problems faced by power system is the stability issue. This is caused due to the lack of various facilities in the generation and the transmission systems and also due to the increasing demand. Hence the non conventional energy sources such as wind power plants are taken into consideration. Significantly, the wind power penetration into the grid has increased drastically in the recent years and it is also satisfying in meeting the load demand in the power system. The major problems that are faced in the wind farm connected to the grid are flicker, voltage stability and harmonics and they affect the stable operation of the power system. Generally, the voltage profile should lie in the limit of 0.95 to 1.05 p.u. The major reasons for the voltage instability are heavily loaded system, faulted or with insufficient reactive power supply. The voltage stability can be improved by using the Static VAR Compensator (SVC), switched capacitors, synchronous condensers and STATCOM [1]-[3].

This paper deals with the design of PID and Fuzzy Logic controllers for the STATCOM at the PCC where a DFIG based wind farm is coupled to the grid. The stability of the grid is affected by the operation of the wind farm. The controller is designed to enhance the voltage stability by properly supplying the required reactive power at the PCC. The effectiveness of the proposed controller is studied using MATLAB/Simulink.

Static Synchronous Compensator

A STATCOM is a shunt compensated equipment which can be seen as a voltage source behind the reactance. It is able to produce or consume the reactive power. It is also purely based on the current and the voltage waveforms of the Voltage Source Converter (VSC). The STATCOM is capable of producing controllable absorbing or generating reactive power with the help of the power electronic converters. They need low pass filters such as LC filters to suppress the switching frequency harmonics of the converter [4].

A STATCOM is able to switch the reactive power along the line because of the presence of the small energy storage device namely dc capacitor. If the capacitor is replaced by a dc storage battery, the controller can exchange real and reactive power within the system. The relationship between converter ac voltage and the dc capacitor voltage is given by equation (2).

$$V_{out} = kV_{dc} \tag{2}$$

Where, ‘k’ is the coefficient which depends on the converter configuration, number of switching pulses and converter controls. The converter output voltage V_{out} can be controlled by varying the dc voltage across the capacitor. The ac current flow between the ac source and the voltage source converter is given by equation (3).

$$I_{abc} = \frac{V_{out} - V_{ac}}{x} \tag{3}$$

Where V_{out} and V_{ac} are the converter voltage and the ac system voltage, while ‘x’ represents the coupling transformer leakage reactance. The corresponding reactive power can be expressed as in equation (4).

$$Q = \frac{V_{out}^2 - V_{out}V_{ac}\cos\propto}{x} \tag{4}$$

The real power transfer between the voltage sourced converter and the ac lines can be calculated using equation (5).

$$P = \frac{V_{ac}V_{out}\sin\propto}{x} \tag{5}$$

The V-I characteristics of the STATCOM is given in figure 1 [4],

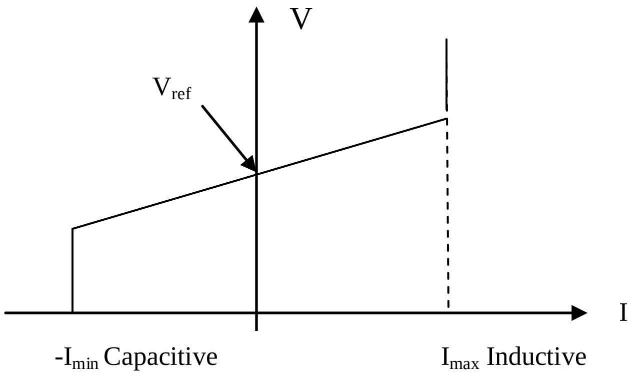


Figure 1: V-I Characteristics of STATCOM

Mathematical Modeling of The Proposed System

A. Mathematical Modeling of Wind turbine

A relationship between the output power and the various variables of the wind turbine system constitute the mathematical modeling. The work done 'W' in displacing the object from rest to a distance 's' under the action of a force 'F', under constant acceleration is [5]

$$E = W = F.s$$

Where 'E' is the kinetic energy. According to Newton's Law, $F = m.a$

Hence, $E = m.a.s$ (6)

Using the third equation of motion,

$$v^2 = u^2 + 2.a.s \tag{7}$$

The acceleration is $a = \frac{v^2-u^2}{2s}$ (8)

Since the initial velocity of the object is zero, u=0,

$$a = \frac{v^2}{2s} \tag{9}$$

From (9) & (6) the kinetic energy is

$$E = 0.5mv^2 \tag{10}$$

The power in the wind is given by the rate of change of energy,

$$P = \frac{dE}{dt} = 0.5v^2\frac{dm}{dt} \tag{11}$$

As mass flow rate is given by, $\frac{dm}{dt} = \rho A\frac{dx}{dt}$

The rate of change of distance is given by,

$$\frac{dx}{dt} = v$$

and therefore rate of change of mass flow is $\frac{dm}{dt} = \rho Av$

From equation (11) the expression for power is,

$$P = 0.5\rho Av^3 \tag{12}$$

The power coefficient C_p of the wind turbine is 0.59.

The available power from the wind turbine is represented by,

$$P_{avail} = 0.5Av^3C_p \tag{13}$$

It is not possible to excerpt the entire kinetic energy and hence it excerpts a portion of the power in the wind, called the coefficient of power for the turbine.

$$P_{mech} = C_pP_{wind} \tag{14}$$

The power that is produced mechanically from the wind turbine is given by [5],

$$P_{mech} = 0.5\rho\pi R^2V_{wind}^3C_p \tag{15}$$

B. Mathematical Modeling of STATCOM

The mathematical modeling of STATCOM is performed with the following presumptions [6],

1. The switches are assumed to be all ideal.
2. The voltage at the source side is balanced.
3. R_s represent the coupling transformer losses.
4. The harmonic contents are negligible.

The Park's *abc* to *dq* transformation matrix is utilized. The original circuit is more complex and so it is divided into sub circuits. The three phase voltages $v_{s,abc}$ lagging with the phase angle α to the STATCOM output voltage $v_{o,abc}$ and differential form of the STATCOM currents are defined in equations (16) and (17).

$$v_{s,abc} = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}}V_s\begin{bmatrix} \sin(\omega t - \alpha) \\ \sin\left(\omega t - \alpha - \frac{2\pi}{3}\right) \\ \sin\left(\omega t - \alpha + \frac{2\pi}{3}\right) \end{bmatrix} \tag{16}$$

$$L_s\frac{d}{dt}\left(i_{c,abc}\right) = -R_si_{c,abc} + v_{s,abc} - v_{o,abc} \tag{17}$$

The above given voltages and currents are then transferred into *dq* axis as given in equations (18) and (19).

$$L_s\frac{d}{dt}\left(i_{cq}\right) = -R_si_{cq} - wL_si_{cq} + v_{sq} - v_{oq} \tag{18}$$

$$L_s \frac{d}{dt}(i_{cd}) = wL_s i_{cq} - R_s i_{cd} + v_{sd} - v_{od} \tag{19}$$

The transformation function S of the STATCOM is given by,

$$\mathrm{s} = \begin{bmatrix} \mathrm{s_a} \\ \mathrm{s_b} \\ \mathrm{s_c} \end{bmatrix} = \sqrt{\frac{2}{3}}\ \mathrm{m} \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \tag{20}$$

The index of modulation (MI), being constant is given by,

$$\mathrm{MI} = \frac{\mathrm{v_{o,peak}}}{\mathrm{V_{dc}}} = \sqrt{\frac{2}{3}}\,\mathrm{m} \tag{21}$$

The output voltages of STATCOM in *dq* frame is given by,

$$v_{o,qdo} = m\,[0 \quad 1 \quad 0]^T\, v_{dc} \tag{22}$$

The capacitor current in dc side in terms of *dq* axis is given by,

$$i_{dc} = m\,[0 \quad 1 \quad 0]\,[i_{cq} \quad i_{cd} \quad i_{co}]^T \tag{23}$$

Thus the current and voltage in the dc side are related by,

$$\frac{d}{dt}(v_{dc}) = \frac{m}{c}\, i_{cd} \tag{24}$$

The entire model of the STATCOM in dq axis is given by [6],

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s} & -w & 0 \\ w & \frac{-R_s}{L_s} & \frac{-m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} + \frac{V_s}{L_s}\begin{bmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{bmatrix} \tag{25}$$

System Description and Simulation Results

In this work, the Western System Coordinated Council (WSCC) – Three machine Nine bus practical power system is considered for study [7]. The base MVA of the system is 100 and the system frequency is taken to be 60 Hz. The system consists of three generators, nine buses, and three loads. The three machines are taken to be the synchronous generators. The loads are connected to the buses 4, 9 and 8. Here the loads are taken to be the constant impedance loads. A DFIG based offshore wind farm is coupled at bus 9 of the test network. The offshore wind farm is illustrated by a corresponding DFIG driven by a gearbox [8]. The one line diagram of the test system is given in figure 2.

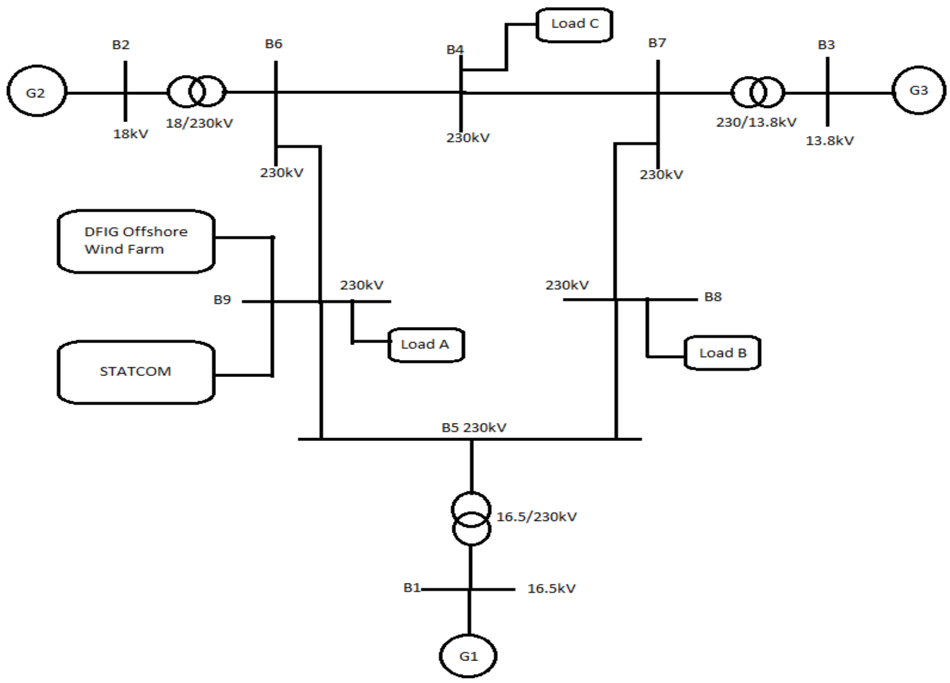


Figure 2: One Line Diagram of Three machine Nine bus System

The Three machine Nine bus system is taken for study for this work is simulated using the software MATLAB/SIMULINK. The simulation is carried out under four different cases.

1) Case 1 – The test system with DFIG

In this first case, the basic configuration of the proposed system is described. The DFIG offshore wind farm is coupled to the Three machine Nine bus system at bus 9. Hence here, bus 9 is the PCC. The simulation diagram with the test system and the DFIG connected to its PCC is given in figure 3.

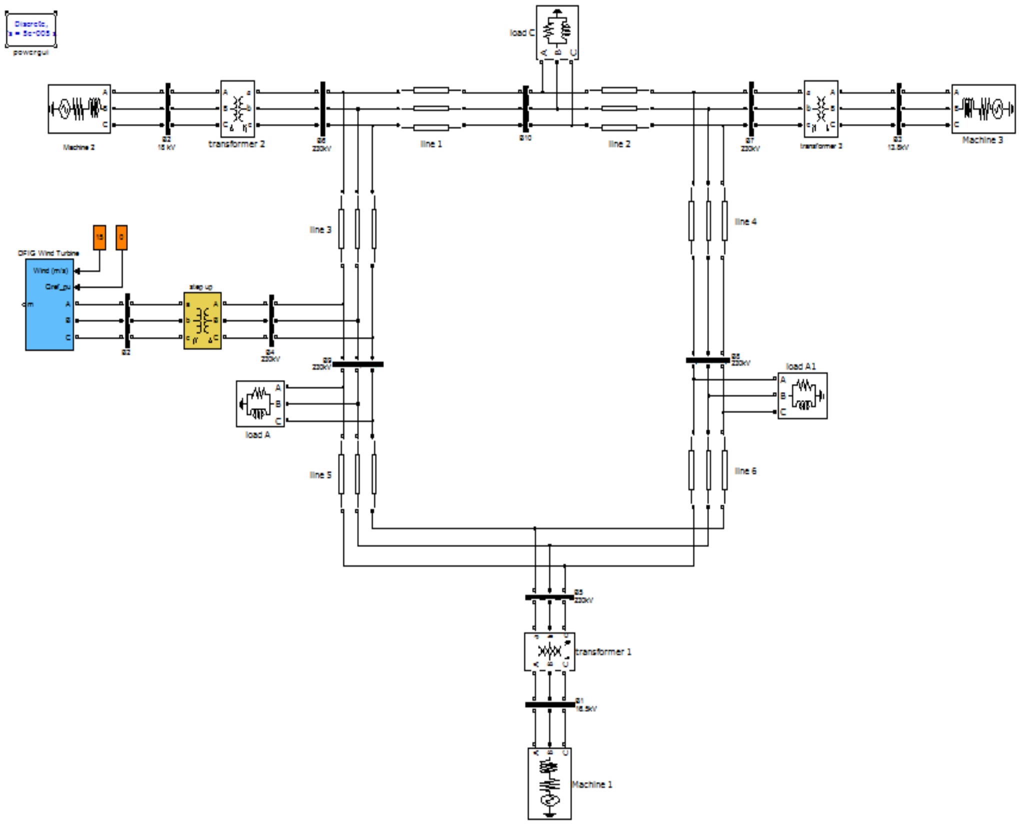


Figure 3: Simulink Diagram of The Test System With DFIG

The voltage and the current waveforms at various buses are obtained as given in figure 4, 5 and 6. Since the voltages and the currents are calculated in terms of per units, the source voltage and the source current from the three generators remains the same.

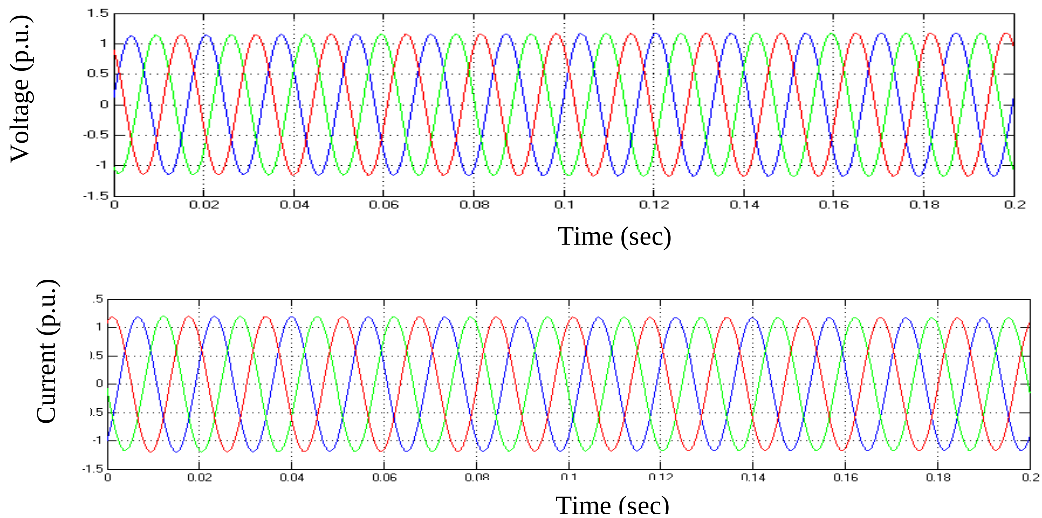


Figure 4: Voltage and Current waveform of three generators

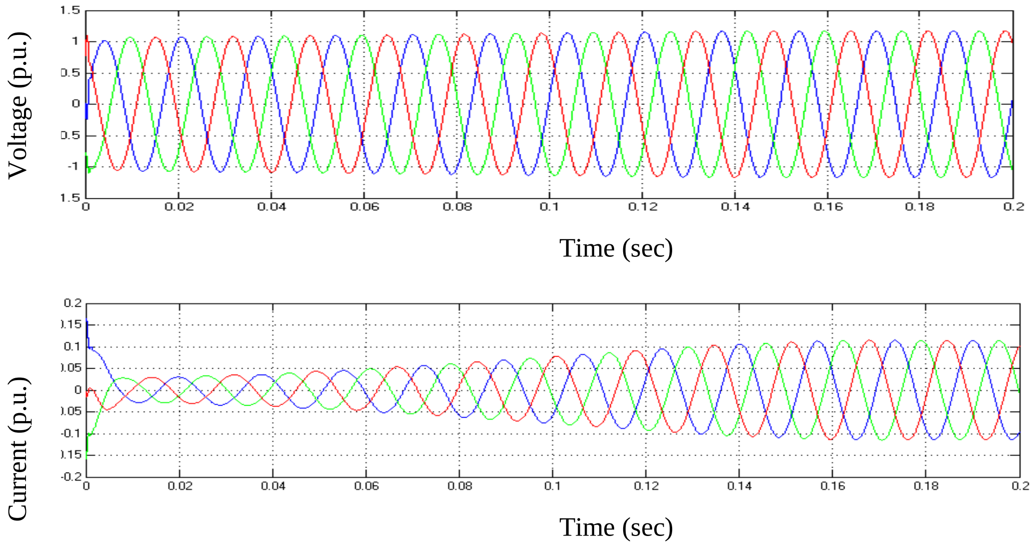


Figure 5: Voltage and Current waveform of DFIG output

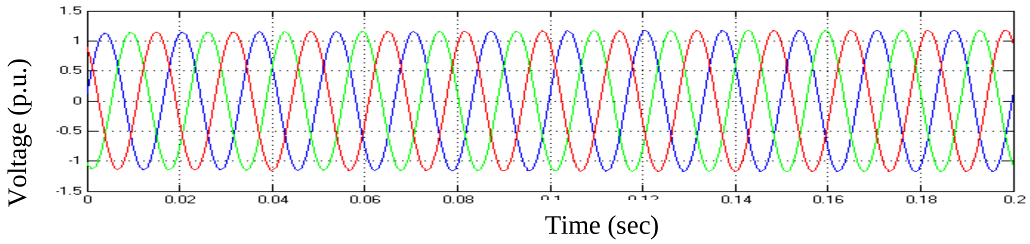


Figure 6: Voltage Waveform At The PCC

2) Case 2 – System with Three phase fault

In this case, a three phase fault is abruptly enforced at bus 9 at $t = 0.02$ sec and it is cleared at $t = 0.05$ sec. Similar type of fault is the most crucial and serious fault to be checked whether the test system can tolerate such severe consequences or not. For analyzing the voltage stability of the test system, a three phase fault is enforced at the PCC i.e. bus 9. The voltage measured is in terms of rms value. The voltage waveform obtained is given in figure 7.

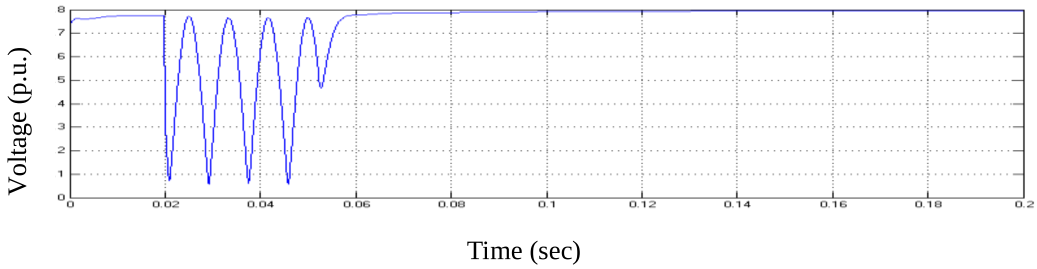
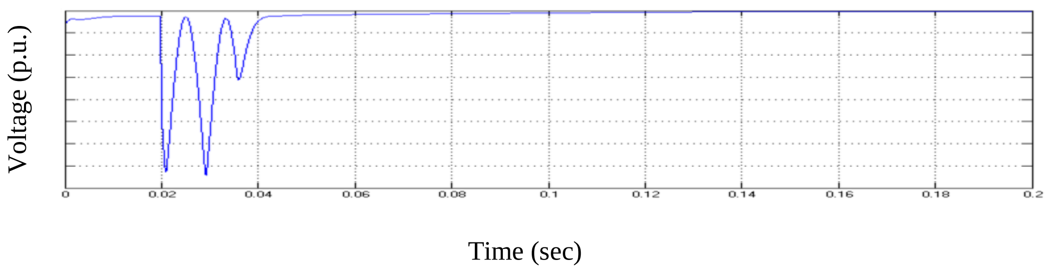


Figure 7: Voltage measured at point of common coupling after the application of three phase fault

From the above simulation result, it is seen that the voltage at the PCC is stable before the occurrence of the fault. Once the fault is applied at bus 9 i.e. the point of common coupling, the voltage gets disturbed and becomes unstable. Hence, due to this, the voltage stability of the overall system is collapsed. This may cause the entire system to get collapsed. Hence, to enhance the system stability the STATCOM is preferred.

3) Case 3 – STATCOM with PID controller

In the previous section it has been observed that the voltage stability of the system is collapsed due to the occurrence of three phase fault at the PCC. Hence to enhance the network stability the STATCOM is coupled at the PCC. STATCOM produces controllable supplying or consuming reactive power by using switching converters. The STATCOM is used to inject the reactive power into the network when the system bus voltage level is lesser than the required voltage level. It is also used to absorb the reactive power from the network when the voltage level is greater that the inverter output voltage. The output of the STATCOM contains some harmonics components in it. Hence, to overcome these harmonics in the output of the STATCOM, the LC (Inductor – Capacitor) filter is used. This filter is very effective in removing the harmonics in the waveform and it gives us the pure sine wave as the output. Hence LC filter is preferred over the other filters. The simulation result after connecting the STATCOM with PID controller at the PCC is given in figure 8. The reactive power injected by the STATCOM is also shown and the waveform of both the voltage and the reactive power supplied are given in figure 8.



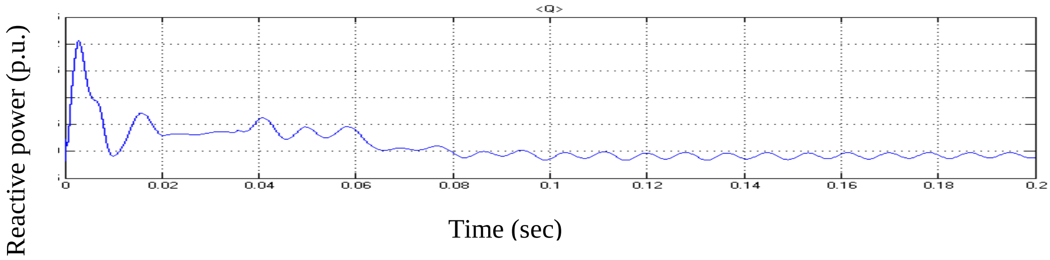


Figure 8: Voltage At PCC and Reactive Power Injected By STATCOM (PID)

It is seen from the above simulation result that the voltage has attained stability at the time t= 0.035 sec. This is due to the reason that the STATCOM produces required reactive power and it is supplied to the PCC. The reactive power supplied is more at the starting stage i.e. during the time t = 0.005 sec to t = 0.05 sec. This is shown in the figure 8.

4) Case 4 – STATCOM with FLC

The Fuzzy Logic controller is used because of its accuracy. It can give more accurate results than any other conventional controller. In FLC it is possible to specify the required output for the inputs at very small interval [10]. In this work, PID controller is replaced by Fuzzy Logic Controller. The voltage at the PCC is measured and it is fed as the input to the controller part of the STATCOM. The simulation result after connecting the STATCOM with Fuzzy Logic Controller at the PCC is given. The reactive power injected by the STATCOM is also monitored and the waveform of both the voltage and the reactive power supplied are given in figure 9.

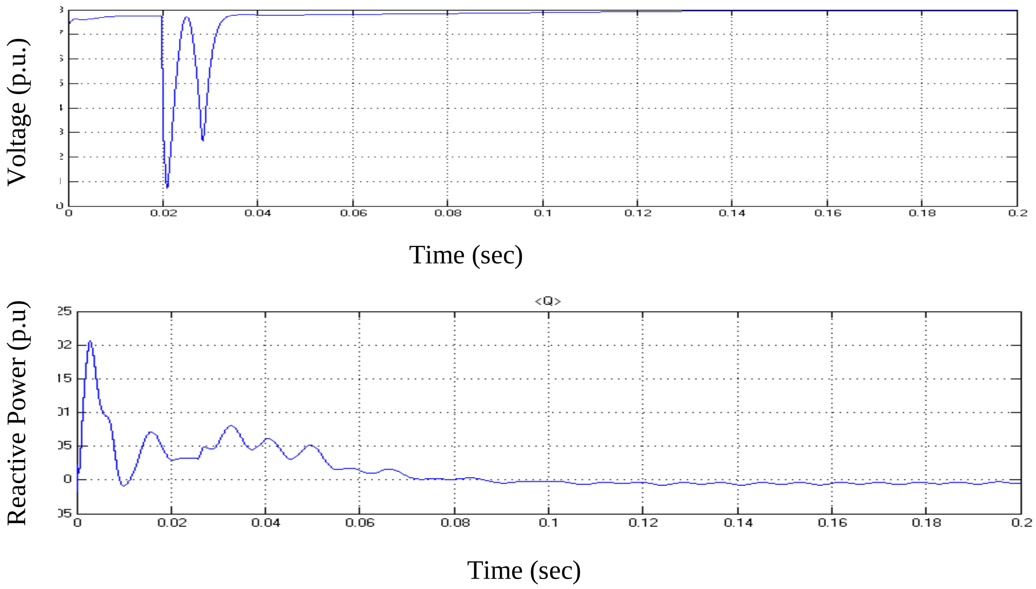


Figure 9: Voltage at PCC and reactive power supplied by STATCOM (FLC)

From the simulation results obtained it is seen that the voltage loses its stability when the three phase fault is enforced at time $t = 0.2$ *sec*. It is seen that the voltage waveform regains its stability at the time $t = 0.026$ *sec*. This implies that the voltage waveform regains its stability at a faster rate. The response is faster when compared to the PID controller. This faster response is attained due to the action of the STATCOM which is controlled by the Fuzzy Logic Controller.

Table 1 gives the comparison of the performance of the controllers of both PID and FLC. The settling time is used as an important parameter to compare their performance.

Table 1: Comparison of Various Controllers

S. No	**Case**	**Settling Time (sec)**
1	Without STATCOM	0.05
2	STATCOM with PID controller	0.035
3	STATCOM with FLC controller	0.026

Thus, from the comparison table given in table 1 it is inferred that the settling time is very less when the Fuzzy Logic Controller (T_s = 0.026sec) is used. The settling time is decreased with the PID controller (T_s = 0.035sec). But the settling time is further decreased with the use of the FLC controller. Hence, the system will attain its stability at a faster rate. Thus the use of the FLC controller helps the system to attain the stability at a faster rate.

Conclusion

In this work, the stability improvement of a DFIG based Offshore wind farm fed to a multi machine system is carried out. The voltage stability is achieved by the use of the STATCOM and its controllers. Two types of controllers such as PID controller and FLC have been analyzed to maintain the working of STATCOM and to inject the necessary reactive power to the network. The damping of voltage fluctuations using PID controller is analyzed by injecting a fault in the system. For the same system the role of FLC in controlling the STATCOM is also analyzed. It is analyzed from the simulation results that the stability of the system is regained at a faster rate when FLC is used along with STATCOM. Thus, it can be concluded that the STATCOM along with the FLC has the improved characteristics to enhance the operation of the DFIG based offshore wind farm fed to a multi machine system.

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