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Intelligent Controller Based STATCOM for Improving Dynamic Stability of a Hybrid Power System

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Abstract*: Renewable energy sources, which are expected to be a promising alternative energy source, can bring new challenges when connected to the power grid. A large amount of wind turbines are connected to the electrical power system in order to mitigate the negative environmental consequence of conventional electricity generation. While connecting the wind turbine to grid it is important to understand the source of disturbance that affects the power quality. FACTS devices are found to be very effective for stability enhancement followed by a disturbance. Static Synchronous Compensator (STATCOM) which is a shunt device of FACTS family is efficient in regulating voltage either by absorbing or by generating reactive power. STATCOM can provide fast and efficient reactive power support to maintain power system voltage stability. This paper proposes a Hybrid control model for STATCOM that controls the voltage during a disturbance. The proposed controller is implemented to the STATCOM under MATLAB/SIMULINK environment. In the simulation test, the hybrid control shows consistent excellence under a severe disturbance like three phase fault.

***Keywords*: STATCOM, power quality, FACTS, power grid, hybrid controller.**

I. INTRODUCTION

Electric power system is a complex system in its structure and operation is facing many challenges day by day. The major problem in power system is its instability. Power system stability is the capability of the system to maintain an operating equilibrium point after being subjected to a disturbance for given initial operating conditions. Traditionally voltage regulation is performed by the excitation system and thereby help in controlling the system voltage. Suitable devices like Automatic Voltage Regulators (AVR) are used for the regulation of generated voltage. AVR's normally maintain the generator voltage magnitude at a specified level. AVR's are extensively used on the dynamic or steady state stability of the power system as low frequencies oscillations persist for a long period and may affect the capability of power transfer. Electrical power demand is rising at a very higher rate because of rapid industrial development. In order to satisfy the demand, power transmission has to be raised along with the existing facilities. Thus it is essential to concentrate on the power flow control. The power system should be flexible to adapt itself to any momentary changes in system conditions. In an AC power system, there must be a balance between the generated power and variations in load demand while keeping the system frequency and voltage levels as constant.

If the generation is not sufficient, the voltage and frequency drop and the load decreases to balance the total generation minus losses in transmission. But there are only a few percent margins for such a self-regulation. Hence the system is collapsed. Generator excitation controller normally improves stability for smaller faults but not suitable for larger faults that occur near to generator terminals. Thus, traditional methods have to be reviewed and new concepts have to be created that emphasizes an efficient use of resources of existing power system maintaining stability and security the system. To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind, biomass, hydro, cogeneration, etc. In sustainable energy system, energy conservation and the use of renewable source are the key paradigms. The need to integrate renewable energy like wind energy into power system is to make it possible to minimize the environmental impact on conventional plant [1]. The integration of wind energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability, power quality problems. The power quality is an essential customer focused measure and is greatly affected by the operation of a distribution and transmission network. The issue of power quality is of great importance to the wind turbine [2]. There has been an extensive growth and quick development in the exploitation of wind energy in recent years. The individual units can be of large capacity up to 2 MW, feeding into the distribution network, particularly with customers connected in close proximity [3]. Today, more than 28000 wind generating turbines are successfully operating all over the world.

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In the fixed-speed wind turbine operation, all the fluctuation in the wind speed is transmitted as fluctuations in the mechanical torque, electrical power on the grid and leads to large voltage fluctuations. The power quality issues can be viewed with respect to the wind generation, transmission and distribution network, such as voltage sag, swells, flickers, harmonics etc. However, the wind generator introduces disturbances into the distribution network. One of the simple methods of running a wind generating system is to use the induction generator connected directly to the grid system.

The induction generator has inherent advantages of cost effectiveness and robustness. However; induction generators require reactive power for magnetization. When the generated active power of an induction generator is varied due to the wind, absorbed reactive power and the terminal voltage of an induction generator can be significantly affected. A proper control scheme in wind energy generation system is required under a normal operating condition to allow the proper control over the active power production. In the event of increasing grid disturbance, a battery energy storage system for the wind energy generating system is generally required to compensate the fluctuation generated by the wind turbine. A nonlinear load on a power system is typically a rectifier or some kind of arc discharge devices such as a fluorescent lamp, electric welding machine, or arc furnace. When interrupted by a switching action, the voltage contains frequency components that are multiples of the power system frequency. It changes the shape of the voltage waveform from a sine wave to some other form and also creates harmonic components in addition to the fundamental frequency voltage.

In order to mitigate the disturbance's a compensating device should be integrated into the network. The most used unit to compensate for reactive power in the power systems is either synchronous condensers or shunt capacitors, the latter either with mechanical switches or with thyristor switch, as in Static VAR Compensator (SVC). The disadvantage of using shunt Capacitor is that the reactive power supplied is proportional to the square of the voltage. Consequently, the reactive power supplied from the capacitors decreases rapidly when the voltage decreases [3]. To overcomes the above disadvantages; STATCOM is best suited for reactive power compensation and harmonic reduction. It is based on a controllable voltage source converter (VSC).

The STATCOM is a shunt-connected reactive-power compensation device that is capable of generating (and/ or) absorbing reactive power and in turn, the output can be varied to control the specific parameters of an electric power system. In general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM, which is a voltage-source converter which when fed from a given input of dc voltage, produces a set of 3-phase ac-output voltages, which are in phase and coupled to the corresponding ac system voltage through a relatively small reactance. The dc voltage is provided by an energy-storage capacitor.

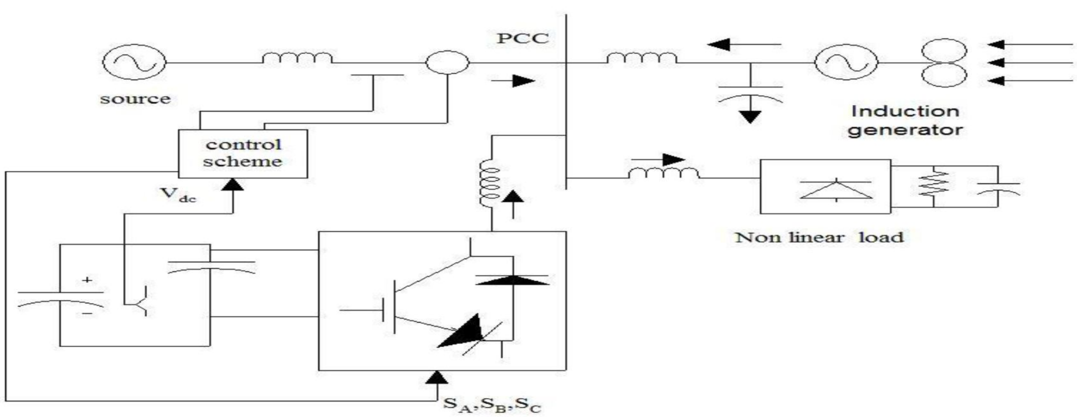

Fig.1 power system model of grid connected system

An STATCOM can improve power-system Performance like:

A. The dynamic voltage control in transmission and distribution systems,
B. The power-oscillation damping in power- transmission systems,
C. The transient stability;
D. The voltage flicker control; and
E. The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

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Furthermore, an STATCOM does the following:

F. It offers modular, factory-built equipment, thereby reducing site work and Commissioning time; and

G. It uses encapsulated compact electronic converters, thereby minimizing environmental impact.

Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. Many control approaches and applications of fuzzy logic control have appeared in the literature since Mamdani published his experiences on using a fuzzy logic controller. The fundamental advantage of the fuzzy logic controller over the conventional controller is a less dependence of the mathematical model and system parameters as known widely. An STATCOM based control technology has been proposed for improving the power quality which can technically manage the power level associated with the commercial wind turbines.

II. SYSTEM CONFIGURATION AND MATHEMATICAL MODELS

Figure.2 shows the configuration of the proposed system 6-MW wind power system consisting of 4 x 1.5- MW DFIG wound rotor induction generator and a back to back converter connected to the power system. An STATCOM is proposed to connect at PCC of the power system [4]. The detail mathematical models of the proposed systems are as follow:

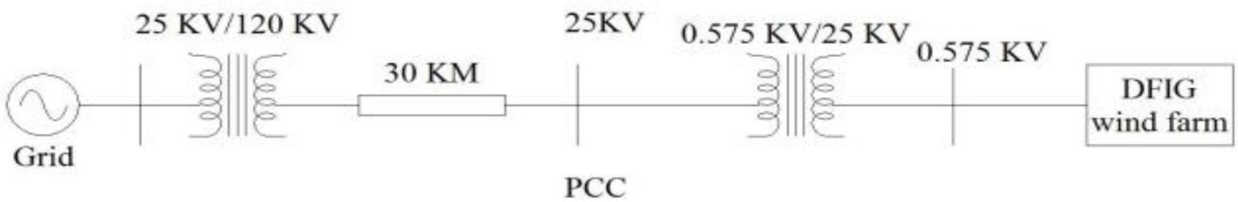

Fig.2 configuration of the proposed system

A. Wind Turbine

The working principle of the wind turbine includes the following conversion processes: the rotor extracts the kinetic energy from the wind creating generator torque and the generator converts this torque into electricity and feeds it into the grid. Presently there are three main turbine types available. They are

1) Squirrel-cage induction generator.

2) Doubly fed induction generator.

3) Direct-drive synchronous generator.

The first one which is the simplest and oldest system consists of a conventional directly grid-coupled squirrel cage induction generator. The slip and the resultant rotor speed of the generator varies with the amount of power generated. The rotor speed variation is small, approximately 1 to 2%, and hence this is normally referred to as a constant speed turbine. The other two generating systems are variable –speed systems. In the doubly fed induction generator, a back to back voltage source converter feeds the three phase rotor winding, resulting in that the mechanical and electrical rotor frequency is decoupled and the electrical stator and rotor frequency can match independently of the mechanical rotor speed. In the direct-drive synchronous generator, the generator is completely decoupled from the grid by power electronics, as a converter is connected to the stator winding and another converter is connected to the grid. Thus the total power delivered by the wind power is transmitted by an HVDC link. In this paper, the configuration of a wind generator is based on constant speed topologies with pitch control turbine. With the wind turbine (WT) model refer from [5], the captured mechanical power by a WT is:

$$P_m = \frac{1}{2}\rho A_r V_w^3 C_p(\lambda,\beta) \qquad (1)$$

When ρ is the air density (kg/m3), A_r is the blade impact area (m2), V_w is the wind speed (m/s), and C_p is the dimensionless power coefficient of the WT.

B. Wind Generator

The DFIG model is shown in Figure.3 and the equations are given in d-q axis as follows [12, 13]:

$$V_{sd} = -R_{sd} i_{sd} - \omega_d \phi_{sq} \qquad (2)$$

$$V_{sq} = -R_{sd} i_{sq} + \omega_d \phi_{sd} \qquad (3)$$

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$$V_{rd} = R_{rd} i_{rd} - s\omega_d \phi_{rd} + \frac{1}{\omega_b} \phi_{rd} \quad (4)$$
$$V_{rq} = R_{rd} i_{rq} + s\omega_d \phi_{rd} + \frac{1}{\omega_b} \phi_{rq} \quad (5)$$

Where ϕsd and ϕrd are the p.u flux linkages of the stator windings and the rotor windings, respectively.

Neglecting the power losses of the rotor side and the grid side converters the power balance equation for the back to back converter shown in Figure.4 can be written as

$$P_r = P_s - P_{dc} \quad (6)$$

Where, $d\ Pdc$ are the active powers at the AC sides and DC link of the rotor. The p.u differential equation of the DC link voltage can be obtained as follows:

$$V'_{dc} = \frac{1}{V_{dc} C_{dc}} \left(V_{sd} i_{sd} + V_{sq} i_{sq} - V_{rd} i_{rd} - V_{rq} i_{rq} \right) \quad (7)$$

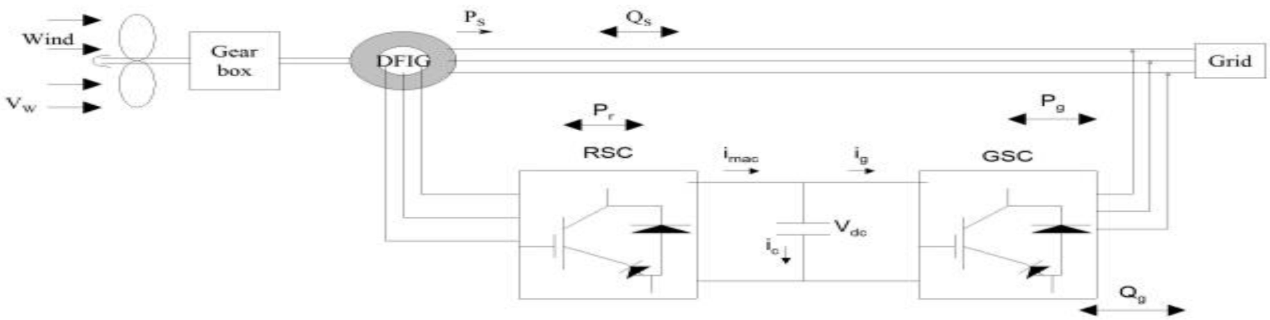

Fig.3. One-line diagram of wind DFIG

C. STATCOM Model

A one-line diagram of an STATCOM represented in Figure.4 has a transformer, a Voltage Source Converter (VSC) and a DC capacitor.

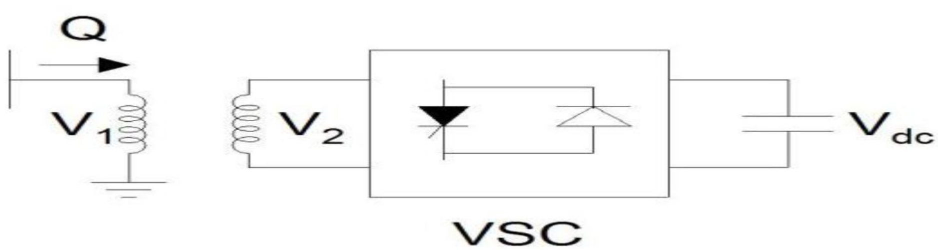

Fig.4. Single line diagram of STATCOM

The output voltages equation in the q-d axis of the proposed STATCOM can be written by, respectively.

$$V_{stat.d} = V_{stat.dc} km_{stat} \sin(\phi_{bus} + \alpha_{stat}) \quad (8)$$
$$V_{stat.q} = V_{stat.dc} km_{stat} \cos(\phi_{bus} + \alpha_{stat}) \quad (9)$$

Where $Vstat.$, $Vstat.q$ are the voltages at the output terminals of the STATCOM in d and q axis respectively. , $\alpha stat$ are the modulation index and phase angle of STATCOM, ϕbus is the voltage phase angle of the common AC bus and $Vstat.dc$ is the p.u DC voltages of the DC capacitor. For controlling the proposed STATCOM, modulation index and/or phase angle can be adjusted [11].

III. DESIGN OF DAMPING CONTROLLER FOR STATCOM

Here three control techniques are used

A. PI Controller

For the generation of reference signal, DC link voltage is measured and compared with the reference values by means of a PI controller. The output of the PI controller is multiplied with the unit vectors. Hence we will get reference currents.

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B. Fuzzy Logic Controller

Fuzzy logic controller, approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision, and fuzziness in the decision-making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system, just by incorporating the expert‘s knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations). The fuzzy logic controller designed as damping controller for STATCOM. The rotor speed deviation of the DFIG ($\Delta\omega DFIG$) and the voltage deviation of PCC (Δ) are fed to the Fuzzy logic damping controller (FLDC) to generate the additional signal ($Vcsi$) in order to control the phase angle (α).

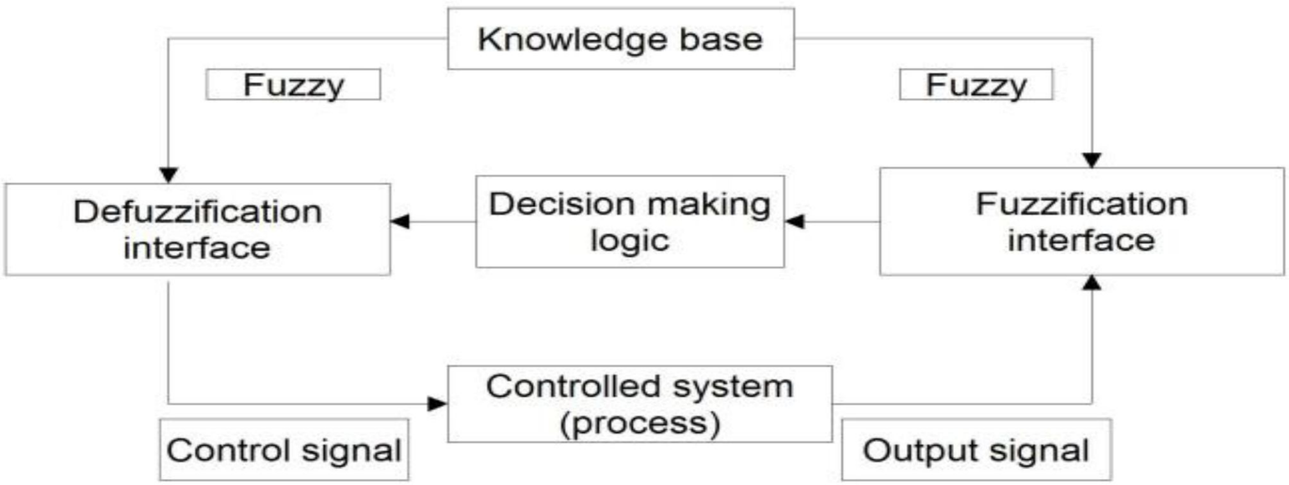

Fig.5 block diagram of fuzzy logic controller

In FLDC design, the following five fundamental design steps are employed:
Normalisation
Fuzzification
Inference
Defuzzification
Denormalisation.

1) *Fuzzification:* The process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.
2) *De-fuzzification:* The rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number).
3) *Database:* The Database stores the definition of the membership Function required by fuzzifier and defuzzifier.
4) *Rule Base:* The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. The control rules subject to the input signals and the output signal are listed in Table I with the structure rules are given as follows:

$$If(\Delta\omega_{DFIG} = A_i)\ and\ (\Delta V_{pcc} = B_i)\ then\ (f_i = V_{csi}) \qquad (10)$$

Where $\Delta\omega DFIG\ and\ \Delta Vpcc$ are the inputs, and Bi are the fuzzy sets, fi are the outputs within the fuzzy region specified by the fuzzy rule, $Vcsi$ are the designed parameters for the output of FLDC, and i is number of membership functions of each input.

For example some rules are

If $\Delta\omega DFIG$ is negative large and $\Delta VPCC$ is negative large then the output is negative large.
If $\Delta\omega DFIG$ is negative medium and $\Delta VPCC$ is negative large then the output is negative large.
If $\Delta\omega DFIG$ is negative small and $\Delta VPCC$ is negative large then the output is negative large.
If $\Delta\omega DFIG$ is zero and $\Delta VPCC$ is negative large then the output is negative large.
If $\Delta\omega DFIG$ is positive small and $\Delta VPCC$ is negative large then the output is negative medium.

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TABLE I: RULE BASE OF THE DESIGNED FLDC

$\Delta\omega_{DFIG}$ / ΔV_{PCC}	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

Two input variables (i.e. derivative of wind speed and voltage at PCC) for FLDC are also employed. In this paper, seven linguistic variables for each input variable are used. These are chosen as: NL (negative large), NM (negative medium), NS (negative small), EZ (zero), PS (positive small), PM (positive medium), and PL (positive large) [13- 15].

C. Hybrid Fuzzy Controller

The objective of the hybrid controller is to utilize the best attributes of the PI and fuzzy logic controllers to provide a controller which will produce a better response than either the PI or the fuzzy controller. There are two major differences between the tracking ability of the conventional PI controller and the fuzzy logic controller. Both the PI and fuzzy controller produce reasonably good tracking for steady-state or slowly varying operating conditions. However, when there is a step change in any of the operating conditions, such as may occur in the set point or load, the PI controller tends to exhibit some overshoot or oscillations The fuzzy controller reduces both the overshoot and extent of oscillations under the same operating conditions. Although the fuzzy controller has a slower response by itself, it reduces both the overshoot and extent of oscillations under the same operating conditions. The desire is that, by combining the two controllers, one can get the quick response of the PI controller while eliminating the overshoot possibly associated with it. Switching Control Strategy the switching between the two controllers needs a reliable basis for determining which controller would be more effective. The answer could be derived by looking at the advantages of each controller. Both controllers yield good responses to steady-state or slowly changing conditions.

To take advantage of the rapid response of the PI controller, one needs to keep the system responding under the PI controller for a majority of the time and use the fuzzy controller only when the system behaviour is oscillatory or tends to overshoot. Thus, after designing the best stand-alone PI and fuzzy controllers, one needs to develop a mechanism for switching from the PI to the fuzzy controllers, based on the following two conditions:

1) Switch when oscillations are detected;

2) Switch when overshoot is detected.

The switching strategy is then simply based on the following conditions: IF the system has an oscillatory behaviour THEN fuzzy controller is activated, Otherwise, PI controller is operated. IF the system has an overshoot THEN fuzzy controller is activated, Otherwise, PI controller is operated. The system under study is considered as having an overshoot when the error is zero and the rate of change in error is any other value than zero. The system is considered oscillatory when the sum of the absolute values of the error taken over time does not equal the absolute values of the sum of the error over the same period of time. Since the system is expected to overshoot during oscillatory behaviour, the only switching criterion that needs to be considered is an overshoot. However, in practice, it is more convenient to directly implement the control signal according to the control actions delivered by the controller. Consequently, the fuzzy controller can be designed so that normal behaviour (no oscillations or overshoot) results in a null fuzzy action. Accordingly, the switching between the two controllers reduces to using PI if the fuzzy has null value; otherwise, the fuzzy output is used. In particular, the fuzzy controller can be designed so that a normal behaviour as shown in Fig.6.

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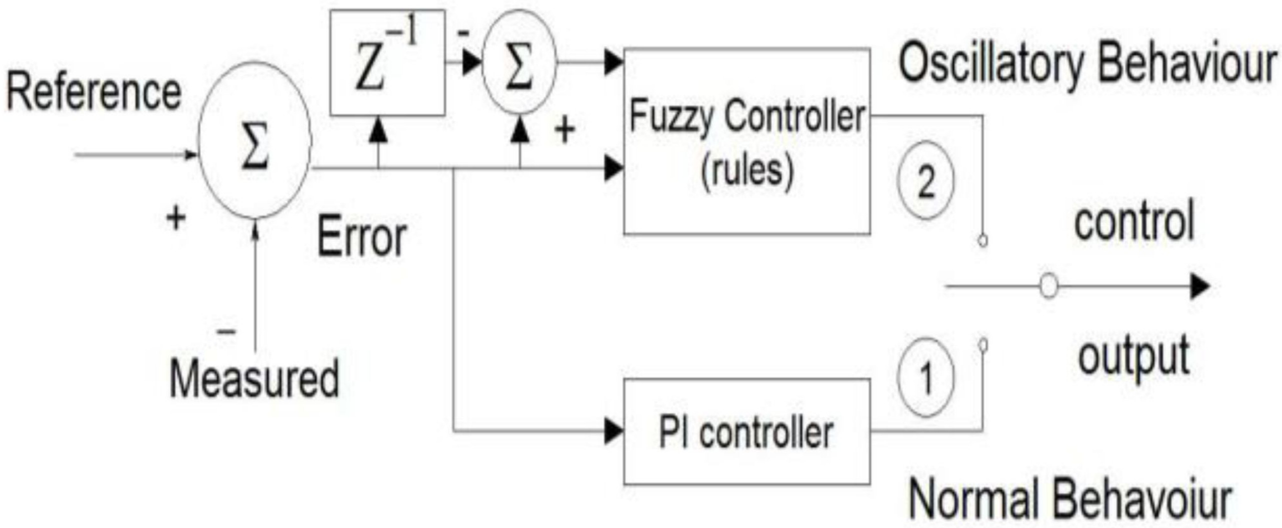

Fig.6.The structure of switching strategy results in a null fuzzy action.

IV. MATLAB/SIMULINK RESULTS

Here simulation is carried out in several cases and the complete model of STATCOM with several control strategies are designed by using MATLAB/Simulink platform. For estimating the advantages of the designed FLDC for the proposed STATCOM to the studied system, in this section the nonlinear system model is employed to compare the damping characteristics contributed by the proposed STATCOM on stability improvement of the studied system subject to a severe disturbance. It is assumed that the operating wind speed is 15 m/s. A three-phase short circuit fault happened in the transmission line is suddenly applied at t =2.0 s and is cleared after t=3.5 s.

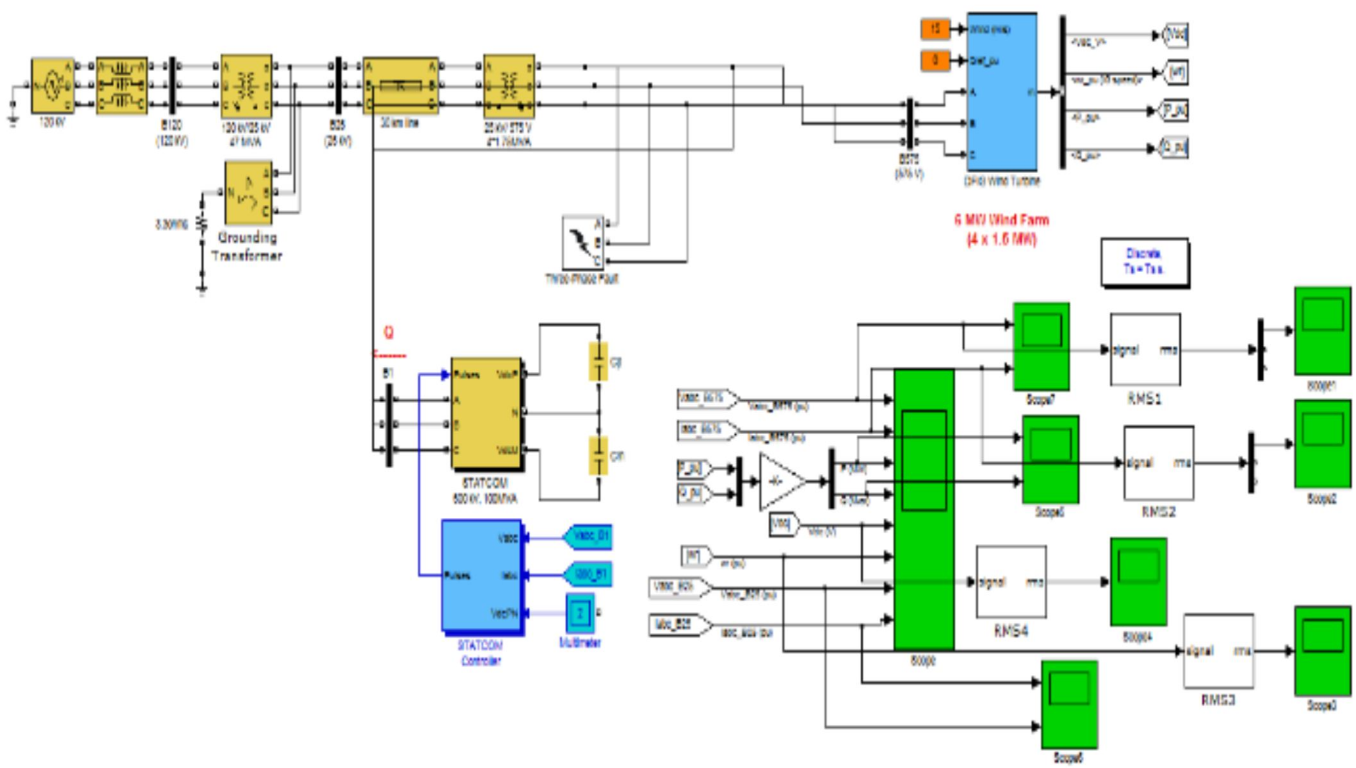

Fig.7 MATLAB/SIMULINK circuit for DFIG with Hybrid fuzzy controller

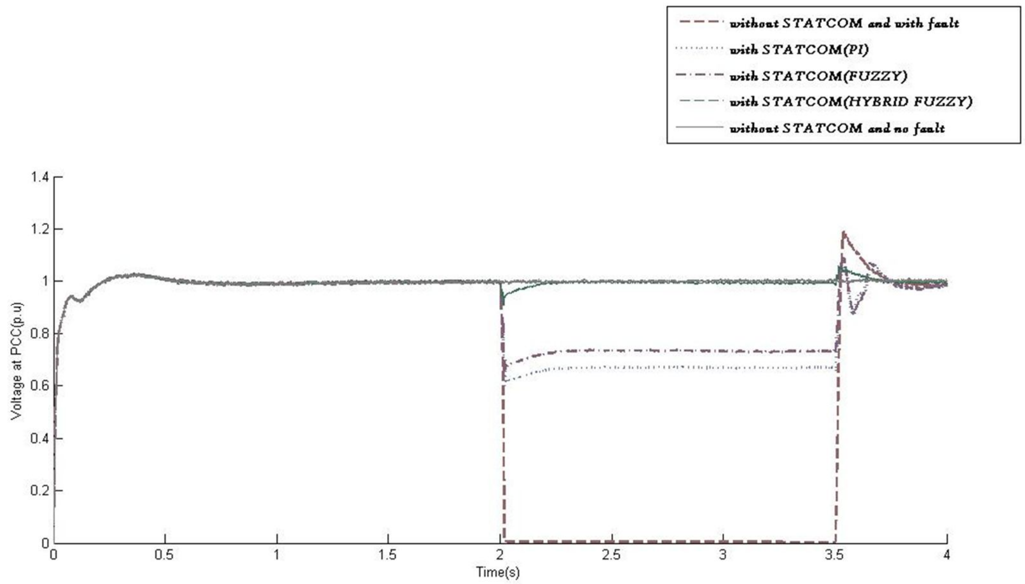

Fig.8 Voltages at PCC in Different Cases

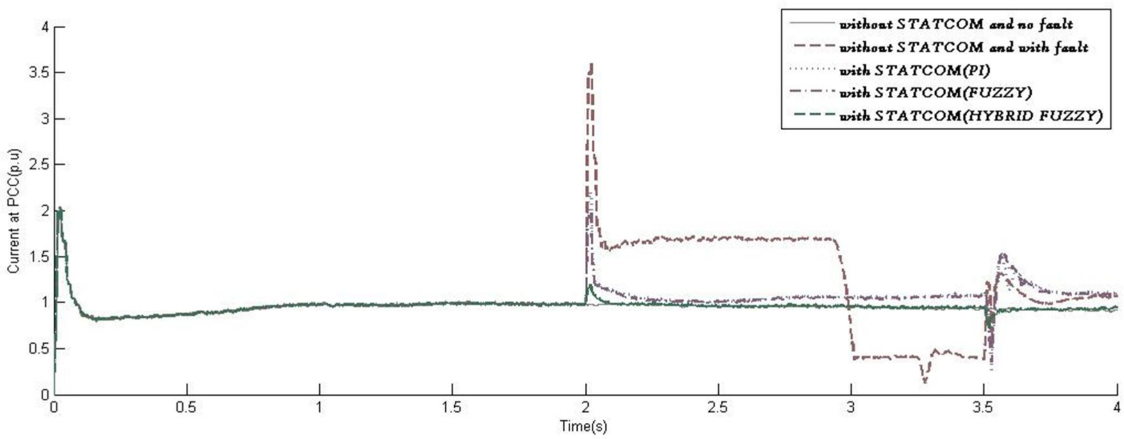

Fig.9 Currents at PCC in Different Cases

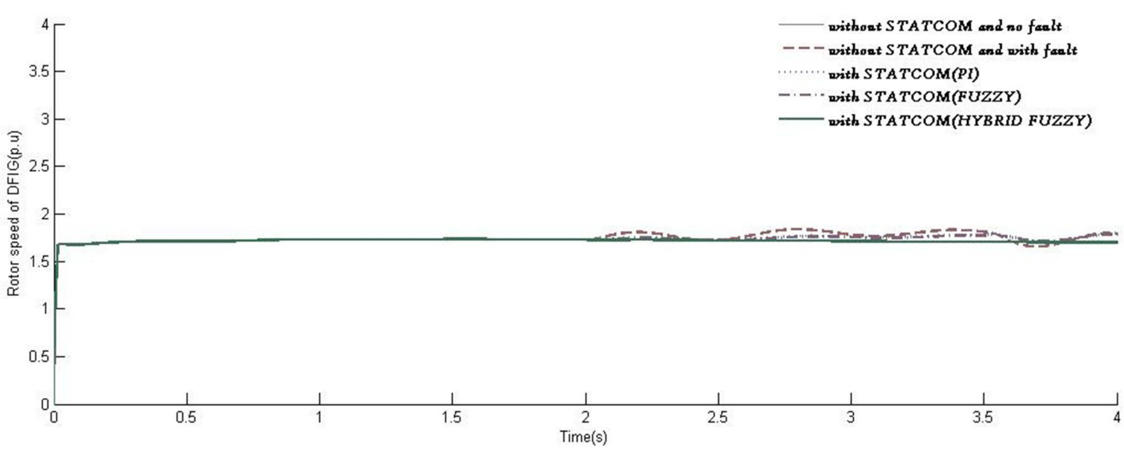

Fig.10 Rotor speeds of DFIG in Different Cases

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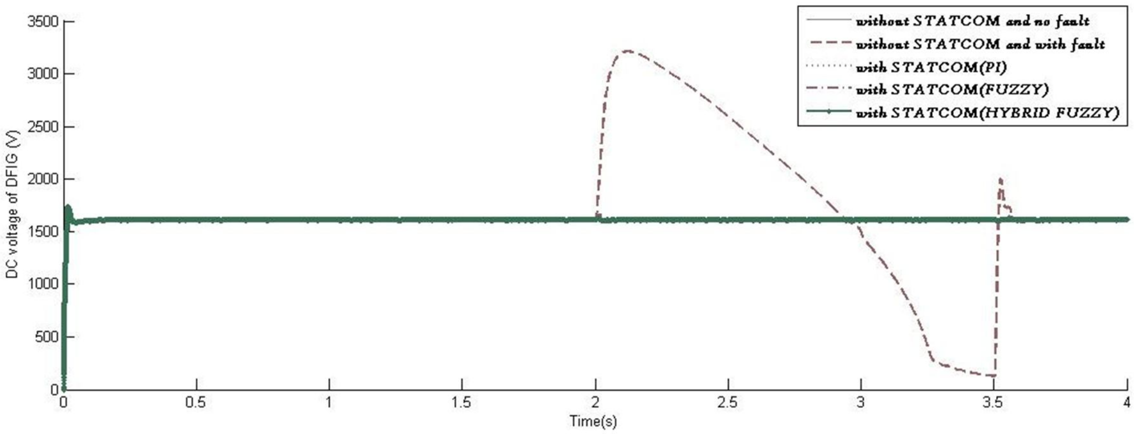

Fig.11 DC voltages at DC-Link of The Converter of DFIG in Different Cases

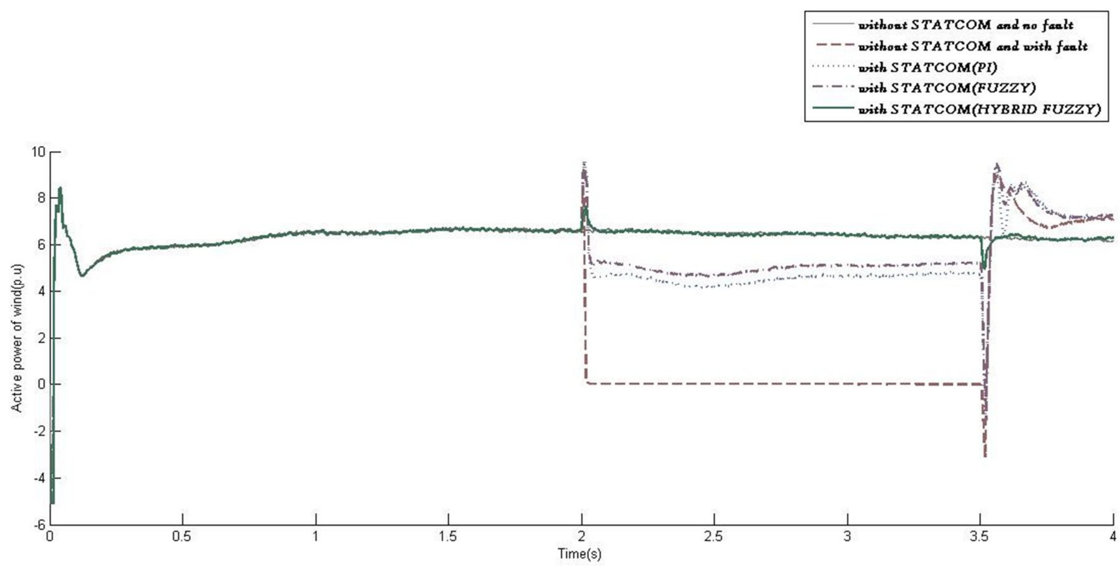

Fig.12 Active powers of DFIG in Different Cases

V. CONCLUSION

This paper has presented the control scheme for stability Improvement of a grid connected wind power system. To supply the adequate reactive power to the system an STATCOM with the designed hybrid controller integrated to the power system.
In time domain simulation of the studied system subject to a three phase short circuit fault at the Point of common coupling (PCC) has been systematically performed in MATLAB environment to demonstrate the effectiveness of the designed hybrid controller for suppressing inherent oscillations in the proposed system.
It can be concluded from the simulation results that a hybrid controller can be used for controlling STATCOM to improve the performance of the grid connected wind power system under a severe operating condition.

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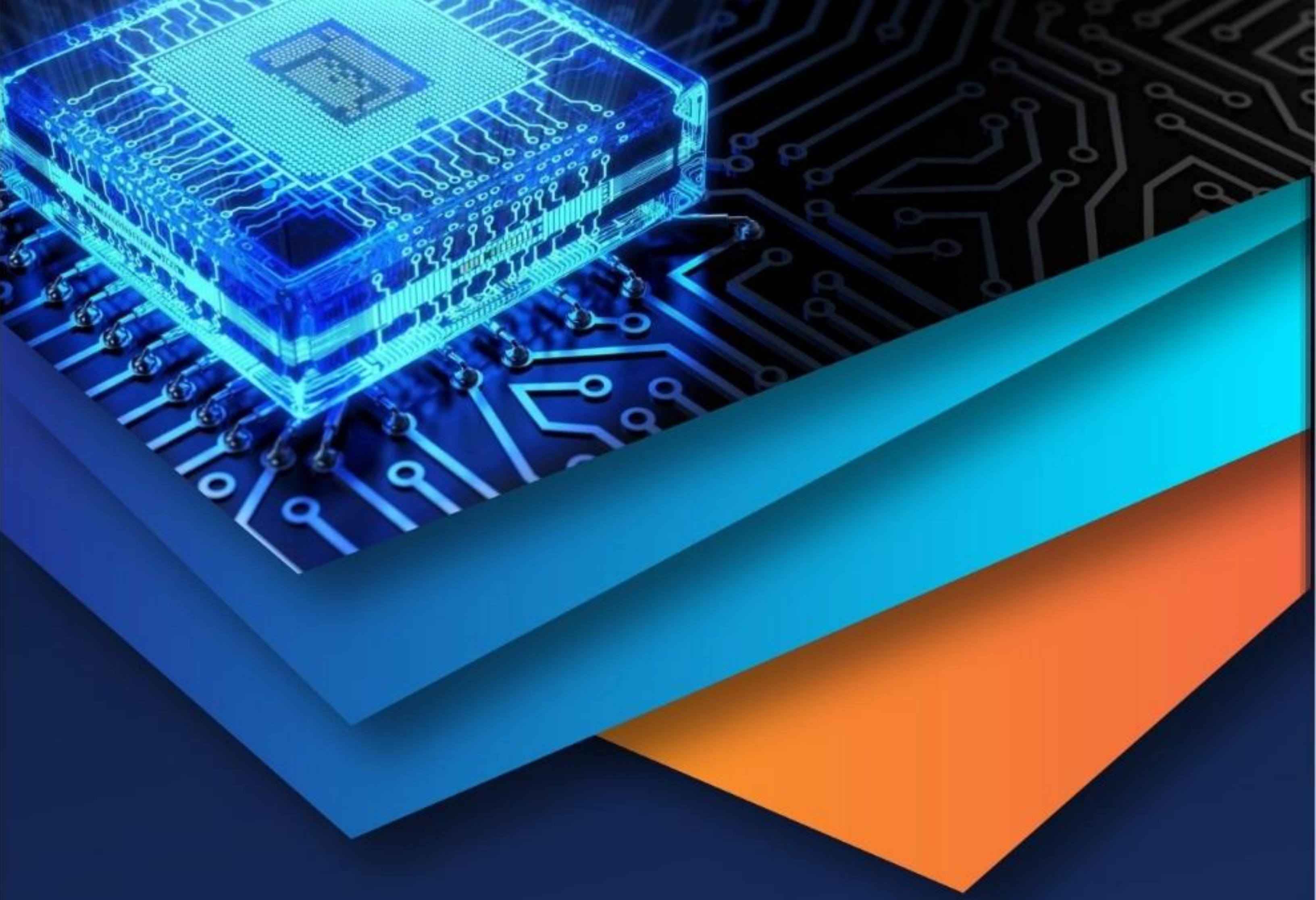

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