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Performance Evaluation of Wind Turbine Driven Squirrel Cage Induction Generator Connected to Grid

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Abstract

Recently various FACTS devices have been used for flexible power flow control, secure loading and damping of power system oscillation. Some of those are used also to improve transient and dynamic stability of wind power generation system (WPGS). In this paper we proposed the static reactive compensator (STATCOM) based on the voltage source converter (VSC) PWM technique to stabilize grid connected squirrel cage wind generator system. The paper deals with the fuzzy logic based control of wind turbine driven by squirrel cage induction generator (SCIG) connected to grid. The controller is proposed to maintain the speed of the squirrel cage induction generator constant for different wind speeds. The proposed fuzzy logic controller (FLC) is used with nine rules to implement the control strategy for the induction generator. These state variables used for fuzzy logic controller design are the error signals from the model of the induction machine. The computer simulation results show the controller is satisfactory in operation of induction generator (IG) with the significant improvement in the reactive power output.

Keywords: *Fuzzy Logic Controller (FLC), Induction Generator (IG), Squirrel Cage Induction Generator (SCIG), Wind Power Generation System (WPGS), Wind Power Plant (WPP), Flexible AC Transmission Systems (FACTS).*

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I. Introduction

The worldwide installed capacity of wind power reached 283 GW by the end of 2012. China (75,564 MW), US (60,007 MW), Germany (31,332 MW) and Spain (22,796 MW) are ahead of India in fifth position (18,421MW) [1]. The short gestation periods for installing wind turbines, and the increasing reliability and performance of wind energy machines has made wind power a favored choice for capacity addition.

Since the installed wind energy capacity is growing continuously, the interaction between the WPGS and grid has to be considered. Earlier, disconnection of wind turbine was not of the important consideration whenever there was a problem of supplying voltage. Today this concept has changed because loss of such a considerable part of the power production due to network disturbances can't be accepted any more as it results into instability of the power grid [2].

Due to its simple, rugged and maintenance free construction Induction generator (IG) is widely used as wind generator. IGs are connected directly to a power grid. For generation of active power IGs require reactive power to maintain air gap flux. This reactive power is provided by the grid. During disturbances like faults occurs the reactive power consumption of IGs increases. If grid is incapable to fulfill the reactive power requirements of IGs, it leads to tripping of wind turbines. This affects voltage profile of the bus to which WPP is connected and results in grid instability. So to maintain grid stability reactive power compensation is must whenever grid disturbances occur.

Recently voltage-source or current-source inverters based flexible AC transmission systems (FACTS) devices such as static var compensator (SVC), static reactive compensator (STATCOM), dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and unified power flow controller (UPFC) have been used for flexible power flow control, secure loading and damping of power system oscillation. Some of those are used also to improve transient and dynamic stability of WPGS. SVC is reported to improve the terminal voltage of induction generator by compensating the reactive power. But STATCOM has somewhat better performance compared to SVC for reactive power compensation, which is reported clearly in [3]. It is reported that STATCOM can recover terminal voltage of wound rotor induction generator after the fault clearance [4] [5].

In this paper, we proposed STATCOM, based on voltage source converter (VSC) PWM technique to stabilize grid connected squirrel cage wind generator system. The PI

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controller is replaced by the FLC. STATCOM are popular flexible AC transmission systems (FACTS) devices which are very useful to simultaneously deliver reactive power and support bus voltage of a WPP. Both regulate voltage at terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, they generate reactive power (capacitive). When system voltage is high, they absorb reactive power (inductive).

In this paper, we propose the STATCOM, based on voltage source converter (VSC) PWM technique to stabilize grid connected squirrel cage wind generator system. A simple control strategy of STATCOM is adopted. Moreover, a comparative analysis for steady state & transient condition has been made between the reactive compensations provided to induction generator with capacitor bank, induction generator with PI based STATCOM & induction generator with Fuzzy based STATCOM. Finally some simulation results are presented where transient stability of WPP is analyzed by using controllers system. Simulations have been done by MATLAB.

II. System Model

Fig. 1 shows the model system used for simulation of the transient stability of power system. Here, one 120 kV three phase programmable source is connected to infinite bus through a transformer (120/25 kV transformer) and a double circuit transmission line. One wind farm (Induction Generator, IG) is connected with the network via 25 km transmission line. The wind farm has 6 x 1.5 MW turbines thus the wind farm is having capacity of 9 MW.

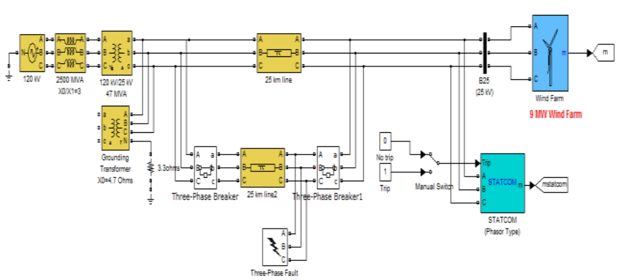

Fig 1 System Model with STATCOM

The fault is occurring on one of the circuits of double circuit transmission line in 20KV grid. A 400 kVAR capacitor bank is connected internally for reactive power compensation at steady state for each of the wind turbine. The STATCOM is connected with 25KV bus. The mathematical relation for the mechanical power extraction from the wind can be expressed as follows:

$$P_m = 0.5\ C_P(\lambda,\beta)\ \rho A v^3 \text{ ----------------(1)}$$

Where, P_m is the mechanical output power of the turbine (W), C_P is the Performance coefficient of the turbine which is a function of both Tip speed ratio of the rotor blade tip speed to wind speed, λ, and Blade pitch angle, β (deg), ρ is the Air density (kg/m3), A is the Turbine swept area (m^2), V is the Wind speed (m/s).

A generic equation is used to model $C_P(\lambda,\beta)$ is as below

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda i}} + c_6\lambda \text{-------- (2)}$$

With,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \qquad \text{----------- (3)}$$

III. STATCOM Control Strategy

The Static Synchronous Compensator (STATCOM) is a shunt device of the Flexible AC Transmission Systems (FACTS) to control power flow and improve transient stability on power grids. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive). The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source. The principle of operation of the STATCOM is explained on the Fig 2 below showing the active and reactive power transfer between a source V1 and a source V2. In this Fig, V1 represents the system voltage to be controlled and V2 is the voltage generated by the VSC. In steady state operation, the voltage V2 generated by the VSC is in phase with V1 (δ=0), so that only reactive power is flowing (P=0). If V2 is lower than V1, Q is flowing from V1 to V2 (STATCOM is absorbing reactive power). On the reverse, if V2 is higher than V1, Q is flowing from V2 to V1 (STATCOM is generating reactive power). The STATCOM used here is modeled as an IGBT-based STATCOM (fixed DC voltage).

The control system consists of a phase-locked loop (PLL) which synchronizes on the positive-sequence component of the three-phase primary voltage V1. The output of the PLL (angle θ=ωt) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltage and currents (labeled as Vd, Vq or Id, Iq on the diagram). Measurement systems measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage Vdc.

An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current Iqref for the current regulator (Iq = current in quadrature with voltage which controls reactive power flow). The output of the DC voltage regulator is the reference current Idref for the current regulator (Id = current in phase with voltage which controls active power flow). An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by the PWM converter (V2d V2q) from the Idref and Iqref reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is assisted by a feed forward type regulator which predicts the V2 voltage output (V2d V2q) from the V1 measurement (V1d V1q) and the transformer leakage reactance.[6]

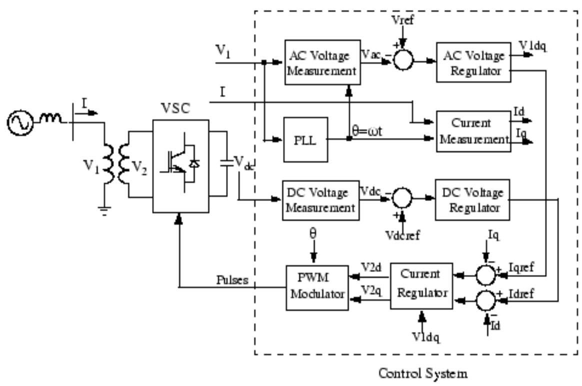

Fig 2 System Model with STATCOM

IV. Fuzzy Controller Design

Fuzzy inference is a method that interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. In this paper PI controller is replaced by FLC to modify the overall output. Fig 3 indicates the PI controller implemented in STATCOM.

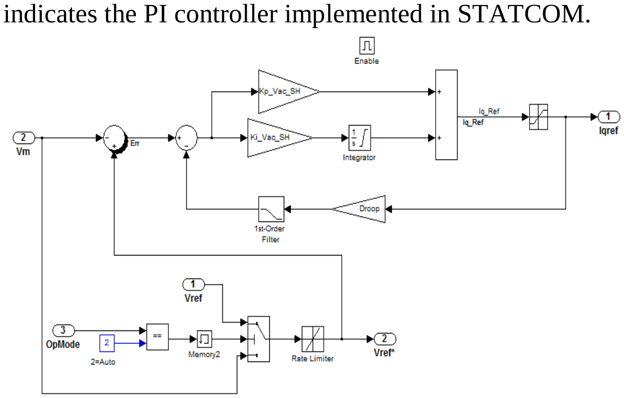

Fig 3 PI Controller connected in STACOM

Fig 4 indicates the FLC connected in the STATCOM. Two inputs used FLC controller are the error signal & the change in the error signal of AC voltage regulator block inside the STATCOM.

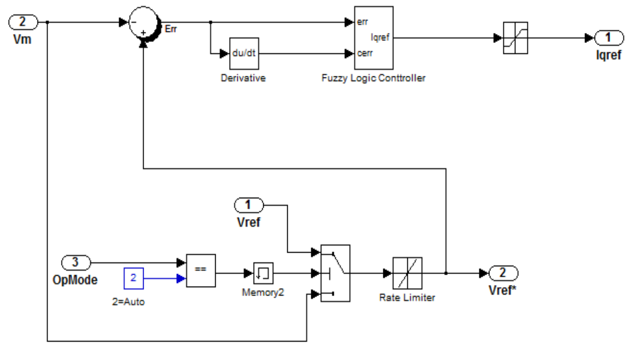

Fig 4 Fuzzy Logic Controller connected in STACOM

Fig 5 indicates the inside view of the FLC three gains are provided for inputs & output. For error signal gain provided is Ke. Gain provided for change in error signal is termed as Kce whereas the gain provided for the output signal i.e Iqref is termed as KIqref.

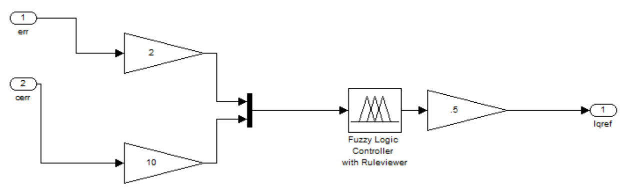

Fig 5 Fuzzy Logic Controller

1) Fuzzification

To design the proposed FLC, the error signal, err(k), and change of error signal, cerr(k) are considered as the controller inputs. The Iqref , is considered as the controller output. For convenience, the output and inputs of the FLC are scaled with coefficients Ke , Kce , KIqref respectively. These scaling factors can be constants or variables and play an important role for FLC design in order to achieve a good response in both transient and steady states. In this work, these scaling factors are considered as constant for the simplicity of controller design, and are selected by trial and error. The values of are Ke , Kce , KIqref chosen 2, 10 and 0.5 respectively. The triangular membership functions with overlap are used for the input & output fuzzy sets as shown in Fig 3. The linguistic variables are represented by N (Negative), Z (Zero), and P (Positive) for input.

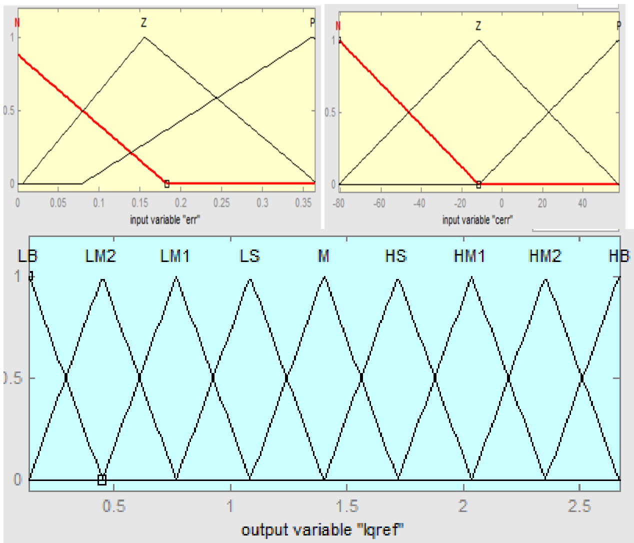

Fig 6 Fuzzy Set and their corresponding membership functions

The linguistic variables are represented by Lower Big (LB), Lower Medium-2 (LM2), Lower Medium-1(LM1), Lower Small (LS), Higher Big (HB), Higher Medium-2 (HM2), Higher Medium-1(HM1), and Higher Small (HS) for output.

2) *Rule Base*

The fuzzy mapping of the input variables to the output is represented by IF-THEN rules of the following forms

IF (err = N) and (cerr = N)THEN (Iqref = LB)
IF (err = N) and (cerr = Z)THEN (Iqref = LM2)

The entire rule base is given in the table-I below. There are total nine rules used for achieving the desired performance of system.

Table 1: Fuzzy Rule Base

Iqref		**cerr**		
		N	**Z**	**P**
err	***N***	LB	LM2	LM1
	Z	LS	M	HS
	P	HM1	HM2	HB

3) *De-fuzzification*

In this work, for the inference mechanism Mamdani's prod-probor [7] method is used for inference mechanism. The center of gravity method [7] is used for defuzzification to obtain Kp and Ki, which is given by following equation:

$$I_{qref} = \sum_{i=1}^{n} \frac{\mu_i C_i}{\mu_i} \text{ ----------- (4)}$$

where, n is the total number of rules, μ_i is the membership grade for the i-th rule, and C_i is the coordinate corresponding to respective output or consequent membership function.

V. Simulation Analysis

The system behavior under steady state & dynamic conditions are the main consideration. [8]

CASE-I: -

In this case the System behavior is compared under steady state condition with different reactive power compensation methods/techniques provided. The simulations are carried out on same system with three different reactive power compensation methods/techniques provided separately i.e with capacitor bank only, with PI STATCOM & Fuzzy STATCOM. Fig 7 shows simulation results recorded. It can be commented after seeing the results that the voltage profile achieved by STATCOM under steady state is better than the voltage profile achieved in the case when only Capacitor bank compensation was provided.

Consider Fig 8 in which the reactive power injected by the STATCOM PI based & Fuzzy based is compared. It is well known that reactive power is needed to Supply from the network to the stator winding of the induction generator to establish the rotating magnetic field of the stator. It can be noted that at starting the stability of Fuzzy based STATCOM is better compared to the PI based STATCOM. In addition to this response is faster.

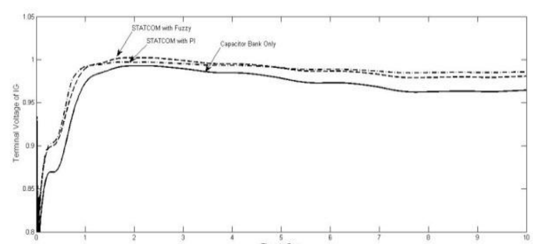

Fig 7 Comparison of the Terminal Voltage of IG under steady state condition

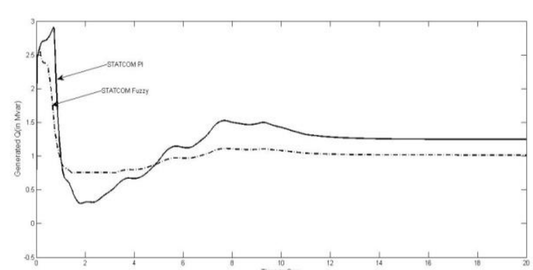

Fig 8 Reactive Power Generated by STATCOM

CASE-II: - Now in Fig 9 & 10, a L-L-L-G fault is considered to occur at a distance of 25 km away from WPP. The fault occurs at 15 sec. To compensate the reactive power demand STATCOM is connected. The performance compared here is of PI based STATCOM & Fuzzy based STATCOM. Seeing the Fig.9 &10, it can be stated that with voltage profile maintained at 1 p.u the reactive power compensation provided under steady state & transient conditions during the fault it is noticeable that the proposed fuzzy controller gives better performance compare to conventional PI controller.

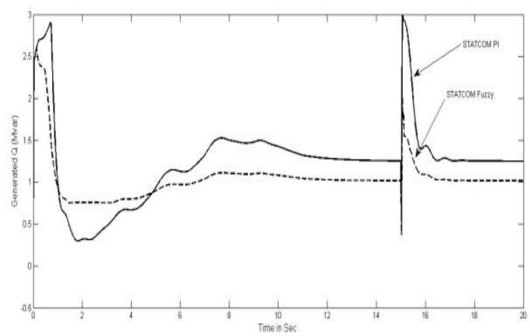

Fig 9 Reactive Power Generated at STATCOM

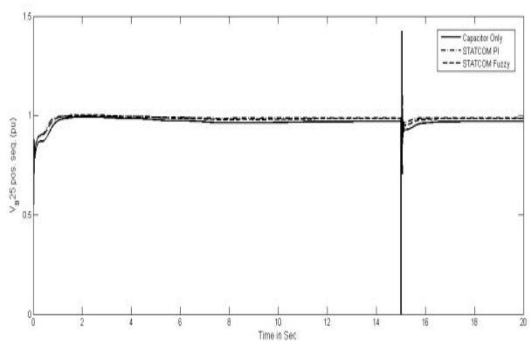

Fig 10 Bus voltage during 3 L-G fault in System at Location of 25km away from WPP

CASE-II: -
To analyze the Transient performance of STATCOM connected with WPP, the 3LG is considered to occur again. Now in Fig 11 & 12, a L-L-L-G fault is considered to occur at terminal bus of WPP. The fault occurs at 15 sec. To compensate the reactive power demand STATCOM is connected. The performance compared here is of PI based STATCOM & Fuzzy based STATCOM. Seeing the Fig.11 &12, it can be stated that with voltage profile maintained at 1 p.u the reactive power compensation provided under steady state & transient conditions during the fault it is noticeable that the proposed fuzzy controller gives better performance compare to conventional PI controller.

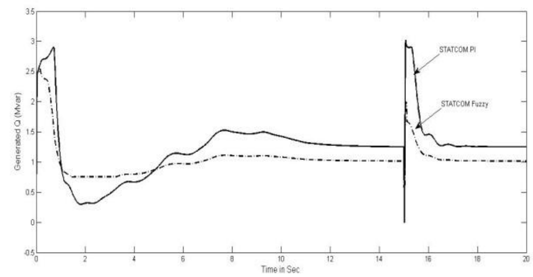

Fig 11 Reactive Power Generated at STATCOM

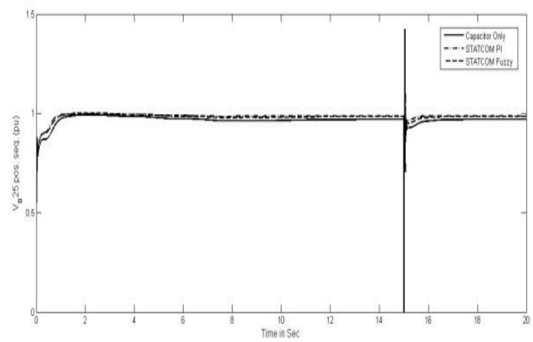

Fig 12 Bus voltage during 3 L-G fault in System near to WPP

VI. Conclusion

In this work the static reactive compensator (STATCOM) based on voltage source converter (VSC) PWM Technique is presented to stabilize gird connected squirrel cage wind generator system. Simulation results clearly indicate that STATCOM equipped with the proposed fuzzy control gives better and faster performance than STATCOM with conventional controller. In addition to this transient performance of WPP as well as of entire power system when severe network disturbances occur in power system can be enhanced to gain the higher system stability. So it is recommended to connect STATCOM with WPP as it can enhance steady state and transient performances of entire power system. In our future study we want to investigate the STACOM behaviour with sudden changes in load demand where WPP is connected with a standard power system network. In addition to this reduction in the capacity of the capacitor banks with implementation of STATCOM is also under consideration.

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