Low Voltage Ride through Capability Improvement of Fixed Speed Induction Generator based Wind Farm by Fuzzy Controller based STATCOM

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Abstract— Environmental and political impact for a sustainable development have encouraged the growth of electrical generation from renewable energies. A pressing demand for more electric power coupled with depleting natural resources has led to an increased need for energy production from renewable energy sources such as wind and solar. The latest technological advancements in wind energy conversion and an increased support from governmental and private institutions have led to increased wind power generation in recent years. Wind power is the fastest growing renewable source of electrical energy Wind power generation of electricity is seen as one of the most practical options and with better relation cost-benefit inside the energetic matrix now a days. Fuzzy based controller is designed to improve the source current in STATCOM. This study provides the results of a study conducted to assess the "Low Voltage Ride through Capability improvement of Fixed-speed induction generator using STATCOM" in a power system.

Key words: Squirrel cage induction generator, Low Voltage Ride through, Wind Turbine Model, Reactive power, STATCOM

I. INTRODUCTION

Due to its potential for bulk generation of clean power, Wind energy has become very popular over the last few decades. However, it is unreliable to supply steady power demand due to the difficulty of regulating the primary energy. Today, wind energy is considered as an economically viable renewable energy source, costing about 5 cents per kWh globally. It is the fastest growing energy market today with the growth rate of 35% per year. With the massive penetration of wind energy conversion systems in the power network, some new problems arise not only in technical areas, but also in economy, policy and regulatory fields [1]

Currently, variable speed wind turbine generators are used in newly installed wind farm but many Fixed Speed Induction Generators (FSIG) directly connected to the grid are still in operation. However, fixed speed induction generator does not have the capacity to control their reactive power exchange because they always need to absorb a certain amount of reactive power.

Grid Codes for wind farms integration have been published in countries such as Denmark, Germany, UK and Spain to ensure proper operation of wind farms. Grid Codes differ from country to country, but most of them include the following [2]

– Ability of wind farms to provide voltage and reactive power control at the point of common coupling (PCC).
– Contribution to active power and frequency control.
– Low Voltage Ride-Through capability.

Low Voltage Ride through (LVRT) capability is one of the most important requirements that have been developed in these grid codes. Typical low-voltage ride-through (LVRT) requirements demand that wind farms remain connected to the grid for voltage levels as low as 5% of the nominal voltage for up to 140 ms [10].

During a fault, due to the imbalance between the mechanical power extracted from the wind and the electrical power delivered to the grid, the WT's generator will accelerate. When the fault is cleared, the reactive power consumed by the wind generator affects the voltage restoration. Therefore, the grid voltage will take some time to be recovered and return to the pre-fault condition. During this period, the wind generator will continue to accelerate and consume larger amounts of reactive power. If wind farm is connected to a weak grid, the above process results in rotor-speed and voltage instability. However if all wind turbines are disconnected in response of a grid fault, wind generators will not be able to supply the grid with the required voltage and frequency during and after fault conditions. This may result in blackouts in the power system if the wind farms' penetration levels are considerably high. To prevent these types of instabilities, pitch control or STATCOM control can be used [4]. The pitch control system is the cheapest solution for the wind generator stabilization, but its response is slow. As a result, the pitch control system cannot be considered as an effective stabilization means for wind energy conversion system [13].

Voltage or current source inverter-based flexible AC transmission system (FACTS) devices such as static var compensator (SVC), static synchronous compensator (STATCOM), D-STATCOM, have been used for flexible power flow control, secure loading and damping of power system oscillation. When compared to SVCs, STATCOMs are faster, smaller and have better performances at reduced voltages and it adds the missing functionality to wind farms in order to become grid-code compliant by providing reactive power control [6-12]. Under unbalanced grid voltage dips, the negative sequence voltage causes heavy generator torque oscillations that reduce the lifetime of the drive train. Investigations on an FSIG-based wind farm in combination with a STATCOM under unbalanced grid voltage fault are given in [7].

In this paper, modelling of fixed speed induction generator (FSIG) is proposed to study the dynamics of the wind farm system and a method of improving Low Voltage Ride through (LVRT) capability of fixed speed induction generator by injecting a reactive power at the point of common coupling with the use of STATCOM is proposed.

II. LOW VOLTAGE RIDE THROUGH ON FSIG

There are two types of trend namely Fixed speed and Variable speed of wind turbine generator systems, between these two trend, constant speed wind generator has weaker fault ride through capabilities. Induction Generators have brushless and rugged construction, low cost, maintenance and operational simplicity and is therefore preferred as wind generators. Statistics shows that the total installation of Fixed Speed WTGS is around 40%. Therefore it is still needed to analyze the Fault Ride Through characteristics in Fixed Speed WTGS [1].

In the past, wind generators were allowed to be disconnected from the network when the voltage of the wind farm is greatly reduced because of a network disturbance in power system. Disconnection of large wind farms is no longer considered to be suitable as it can have serious effect on the power system operation. Thus, a new set of grid codes has been defined to suit the wind farm grid interfacing. As a result, specifications are now being revised to reflect new requirements for wind turbine integration into the network. Some measures are proposed about the low voltage ride through capability of the wind turbine with Fixed Speed Induction Generator. Flexible AC Transmission Systems (FACTS) have recently emerged as more promising devices for power system applications as FACTS have the ability to improve both voltage and power quality of wind generator.

III. WIND TURBINE MODEL

The modeling of FSIG wind farms is documented in the literature [17]. The main components that need to be modeled are:

- Aerodynamic rotor (converts the wind power into mechanical power).
- Mechanical system (connects the aerodynamic rotor to the electrical generator using shafts and gearbox).
- Generator (converts the mechanical to electrical power using an asynchronous generator).
- Control system (controls and optimizes the wind turbine operation).
- Capacitor bank (provides partial or total compensation of the reactive power demanded by the generator)

A. Aerodynamic Model

The wind turbine rotor transforms the absorbed kinetic energy of the air into mechanical power. The energy available in the air is given by:

$$P_w = \frac{1}{2}\rho_{air}\pi R^2 V_w^3 \qquad (1)$$

Where, ρ_{air} is the air density (1.225Kg/m3), R is the rotor radius (m), and V_w is the wind speed (m/s).

The amount of power that a wind turbine can actually extract depends on the power coefficient (c_p), hence the turbine mechanical power (P_{mech}) is defined as [17, 18]:

$$P_{mech} = c_p P_w = 0.5 c_p \rho_{air}\pi R^2 V_w^3 \qquad (2)$$

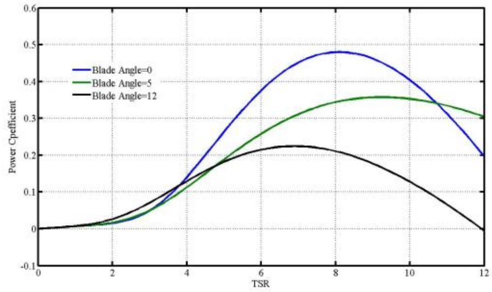
The maximum limit for the power coefficient is 59% (Betz limit) and is a function of the turbine tip-speed ratio (TSR or λ) and the pitch angle (β). The general expression for the power coefficient is:

$$c_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{(\frac{-c_5}{\lambda_i})} + c_6\lambda \qquad (3)$$

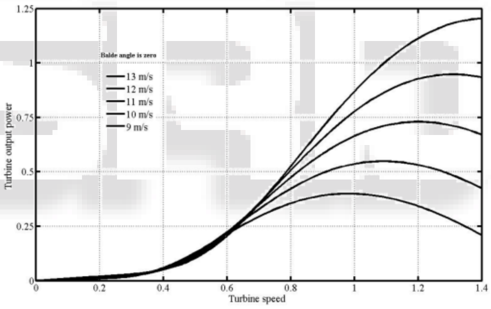
Where the value of λ_i is calculated as:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta+1} \qquad (4)$$

The optimal rotor speed for extracting maximum power from the prevailing wind can be found from the wind turbine characteristics shown in Fig. 1, at higher then rated wind speeds the generated power will exceed the nominal power, and therefore it is necessary to reduce the mechanical power using pitch control.



(a) Power efficiency coefficient for different blade angle



(b) Mechanical power curve of a FSIG for different wind speed

Fig.1: Fixed speed wind turbine characteristics [2]

B. Shaft System Model

The drive train of the wind turbine generator can be represented by a two-mass model as shown in Fig. 2, the first mass represents the blade, hub and low-speed shaft while the second mass represents high-speed shaft. The relationship between the torque supplied by the wind turbine (T_{wt}), mechanical torque (T_m) and the electromagnetic torque developed by the generator (T_e) is defined as [16, 17]:

$$2H_{wt}\frac{d\omega_r}{dt} = T_{wt} - T_m$$
$$2H_e\frac{d\omega_e}{dt} = T_m - T_e \qquad (5$$
$$T_m = D_m(\omega_r - \omega_e) + K_m\int(\omega_r - \omega_e)dt$$

Where H_{wt}, H_e, ω_r, ω_e, D_m, and K_m are wind turbine inertia, generator inertia, wind turbine rotational speed, generator rotational speed, mechanical damping constant and mechanical stiffness respectively.

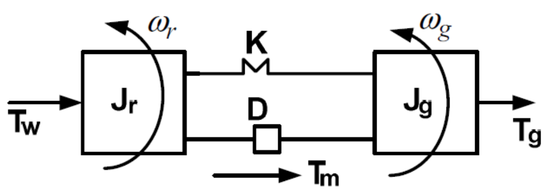


Fig. 2: Drive train two-mass model [2]

C. Induction Generator Model

A FSIG wind turbine uses a squirrel cage induction generator [4, 6]. A reduced order model commonly used to describe the electromagnetic transient of an induction generator is given in (6). The following assumptions are considered: magnetic saturation is neglected, flux distribution is sinusoidal, and stator transient is neglected. The equations describe both stator and rotor in the synchronous d-q reference as follow:

$$v_{ds} = -R_s i_{ds} - \omega_s \psi_{qs}$$
$$v_{qs} = -R_s i_{qs} + \omega_s \psi_{ds}$$
$$0 = -R_r i_{dr} - S\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \qquad (6)$$
$$0 = -R_r i_{qr} + S\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt}$$

Where v is the voltage, R is resistance, i the current in, ω is frequency, S the machine slip, and ψ is flux linkage; d and q indicate the direct and quadrature axis components and r and s denote rotor and stator quantities.

The flux linkage in equation can be calculated using equation

$$\psi_{ds} = -(L_s + L_m) i_{ds} - L_m i_{dr}$$
$$\psi_{qs} = -(L_s + L_m) i_{qs} - L_m i_{qr}$$
$$\psi_{dr} = -(L_r + L_m) i_{qr} - L_m i_{ds} \qquad (7)$$
$$\psi_{qr} = -(L_r + L_m) i_{qr} - L_m i_{ds}$$

Where L_s, L_r, L_m are stator leakage inductance, rotor leakage inductance, and mutual inductance respectively

Voltage equation can be written as:

$$v_{ds} = -R_s i_{ds} + \omega_s ((L_s + L_m) i_{qs} + L_m i_{qr})$$
$$v_{qs} = -R_s i_{qs} - \omega_s ((L_s + L_m) i_{ds} + L_m i_{dr})$$
$$0 = -R_r i_{dr} + S\omega_s ((L_r + L_m) i_{qr} + L_m i_{qs}) + \frac{d\psi_{dr}}{dt} \qquad (8)$$
$$0 = -R_r i_{qr} + S\omega_s ((L_r + L_m) i_{dr} + L_m i_{ds}) + \frac{d\psi_{qr}}{dt}$$

The equation of motion of the generator is:

$$\frac{d\omega_m}{dt} = \frac{1}{2H_m}(T_m - T_e) \qquad (9)$$

The active and reactive power of the generator is given by:

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \qquad (10)$$
$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs}$$

D. Control system Model

From Fig.1 it is shown that the maximum power extraction is achieved at β=0. At high wind speed, β must be adjusted to limit the aerodynamic power. The blade angle will not change immediately, practically, the rate of change in pitch angle is in the range (3-10) degree/s depending on wind turbine design. A simple *PI* controller is used to adjust the pitch angle by comparing the reference rotor speed (ω_r) and measured rotor speed (ω) as shown in Fig. 3.

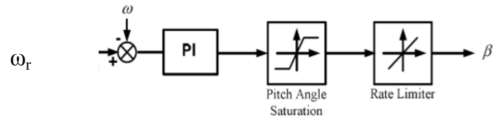


Fig. 3: control scheme of pitched regulated wind turbine [2]

IV. STATCOM CONTROL

The Static Synchronous Compensator (STATCOM) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics 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) [20]. 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 figure 4 below, showing the active and reactive power transfer between a source V1 and a source V2. In figure 4, V1 represents the system voltage to be controlled and V2 is the voltage generated by the VSC [20].

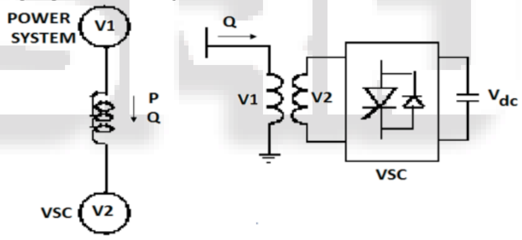


Fig. 4: The active and reactive power transfer between a source V1 and a source V2 [20]

Fig. 5 shows the block diagram of the STATCOM controller.

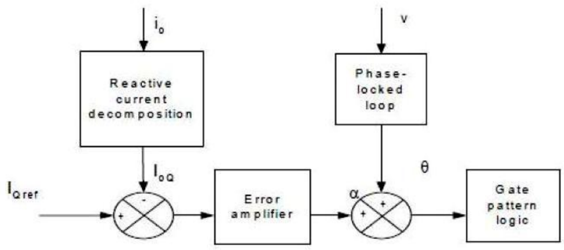


Fig. 5: Basic STATCOM control scheme [22]

A STATCOM injects almost a sinusoidal current Io of variable magnitude at a point of connection. The injected current is almost in quadrature with the line voltage V, thereby emulating an inductive or a capacitive reactance at the point of connection with the transmission line. The functionality of the STATCOM model is verified by regulating the reactive current flow through it this is useful to generate or absorb reactive power for regulating the line voltage of the bus where the STATCOM is connected.

Fig. 6 shows simple gain control of STATCOM voltage.

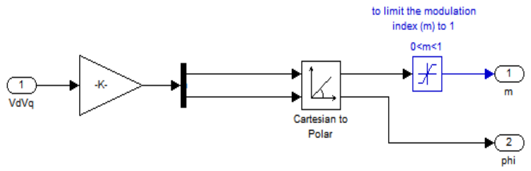


Fig. 6: Gain control of STATCOM voltage [20]

V. FUZZY CONTROL

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).

Fig. 7 shows the fuzzy logic control of STATCOM voltage.

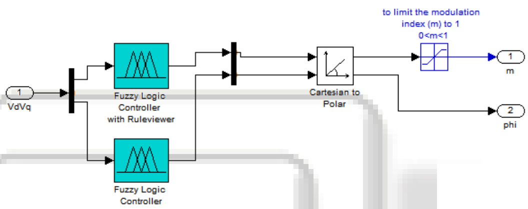


Fig. 7: Fuzzy logic control of STATCOM voltage [20]

FLC voltage regulator is fed by one input that is voltage error (Ve). The rules for the proposed FLC voltage controller are:

- If input is ‘mf1’ then output is ‘mf1’
- If input is ‘mf2’ then output is ‘mf2’
- If input is ‘mf3’ then output is ‘mf3’
- If input is ‘mf4’ then output is ‘mf4’
- If input is ‘mf5’ then output is ‘mf5’

This paper focuses on fuzzy logic control based on mamdani's system. This system has four main parts. First, using input membership functions, inputs are fuzzified then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the main control system. Error of inputs from is chosen as input.

Fig. 8 shows input and output membership functions. To avoid miscalculations due to fluctuations in wind speed and the effects of noise on data, triangular membership functions are chosen to have smooth and constant region in the main points.

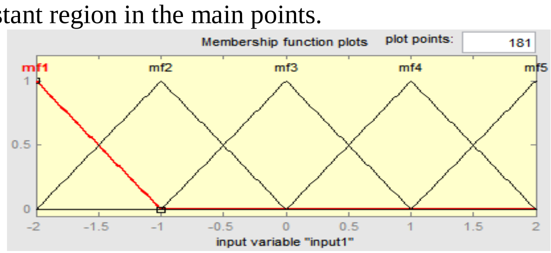


Fig. 8(a): Input membership function

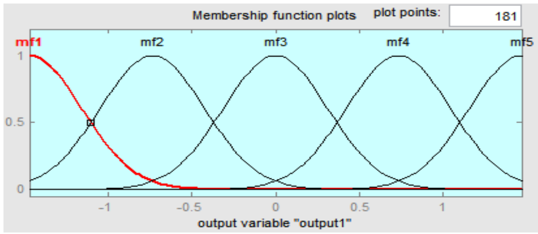


Fig. 8(b): Output membership function

Fig. 8(a,b): Input and output membership function of FLC voltage regulator

VI. MODELLING OF LVRT

A wind farm consisting of six 1.5-MW wind turbines is connected to a 25-kV distribution system exports power to a 120-kV grid through a 25-km 25-kV feeder. The 9-MW wind farm is simulated by three pairs of 1.5 MW wind-turbines. Wind turbines use squirrel-cage induction generators (IG). The stator winding is connected directly to the 60 Hz grid and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s)[20]. In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.

Initially, wind speed is set at 8 m/s, then starting at t=4s for wind speed is rammed to 11 m/s in 2 seconds. Then, at t=10 s a temporary fault is applied at the high voltage side which is grid side and fault is cleared at 10.1 second.

Under grid fault pitch angle control response is slow to limit the generator output and requirement of reactive power is much high to stabilize the voltage at Point of common coupling (PCC). Therefore we have used external dynamic reactive power compensation device namely STATCOM to provide the excessive reactive power during grid fault.

VII. SIMULATION PROCESSES AND RESULTS

In the scope of this paper, an integrated dynamic model of FSIG based WECS is simulated in MATLAB®/SIMULINK to investigate their dynamic performance.

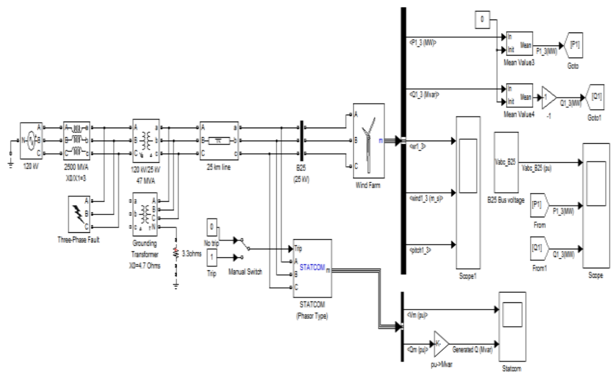


Fig. 9: Wind model with STATCOM

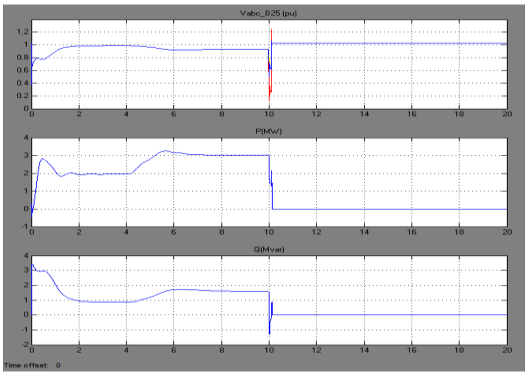


Fig. 10: Voltage, active power and reactive power without STATCOM compensation

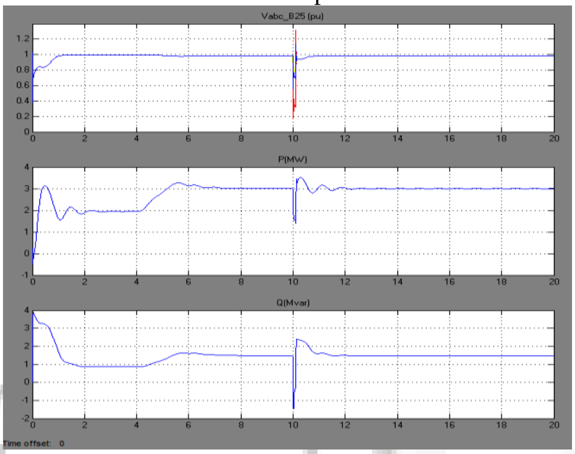


Fig. 11: Voltage, active power and reactive power with STATCOM compensation

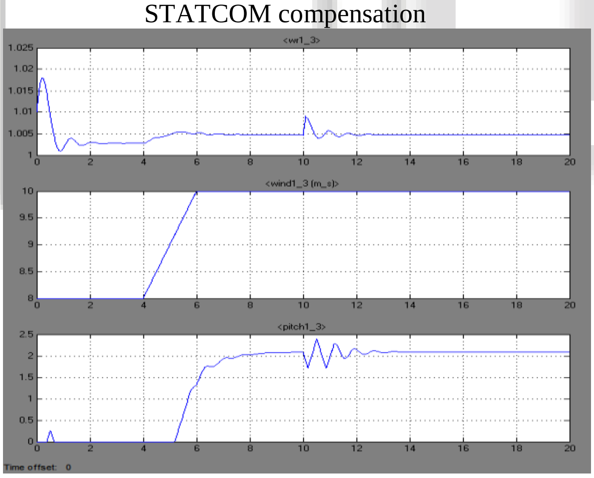


Fig. 12: Rotor Speed, Wind Speed, and pitch angle

VIII. CONCLUSIONS

In this paper, the effect of low voltage profile of grid connected wind farms is studied with detailed analysis of mathematical modelling of Wind Energy Conversion System (WECS). Also Fuzzy logic controller based STATCOM is presented for grid connected Wind Energy Generating System. The proposed FLC based STATCOM have improved the Low Voltage Ride through (LVRT) Capability of Fixed Speed Induction generator.

In this paper the effect of low voltage profile on grid connected wind farms and it's improvement through STATCOM have been studied. fuzzy logic controller of STATCOM is better than PI control.

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