Low Voltage Ride Through Capability Enhancement in Wind Farms by UPQC Based Fuzzy Controller

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Abstract—In this paper a novel control strategy presented to grid integration of wind farms using squirrel-cage induction generators (SCIG) by unified power quality conditioner (UPQC) based on Fuzzy Logic Controller (FLC). The interaction between wind generators and grid cause increasing short circuit current level, instability, fault ride-through (FRT) or low voltage ride-through (LVRT) capability problem during fault condition. A new control strategy established for generation reference signals of series converter (SERC) and shunt converter (SHUC) considering Spanish grid code. This control scheme can fulfill compensate all types of voltage sags. Also the proposed controller supplements the phase jump recovery. This control scheme deal with a dual control of real and reactive power transaction between wind energy conversion system based SCIG (WECS-SCIG) and grid. As well as, FLC makes a fast dynamic response to any changes in speed, voltage and other important parameters of SCIG facing of short circuit and instability of wind farm. The simulation results can verified the high efficiency of proposed FLC-UPQC strategy to enhancement of Low Voltage Ride Through (LVRT) capability of wind farm.

Keywords—UPQC; Wind Farm; LVRT; Fuzzy Controller; Grid Code

I. INTRODUCTION

In recent years, dramatically increasing the penetration of wind farms in electrical power system, caused the importance behavior of wind turbines under grid faults and low voltage conditions or other disturbances. Therefore comprehensive survey to recognize the interaction between wind farms and power grid is necessary [1]. Some literatures studies different impact of wind farms on power system under symmetrical and asymmetrical grid faults [2-5].

Faults or low voltage in the grid cause voltage sag at the point of common coupling (PCC). Voltage sag and other voltage disturbances will decrease the electrical torque of Squirrel-Cage Induction Generators (SCIG); consequently, the active power of Wind Energy Conversion System based SCIG (WECS-SCIG) will be reduced. Whereas, the mismatch between mechanical and electrical power make increasing the speed of rotor of SCIG. By increasing of rotor speed, the wind farm absorb more reactive power that can cause more depression in voltage magnitude. After clearing the fault, if the rotor speed does not over its critical speed, SCIG can get the equilibrium point. Otherwise, if the wind generators unable to withstand against faults, it must be disconnected from the grid and it may cause a cascading voltage collapse and the breakdown of the rest of wind farm generators. In order to overcome of these mentioned drawbacks, it is necessary to restore the wind turbine normal operation by passing of Grid Code Integration (GCI) requirements.

In this paper the Spanish grid code is used to improve the stability of WECS-SCIG facing the fault conditions.

Fig. 1 defines the area of voltage sag at the PCC that should be borne by wind farms and Fig. 2 depicted the admissible reactive power absorption by wind farms during the voltage sag period [2].
In Fig. 1, shaded area demonstrated that wind farm must be stay connected during the voltage sag under this requirements. Additionally, wind farm must injected maximum current for voltage sag recovery during the fault (see Fig. 2). For example, wind farm must be stay connected during a voltage sag (with 80% depth) at PCC for 500 msec.

Some methods to improve LVRT have been investigated in [6], [7]. Flexible AC Transmission System (FACTS) devices such as Static Var Compensator (SVC) [8], STATic synchronous COMpensator (STATCOM) [9], Dynamic Voltage Restorer (DVR) [10]-[11] are effective solution for LVRT capability enhancement of WECS-SCIG. These devices absorb or inject reactive and active power to the grid to overcome the fault problems. In the other hand, FACTS devices can control the transaction power between SCIG and grid to avoid disconnection of wind turbine from grid [4]-[5].

Unified power quality conditioner (UPQC) is one of the versatile FACTS devices that consists of two parts which are connected in series (SERC) and shunt (SHUC) Voltage Source Inverters (VSI) [12] [13]. Depending on the type of control system, the UPQC represents a practical solution to protect sensitive loads in the presence of grid disturbances, such as voltage sags, swell, unbalance and etc. Some methods have been published to control of UPQC such as UPQC-P [12], [14], UPQC-Q [14]. UPQC-P can compensate only the magnitude of voltage but it could not compensate the phase jump recovery. This control scheme compensate the voltage sag by minimum injected voltage. UPQC-Q injected a large voltage magnitude and this can increase the rating of UPQC. However, UPQC-Q injected the minimum energy to the grid [14]. Also the conventional Proportional Integral (PI) controllers that use in these control strategy, requires precise linear mathematical model. It is difficult to obtain its model under parameter variations, non-linearity, load disturbance etc. Recently, intelligence controllers such as fuzzy logic controller (FLC), artificial neural network etc, have been applied to achieve suitable performance of the controller [15], [16].

So, this paper presented a new control strategy for SERC and SHUC parts of UPQC with a fast response under any faults. This controller is based on FLC by substitution of PI controllers. Also, phase jump recovery is one of the other advantages of this control scheme.

This paper is organized as follows. Section II introduces the model of power system; Section III describes the control strategy of the UPQC in wind farm interconnected to the grid. Section IV introduces the UPQC based FLC; Section V illustrates simulation results and compares responses of the tested system with conventional controller and FLC during transient condition.

II. THE MODEL OF POWER SYSTEM

The power generated by wind turbine $P_w$ and speed ratio is presented as following equations:

$$P_w = \frac{1}{2} \rho S v^3 C_p(\lambda, \beta)$$

$$\lambda = \frac{\Omega R}{v}$$

Where $\rho$ is air density, $S$ is the swept area, $\Omega$ is the rotor speed, $v$ is the wind speed, and $C_p$ is the power coefficient, $\lambda$ is the speed ratio and $\beta$ is the pitch angle. $C_p$ values are taken from a widely used classical model [13].

Fig. 4 demonstrate the wind farm based 6 set of 250 Kw SCIG that interconnected to the grid via UPQC. Wind farm interconnected to the grid through transformer $T2$ (25/0.66 kV, $Y/\Delta$). Distribution system export 1.5 MW power generated by wind farm into the grid through the two transmission lines with 20 miles length.

A. Wind Farm Stability Under LVRT Conditions

Fig 4. [8], as shown electrical torque-slip and reactive power-slip of SCIG under LVRT on stable conditions. At the point of $A_1$, when $V_1$ decrease to $V_2$, slip increased to $S_2$ until fault clear at $C_1$. After, voltage can recovered by find of the initial equilibrium point at $A_1$. During the fault, generator draw more reactive power by increasing the slip and it maybe cause the voltage of generator could not restore even after the fault is cleared. Fig. 5, shows the instability conditions. For obtaining the constraint and margin of stability of SCIG;

$$T_m - T_e = J \frac{d\omega}{dt}$$

Where; $T_m$ and $T_e$ are mechanical torque and electrical torque respectively. Also, $\omega$ is angular velocity of rotor. Perturbation gives:

$$\Delta T_m - \Delta T_e = J \frac{d(\Delta \omega)}{dt}$$

For small perturbation, the torque-slip curve can be assumed to be straight lines. Thus;
\[ \Delta T_m = \left( \frac{\partial T_m}{\partial \omega} \right) \Delta \omega \quad \text{and} \quad \Delta T_m = \left( \frac{\partial T_m}{\partial \Delta \omega} \right) \Delta \omega \tag{5} \]

Substituting from eq. (5) into eq. (4) gives:

\[ \left( \frac{\partial T_m}{\partial \omega} \right) \frac{\partial T_e}{\partial \omega} \Delta \omega = J \frac{d}{dt} (\Delta \omega) \tag{6} \]

By solving of differential eq. (6), obtained eq. (7):

\[ \Delta \omega = \left[ \left( \frac{1}{\left( \frac{\partial T_m}{\partial \omega} \right)} \right) \left( \frac{\partial T_m}{\partial \Delta \omega} \right) \right] + k \tag{7} \]

Where; \( k \) and \( \Delta \omega \) are constant parameters and obtained from initial conditions.

Hence, the stability equilibrium point should have the below constraint:

\[ \frac{\partial T_m}{\partial \omega} \frac{\partial T_e}{\partial \omega} \quad \text{(8)} \]

As well by considering Fig.4 and Fig.5, the margin point of stability of WECS-SCIG is the pull-out point of electrical torque. If the fault continued insofar as electrical torque reach over the pull-out point, SCIG will be instable and may lead to system collapse and so it must be disconnected from grid.

In other hand; according to to Fig.4, when the grid fault is cleared, PCC voltage will return to equilibrium point \((A_1)\) point. Because the rotor slip not able to change momentarily due to mechanical momentum inertia, a large amount of reactive power is absorbed by SCIG and the slope of electrical torque-speed curve \(\frac{\partial T_e}{\partial \omega} \) will be more than the slope of mechanical torque-speed curve \(\frac{\partial T_m}{\partial \omega} \). It causes the rotor acceleration to reduce. The deceleration of the SCIG and reduction of rotor slip lead to reduction of reactive power absorbed by the SCIG and it causes voltage to increase. Therefore, according to Fig. 4, the reactive power and electrical torque come back to their steady state condition. According to Fig. 5, if the fault is not cleared at suitable time (before to reach the pull-out electrical torque), the rotor slip may increase extensively and the WECS-SCIG will be instable.

Fig. 6 and Fig. 7 shows the magnitude and phase of voltage, respectively (when fault occurs between \( t=3 \) sec. to \( t=3.5 \) sec.) without utilizing UPQC. The magnitude of the voltage has been decreased significantly and the phase of voltage has been changed. Changing in voltage phase may cause to tripping of sensitive loads and equipments and other power electronic based devices such as battery chargers and Uninterruptable Power Supply (UPS).

In these figures, voltage sag at the PCC is 0.8 per-unit (pu) and phase jump \((\Delta \phi)\) is approximately equal to \(-28^\circ\).

Fig. 8 indicates the rotor speed of SCIG without utilizing UPQC. This figure shows, when the fault is cleared at \( t=3.5 \) sec., rotor speed increased extremely. Thus, wind generator should be disconnected from the grid.

Fig. 9. active power \((p)\) and reactive power \((q)\) are shown separately. Increasing the value of reactive power cause the voltage magnitude collapse. On the other side, when
the fault is cleared at t=3.5, the active power where generated by wind farm tending to null.

Thus, considering to Spanish grid code integration requirements, the wind farm performances should be to improve and make better results under low voltage or fault events.

Fig. 9. Active power (p) and reactive power (q) of SCIG without UPQC

III. THE CONTROL STRATEGY OF THE UPQC

The conventional control strategy of UPQC are based on PI controller that has been studied in the literatures [12–14].

Fig. 11 and Fig. 12 show a novel method to control of SERC and SHUC part of the UPQC to overcome any voltage sag without using any Energy Storage Systems (ESS) for DC-link of UPQC. The SHUC part regulates the voltage of DC link and control of the reactive power via control of current. The SERC part, regulates the bus voltage through stored energy in DC link through SHUC part [17].

A. SERC part Control Strategy

Some control strategies investigated in [12-14]. UPQC-P and UPQC-Q are two effective schemes for voltage sag compensation. These methods cannot restore phase jump of voltage and only compensated the magnitude of voltage.

Voltage phase jump is one of the drawback of these schemes. Because, the internal flux of SCIG is out of phase with the voltage. So this can cause a large transient at the beginning and end of the voltage dip [18].

Fig. 10 represent two methods for voltage sag compensation (Fig. 10(a): UPQC-Q) and (Fig. 10(b): UPQC-P).

Fig. 10. Phasor presentation of (a) UPQC-Q, (b) UPQC-P methods

When a fault occur in the grid, the voltage of wind farm (V_{pre-sag}) changed to V_{sag} with a phase angle jump (θ).

![Fig. 11. Series converter control strategy of UPQC](image)

\[ V_{q} = \sqrt{\left(V_{p-\text{sag}} \sin(\theta)\right)^2 + \left(V_{p-\text{sag}} \cos(\theta) - V_{sag}\right)^2} \] (9)

\[ \angle \theta_{ij} = \tan^{-1}\left(\frac{\sin(\theta)}{\cos(\theta)}\right) \] (10)

Phase locked loop (PLL) track the phase of PCC voltage. The PCC voltage is transformed to V_d, V_q and V_o based on Park’s transform [19],[20]. For regulation of PCC voltage, \[ [V_{d}, V_{q}, V_{o}]^{\text{T}}_{\text{inj}} \] extracted from (9) and (10) and added to \[ [V_{d}, V_{q}, V_{o}]^{\text{T}}_{\text{PCC}} \].

B. SHUC part Control Strategy

The Fig. 12 represented the phasor diagram of different current due to phase angle jump (θ) advancement.

In steady state stability,

\[ I_{g} = I_{w} + I_{sh} \] (11)

During voltage sag, eq. (11) changed to eq.(12)

\[ I_{g}^{'} = I_{w}^{'} + I_{sh}^{'} \] (12)

If only inject a series voltage in such a way that it is not at quadrature of source current, it causes a phase angle difference between PCC voltage and wind farms voltage (termed as power angle) without changing the resultant wind farm voltage magnitude. In that case then a certain amount of reactive as well as active power would flow through series inverter.

Briefly, this control strategy for UPQC can be stated as to inject a voltage through series inverter, with proper magnitude and phase angle, such that both the shunt and series inverters will share and support the wind farm reactive power demand, without increase or decrease in the steady-state or transient voltage.
In order to recover the reactive power demand, it is necessary to equalize power at wind farm, bus M (P_M) to the value of pre-sag power.

\[ P_{\text{rec}} = P_M \]

\[ |V_{\text{sag}}| |I'_{\text{sag}}| \cos(\theta) = |V_{\text{pre-sag}}| |I'_{\text{w}}| \cos(180^\circ - (\gamma + \theta)) \]  

Hence;

\[ |I'_{\text{sag}}| = \left( \frac{|V_{\text{pre-sag}}|}{|V_{\text{sag}}|} \right) \cdot |I'_{\text{w}}| \cdot \cos(\gamma + \theta) \]

\[ |I'_{\text{sh}}| = \left( \frac{|V_{\text{pre-sag}}|}{|V_{\text{sag}}|} \right) \cdot |I'_{\text{sag}}||\cos(\gamma + \theta) - \cos(\gamma)| \]

\[ |I'_{\text{sh}}| = |I'_{\text{w}}| \cdot \sin(\gamma) \]

Consequently, by (18) the magnitude of shunt injected current extracted.

\[ |I'_{\text{sh}}| = \left( \frac{|V_{\text{pre-sag}}|}{|V_{\text{sag}}|} \right) \cdot |I'_{\text{w}}| \cdot \sqrt{\left( \cos(\gamma + \theta) - \cos(\gamma) \right)^2 + \left( \sin(\gamma) \right)^2} \]

(18)

IV. UPQC BASED ON FUZZY LOGIC CONTROLLER

Recently, fuzzy logic controllers (FLC) have generated a great deal of interest in various applications and have been applied in the power electronics and FACTS devices. The advantages of fuzzy logic controllers over the classic (PI controller) controller are that they do not require an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the classic controller [15].

The fuzzy controller configuration incorporates attractive features such as simplicity, fast dynamic response, and automation, while using a low cost hardware and software implementation.

Fig. 13 shows the control system of the UPQC based on FLC. By replacement of FLC to PI controllers in both SERC and SHUC parts of UPQC improved the dynamic response of UPQC against LVRT.

In this case, a two-input, one-output fuzzy logic controller was considered. The input signals for the FLC are the DC-link voltage variations in the SHUC controller that obtained from active powers of SERC and SHUC (P_{\text{SERC}}, P_{\text{SHUC}}). Also variations of dq-components of the PCC voltage with the deviations are FLC input signals in the SERC controller.
The control strategy of the UPQC; a) SERC, b) SHUC

It is consists of fuzzification part, fuzzy inference part and constant outputs. The inference part consists of membership functions and rule bases which are obtained from an understanding of the UPQC behavior and using of systematic procedure. They are modified and tuned by simulation performance. A triangular membership function has the advantages of simplicity and easier implementation and is chosen for this application [15].

There are seven linguistic variables for each input and seven linguistic variables for output variable, namely, Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM), and Negative Big (NB) has been shown in Fig. 14. Generally, FLC generates the required variable signal to change amplitude modulation ratio and control the magnitude of the injected voltage based on these rules.

Table 1 shows the utilizing 49 linguistic rules directly processes three phase supply voltages to improve the response time of UPQC.

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V. SIMULATION RESULTS

Fig. 15 to Fig. 18 indicate the comparison of PI-UPQC and FLC-UPQC. These figures show the fast dynamic responsible of fuzzy controller to improve the transient stability of wind farm. Fig. 15 shows the more better dynamic response of FLC-UPQC than PI-UPQC. Rising time of FLC-UPQC is very small and oscillation of speed of rotor at fault time (t=3 to 3.5 sec.) is very low. Fig. 16 and Fig. 17 show the active power (p) and reactive power (q) of SCIG by PI-UPQC and FLC-UPQC, respectively. Fig. 18 indicate the voltage of SCIG by PI-UPQC and FLC-UPQC.

![Fig. 15. Comparison the rotor speed of SCIG without UPQC, PI, Fuzzy](image)

![Fig. 16. Active and reactive power of SCIG with PI-UPQC](image)

![Fig. 17. Active and reactive power of SCIG with FLC-UPQC](image)
REFERENCES


