# Improving LVRT Characteristics in Variable-speed Wind Power Generation by means of Fuzzy Logic

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Abstract-Wind system using a fixed-speed wind power generation SCIG (Squirrel-cage Induction Generator) tends to drain large amount of reactive power from the grid, potentially causing a drop voltage and perhaps voltage stability conundrum. To improve the SCIG's low voltage ride through (LVRT) characteristics, this paper presents a new control strategy for a variable-speed wind power generation DFIG (Doubly-fed Induction Generator) located closely to the SCIG-based wind system by utilizing the control capability of fuzzy logic technique. The proposed control system regulates effectively reactive power output of the DFIG wind turbine by controlling both grid-side and rotor-side converters to compensate the reactive power absorbed by the SCIG-based wind turbine. The effectiveness of the proposed control strategies is proven by simulation results. These illustrates that the LVRT characteristics and stability margin of the SCIG-based wind system is significantly improved when extra reactive power is compensated from the DFIG wind system in the proximity.

# I. INTRODUCTION

As a result of the high increase in the environmental attention, the installed capacity of grid-connected renewable energy sources is concerned up to date that minimized the impact of conventional electricity generation on the environment [1], [2], [3]. Wind plants is the most rapidly growing electricity generation source with a 20% yearly rise rate in the last five years. As wind energy is fed into the power system, the stability of already existing grid is becoming importance, wind farms should not defile the stability of the existing grid, if feasible, offer to enlarged system stability. Therefore, wind plants should behave responsibly. For example, the important point during last several years is the continued grid-connection of wind turbine at definite grid-voltage disturbance levels, to avoid voltage drops and sectional energy deficits when wind energy units are disconnected.

The fixed-speed wind energy conversion system using squirrel-cage induction generator (SCIG) was very popular

machine in the 90s due to its reliability, low cost and robustness construction [4]. However, the key issue with the SCIG is its lack of control ability, indicating that it always requires reactive power from the grid during normal operation and transient state as well. It has poor reactive power capabilities to meet the new grid connection requirements, potentially leading to voltage instability from grid faults [5], [6].

The issue of grid code compliance has been the driving force behind development of variable-speed technologies, especially the doubly-fed induction generator (DFIG)-based wind system which uses a back-to-back converter connected via slip rings to the rotor. The DFIG offers several advantages such as speed control, reduced flicker, and four-quadrant active and reactive power control capabilities when compared with the SCIG. These excellent features are primarily achieved via the control of a rotor side converter, which is typically rated at around 25% of the generator rating for a given rotor speed range of  $0.75 \sim 1.25$  pu under normal operating condition [7].

The DFIG's ability to provide terminal voltage and reactive power control has been well documented in [8]. However, wind farms are usually located remotely from the main grid. The remoteness and high interconnection impedance through which they are connected may restrict their application to the grid. The rapid growth of DFIG technology has led to the case where these turbines can be installed alongside the existing SCIGs to compensate for the SCIG's poor reactive power capability. In [9], the authors discussed the reactive power control of a DFIG wind farm immediately after the grid fault to boost the AC voltage of a nearby SCIG wind farm, but a detailed study on the DFIG controller has not been addressed. In [10], the authors proposed fuzzy controller for pitch angle control to smooth power as well as improve grid connection capability for SCIG during wind speed variation.

This paper aims to investigate a control strategy for a DFIG-based wind turbine located closely to a SCIG-based wind farm in order to improve LVRT performance of the

SCIG wind turbine by utilizing control capability of the DFIG wind system using Fuzzy Logic. The proposed control system regulates effectively reactive power output of the DFIG wind turbine by controlling both the grid and rotor side converters to compensate the reactive power absorbed by the SCIG-based wind turbine.

# II. MODEL OF GRID-CONNECTED WIND FARM WITH DFIG AND SCIG

Fig. 1 illustrates SCIG and DFIG-based wind farms closely coupled to a grid at the same point of common connection (PCC).

### A. DFIG Model

The equivalent circuit of a DFIG can be expressed in different reference frames such as the stationary frame, the rotor frame or the synchronous frame, fixed to either the stator voltage [11] or the stator flux [12].

The stator and rotor flux as well as voltages are given by

$$\Psi_s = L_s I_s + L_m I_r \tag{1}$$

$$\Psi_r = L_r I_r + L_m I_s \tag{2}$$

$$U_s = R_s I_s + \frac{d\Psi_s}{dt} + j\omega\Psi_s \tag{3}$$

$$U_r = R_r I_r + \frac{d\Psi_r}{dt} + j(\omega - \omega_r)\Psi_r$$
(4)

where  $\Psi$ , U and I represents the flux, voltage and current, respectively. The subscript s and r denote the stator and rotor quantities.  $L_s$  and  $L_r$  are the stator and rotor inductances,  $R_s$ and  $R_r$  are the stator and rotor resistances,  $L_m$  is the mutual inductance, and  $\omega_r$  is the rotor angular speed. The stator output active and reactive power and the electromagnetic torque are presented as following equations

$$T_e = \frac{3}{2} p_n \operatorname{Im}(\Psi_s I_s) = -\frac{3}{2} \frac{L_m}{L_s} p_n \operatorname{Im}(\Psi_s I_r)$$
(5)

$$P_s + jQ_s = -\frac{3}{2}U_sI_s = -\frac{3}{2L_s}U_s(\Psi_s - L_mI_r)$$
(6)

where  $p_n$  is the generator pole pairs.

The voltage equations of the back-to-back converter in the arbitrary reference frame can be expressed as

$$U_g = U_s - R_c I_g - j\omega L_c I_g - L_c \frac{dI_g}{dt}$$
(7)

$$C\frac{dU_{dc}}{dt} = \frac{P_g}{U_{dc}} - \frac{P_r}{U_{dc}}$$
(8)

where the subscript g denotes the grid side quantities of the converter.  $U_{dc}$  and C are the DC bus voltage and capacitor, respectively.  $R_c$  and  $L_c$  are the smoothing resistance and inductance.

The active and reactive power input to the GSC and the active power output from the RSC are given as

$$P_r = P_s - P_e = P_s - T_e \Omega_r \tag{9}$$

$$P_g + jQ_g = \frac{3}{2}U_s I_g \tag{10}$$

where  $\Omega_r$  is the rotor mechanical speed.

The total power output of DFIG is given as

$$P_{DFIG} + jQ_{DFIG} = (P_s + jQ_s) + (P_g + jQ_g)$$
 (11)

### B. SCIG Model

The developed DFIG model can also be applied to SCIG by assuming a zero rotor side voltage  $U_r$ . Under steady-state and neglecting the stator resistance, the voltage and current equations in arbitrary reference frame are given as

$$U_r = R_r I_r + j(\omega - \omega_r)(\sigma L_r I_r + \frac{L_m}{L_s} \Psi_s)$$
(12)

$$I_r = \frac{1}{L_m} (\Psi_s - L_s I_s) \tag{13}$$

$$U_s = j\omega\Psi_s \tag{14}$$

where  $\sigma = 1 - \frac{L_m^2}{(L_s L_r)}$  is the generator's leakage factor. Substituting  $U_r = 0$  into (12) yields

$$U_s = \frac{1}{sL_r} R_r \Psi_s - \frac{R_r L_s I_s}{sL_r/L_m} + j\omega\sigma L_s I_s$$
(15)

where  $s = (\omega_r - \omega)/\omega$  is the rotor slip.

Neglecting the rotor resistance, the above voltage equation can be simplified to

$$U_s \approx j \omega \sigma L_s I_s \tag{16}$$

In per unit terms, the amplitude of the stator current can be estimated as

$$I_{spu} = \frac{U_s}{\omega \sigma L_S I_{SN}} = \frac{U_{SN}}{\omega \sigma L_S I_{SN}} \frac{U_s}{U_{SN}} = k_{st} U_{spu}$$
(17)

where  $U_{SN}$  and  $I_{SN}$  are the rated voltage and current of the DFIG, respectively, and  $k_{st}$  is the SCIG's current ratio between zero speed (starting) and rated speed (rated current).

Thus, (17) indicates that a small voltage drop can result in a large current variation for the SCIG.

# III. COORDINATED CONTROL STRATEGY FOR DFIG AND SCIG BASED WIND FARMS

For DFIG output behavior, power converter control is essential both in normal operation and during fault conditions. Power converters usually utilize vector control techniques [13]. Vector control allows decoupled control of active and reactive power. The idea is to use a rotating reference frame based on an AC flux or voltage and then to project currents on this rotating frame. Such projections are usually referred to as the d-q components of their respective currents. With a suitable choice of reference frames the AC currents appear as DC quantities in the steady-state. For a flux-based rotating frame, changes in the q component will lead to active power changes. The effect is the opposite in a voltage-based rotating frame due to 90 degree ahead of the flux-based frame.

Because the rotor side converter (RSC) operates in the stator flux reference frame, the q-axis and d-axis current of the RSC is used to control the active and reactive power, respectively, while the grid side converter (GSC) operates in the stator



Fig. 1. Closely coupled DFIG and SCIG based wind farms with the same PCC

voltage reference frame, the d-axis and q-axis current is used to control the DC link voltage and reactive power, respectively.

Fig. 2 illustrates overall control schemes of the DFIG wind system where both RSC and GSC are controlled by two stage controllers. The first-stage consists of very fast current controllers regulating the RSC and GSC currents to the reference values that are specified by a slower power controller in the second-stage. The reference signals  $P_{s-ref}$ ,  $Q_{s-ref}$ ,  $Q_{g-ref}$  for the second-stage are defined depending on which operational mode the DFIG is working in. The reference signal  $U_{dc-ref}$  is set to a constant value not depending on the wind turbine operation mode, but strictly depends on the size of the converter.

### A. Independent DFIG Control without Considering SCIG

The independent DFIG control without being connected to SCIG nearby has been discussed in a variety of publications [12]. The aim of the RSC control is to control independently the active and reactive power on the grid while that of the GSC is to maintain the DC link voltage at a preset value regardless of the magnitude and direction of the rotor power and to guarantee converter operation with unity power factor (zero reactive power).

The reference signals for the second-stage controllers are defined specifically. The reference  $P_{s-ref}$  for the active power is given by the maximum power point tracking (MPPT) lookup table as a function of the optimal generator speed. The reference  $Q_{s-ref}$  for the reactive power of the RSC is not the same as that in Fig. 3, and can be set to zero. The reference  $Q_{g-ref}$  for the GSC is not the same as that in Fig. 3, either, and usually set to zero.

# B. Coordinated DFIG Control to Improve the Characteristics of SCIG

For closely coupled SCIG and DFIG-based wind farms, increasing reactive power from the DFIG-based wind farm after PCC voltage dip can boost the PCC voltage, and therefore improve the operational characteristics of the nearby SCIGbased wind farm. The reactive power contribution is performed by both converters in a coordinated manner. The third-stage in Fig. 2 describes the proposed controller, namely coordinated control strategy of the DFIG, which is based on the voltage controller using both RSC and GSC for voltage regulation and reactive power support. The reactive power of DFIG can be controlled from the RSC and GSC to maintain the voltage at the PCC constant.

A difference between the PCC voltage reference and the measured PCC voltage goes through the Fuzzy controller and the reactive power references are produced. Then these are sent to the power controllers (second-stage) of DFIG so that the actual reactive powers are adjusted to support the PCC voltage by controlling the currents (first-stage). The reactive power reference value required for voltage regulation can be split between the RSC and GSC in a controlled manner according to a given ratio of the share block. In this research, two-third of  $Q_{ref}$  is supplied by the stator and one-third by the rotor since the machine rating is about three times greater than the one of GSC.

Due to nonlinearity of power system and linearization problems, Fuzzy logic control (FLC) is proposed in the thirdstage (Fig. 2). FLC, proposed by Lotfi Zadeh [14], is one of the most successful applications of fuzzy set theory. The main feature is the use of linguistic variables rather than numerical variables. It provides a principle of translating ambiguous verbal expressions, imprecise and qualitative, common in human communication, in numerical values [15]. The FLC is composed of fuzzification, membership function, rule base, fuzzy inference engine and defuzzification [15]. As shown in Fig. 2, the input control variables to the FLC are the  $U_{pcc}$  voltage error signal  $\epsilon$  and its rate of change. With an incremental (or decremental) of  $U_{pcc}$ , the corresponding incremental (or decremental) of  $Q_{ref}$  is estimated. If  $\epsilon$  is increased with last positive derivative, that indicates that the search of  $Q_{ref}$  is continued in the same direction. Otherwise,

TABLE I FUZZY PITCH ANGLE REGULATOR RULES

$\frac{d\epsilon}{dt}$	Error				
	Ν	Р	SP	MP	BP
N	BN	Ζ	Р	SP	MP
Ζ	N	Р	SP	MP	BP
Р	Z	SP	MP	BP	BP



Fig. 2. Overall control scheme of coordinated DFIG



Fig. 3. Input fuzzy set for PCC voltage error



Fig. 4. Input fuzzy set for derivative



Fig. 5. Output fuzzy set for Reactive power reference



Fig. 6. PCC voltage

# **IV. SIMULATION RESULTS**

negative derivative causes decrease in  $\epsilon$ , the direction of search suitable  $Q_{ref}$  is reversed immediately. All variables are described by fuzzy language as reported in Fig. 3, 4, 5 and the relationship between input and output via heuristics rules is shown in Table. I.

The performance of the proposed control system was evaluated with Matlab/simulink simulation for a wind farm containing a 3 MW SCIG-based wind turbine and a 3 MW DFIG-based wind turbine. The simulated system has the same configuration as the one shown in Fig. 1. Each wind turbine is



Fig. 8. PCC reactive power





Fig. 10. PCC voltage

connected directly to the 22.9 kV lines. The two 22.9 kV lines are connected together at the PCC which is then connected to the grid through two 10 km parallel power lines.

Prior to illustrates the contribution of the coordinated DFIG using fuzzy control system to the characteristics operation of a SCIG wind turbine system in transient-state, the SCIG dynamic behavior is briefly analyzed and discussed [15].

### A. SCIG dynamic behavior

As reported in Fig. 1, the fault event is a three phase to ground fault at the mid point of one of the two parallel lines. The fault occurs at 80s and it is cleared by the breakers after 70ms and 160ms, respectively. This part shows transient-state responses of the only SCIG wind system.

When the fault duration is 70ms, the voltage variation at the PCC is illustrated in Fig. 6. It is evident that the rapid decrease of the PCC voltage leads to a decrease in the electromagnetic torque. The PCC voltage recovery is slow and high oscillation to pre-fault profile after the fault clearance appears. The PCC active power is dependent on the PCC voltage, so the PCC active power falls right after the faults as shown in Fig. 7. The power factor correction capacitor is not able to provide enough reactive power to the SCIG because of the fall of the PCC voltage. Fig. 8 shows the reactive power at the PCC that the generator needs to absorb from the grid. The SCIG wind

turbines is restored to its normal operating condition after a considerable time. The same fault study is repeated for 150ms fault duration. It can be seen from the same figures that the PCC voltage and the active power at PCC are not recovered to the pre-fault values. Thus the SCIG wind turbine has to be disconnected from the grid.

# B. Transient-state operation characteristics of SCIG and coordinated DFIG

Transient-state performance of the proposed controllers for the coordinated SCIG and DFIG wind turbines system is investigated for the same fault condition described before but only for fault duration of 160ms. The simulation results related to the PCC voltage behavior are depicted in Fig. 9. The PCC voltage with the coordinated system has regained its pre-fault value while that of the SCIG alone as well as coordinated with independent DFIG (without fuzzy logic controller) has collapsed as Fig.10. It should be noted that the large amount of reactive power available from the coordinated system boosts the PCC voltage at fault clearance. Fig. 11 represents a comparison of the PCC reactive powers for the two cases. The PCC reactive power with the coordinated system is well recovered to the pre-fault value, but the SCIG alone draws lots of reactive power. The PCC active power is also recovered with the coordinated system in Fig. 12 in a similar way.



Fig. 11. PCC reactive power



Fig. 12. PCC active power

#### V. CONCLUSION

This paper has proposed a control strategy using fuzzy technique for a DFIG-based wind turbine located closely to a SCIG-based wind farm in order to improve LVRT performance of the SCIG wind turbine by utilizing the good control capability of the DFIG wind system. The behavior of DFIG and SCIG wind systems was described using mathematical models. The control reactive power from the stator and GSC of the DFIGbased wind turbine system is investigated for a voltage control purpose. The proposed control system regulates effectively reactive power output of the DFIG wind turbine to compensate the reactive power absorbed by the SCIG-based wind turbine.

The simulation results have shown that when the coordinated control strategy is used, the extra reactive power from the coordinated system enables the SCIG wind system to improve LVRT characteristics in transient-state. After the fault clearance, the coordinated system recovers more quickly and remains stable compared to the SCIG-alone system that is not happen in the independent control ( without fuzzy controller) case. Therefore, this coordinated configuration might be an effectively solution to enhance LVRT capability of the existing SCIG wind farm by taking the advantage of fuzzy logic control flexibility inside DFIG wind turbine systems.

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