ANFIS-PI Controller based Coordinated Control Scheme of Variable Speed PMSG based WECS to Improve LVRT Capability of Wind Farm Comprising Fixed Speed SCIG based WECS

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Abstract

Objective: This paper proposes a novel ANFIS-PI controller based coordinated control scheme of VS-PMSG based WECS, located in close proximity of FS-SCIG based WECS; for improving LVRT capability of FSIG based WF. Methods/Statistical Analysis: Conventional PI controller based coordinated control scheme is simple and gives a good performance. But, with changing parameters of the grid, especially at the time of grid disturbance; the conventional PI controller cannot effectively control the system. To perform this online returning of parameters, a novel ANFIS-PI controller based coordinated control scheme is proposed here; which dynamically changes the controller parameters in accordance with the change in power system impedance during grid disturbance. Findings: MATLAB simulations are performed to check the effectiveness of the proposed ANFIS-PI controller based coordinated control scheme on a typical arrangement of two MW-size WFs connected to an infinite bus. It has been observed that at the time of grid disturbance, the reactive power requirement of the FS-SCIG based WECS is effectively controlled by the ANFIS-PI controller based coordinated control scheme on a typical arrangement of two MW-size WFs connected to an infinite bus. It has been observed that at the time of grid disturbance, the reactive power requirement of the FS-SCIG based WECS is effectively controlled by the ANFIS-PI controller based coordinated control scheme on a typical arrangement of two MW-size WFs connected to an infinite bus. Simulation results exhibit the improvement in LVRT capability of the whole wind farm, comprising VS-PMSG based WECS with FS-SCIG based WECS. Results of the ANFIS-PI controller based coordinated control scheme are compared with the conventional PI controller based coordinated control scheme. Wherein, results with ANFIS-PI controller are proven better than the results with conventional PI controller. The proposed approach for improving LVRT capability of FS-SCIG based WECS seems to be a cost effective, as it need not have any additional installation of FACTS devices. Application/Improvements: The largely installed FS-SCIG based WECS could be made LVRT capable by the proposed method. The prototype model of the proposed simulation work is the future scope of research.

Keywords: Adaptive Neuro-Fuzzy Inference System, Coordinated Control Scheme, Low Voltage Ride Through, Wind Farm.

1. Introduction

Due to the sizeable penetration of the wind power with other intermittent renewable energy, it is very difficult to maintain the power system stability. So new supplementary grid codes (i.e. connection requirements) are announced by various power system operators, which includes the most challenging and important requirement known as Low Voltage Ride-Through (LVRT) capability.
during power system disturbances\textsuperscript{1–4}. According to this LVRT requirement, the plant must stay connected for specified duration of time during grid disturbance. In accordance with the dynamic characteristics of the power system, LVRT requirement of various power system operators is different\textsuperscript{5}. According to the US grid codes declared by the Federal Energy Regulatory Commission (FERC): “If the voltage does not fall below the minimum voltage indicated by the solid line in Figure 1 and returns to 90 percent of the nominal voltage within 3 seconds after the beginning of the voltage drop, the plant must stay online”\textsuperscript{6}.

![Figure 1. Low voltage ride-through standard set by FERC, U.S.\textsuperscript{4}](image-url)

Fixed Speed Squirrel Cage Induction Generator (FS-SCIG) based Wind Energy Conversion System (WECS) have been popular and largely installed in early days due to its well-known advantages, but it does not have any LVRT capability\textsuperscript{7–10}. Various FACTS devices and Energy Storage Systems (ESS) like Static Var Compensator (SVC), STATic synchronous COMpensator (STATCOM), Unified Power Flow Controller (UPFC), Solid State Transfer Switch (SSTS), Dynamic Voltage Restorer (DVR), Superconducting Magnetic Energy Storage (SMES), Energy Capacitor System (ECS), Battery Energy Storage System (BESS), etc. have been proposed by different researchers so as to improve LVRT capability of FS-SCIG based WECS, but it increases the cost due to additional installation of these FACTS devices and ESS\textsuperscript{11–21}.

Variable Speed Permanent Magnet Synchronous Generator (VS-PMSG) based WECS consists of full-capacity back-to-back power electronic converter. These VS-PMSG and VS-DFIG based WECSs have much better LVRT capability compared to FS-SCIG based WECS. Full-capacity converter of VS-PMSG based WECS is better than a reduced-capacity converter of VS-DFIG based WECS in order to have LVRT capability\textsuperscript{12,13}. So, for improving LVRT capability of FS-SCIG based WECS; some of the researchers have proposed the combined installation of VS-PMSG based WECS in close proximity of the FS-SCIG based WECS, so as to take advantage of the control scheme flexibility available in VS-PMSG based WECS\textsuperscript{7–8,14–16}.

Conventional PI controller based coordinated control scheme for the combined installation of VS-PMSG and FS-SCIG in a WF is simple and gives a good performance. However, power system impedance changes dynamically during fault; needs to vary the controller parameters for effective control. This paper proposes Adaptive Neuro-Fuzzy Inference System optimized PI (ANFIS-PI) controller based coordinated control scheme of VS-PMSG based WECS to improve LVRT capability of a wind farm consisting of FS-SCIG based WECS. The ANFIS-PI controller enables online returning of their parameters in accordance with the dynamically changing power system impedance during grid disturbance. MATLAB simulation results show the improvement in LVRT capability by ANFIS-PI controller based scheme compared to conventional PI controller based scheme.

In next section, the system model used for the simulation is presented. After that, wind turbine modeling is discussed. Then, the control scheme of VS-PMSG based WECS and ANFIS-PI controller design are described. Finally, result and conclusion parts are offered.

## 2. System Modeling

Figure 2 shows the system model of a typical wind farm considered in this simulation\textsuperscript{23}. It consists of two wind farms linked at a Point of Common Connection (PCC), which further connected to infinite-bus via a double-circuit transmission line. WF-1 is FS-SCIG based WECS, rated 5 MVA, 50 Hz and connected to PCC through the 5 MVA, 0.48/66 kV transformer and a single-circuit transmission line. Here, the generator is connected to wind turbine through the Gear Box (GB). Also, a capacitor bank is provided with WF-1 for reactive power compensation, whose capacitance value is determined so as to get unity power factor in rated operating conditions. WF-2 is VS-PMSG based
WECS, rated 5 MVA, 20 Hz and connected to PCC through the back-to-back power converter, L-filter and 5 MVA, 0.575/66 kV transformer. In Figure 2, transmission line impedances are shown in the rectangular form. The grid frequency is 50 Hz and 10 MVA is the system base value. Table 1 shows the generator parameters.

Table 1. Generator Parameters.

<table>
<thead>
<tr>
<th></th>
<th>FS-SCIG</th>
<th>VS-PMSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.01 pu</td>
<td>0.01 pu</td>
</tr>
<tr>
<td>$X_1$</td>
<td>0.1 pu</td>
<td>0.06 pu</td>
</tr>
<tr>
<td>$X_m$</td>
<td>3.5 pu</td>
<td>0.9 pu</td>
</tr>
<tr>
<td>$R_{21}$</td>
<td>0.035 pu</td>
<td>0.7 pu</td>
</tr>
<tr>
<td>$R_{22}$</td>
<td>0.014 pu</td>
<td>Field Flux 1.4 pu</td>
</tr>
<tr>
<td>$X_{21}$</td>
<td>0.03 pu</td>
<td>H 3.0 s</td>
</tr>
<tr>
<td>$X_{22}$</td>
<td>0.089 pu</td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>1.5 s</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2. System model.](image)

3. Wind Turbine Modeling

The wind power captured by wind turbine is given by Equation (1):

$$P_w = 0.5 \rho \pi R^2 V_w^3 C_{p} (\lambda, \beta)$$  \hspace{1cm} (1)

Here, $P_w$ is the captured wind power in W, $\rho$ is the air density in Kg/m$^3$, $R$ is the radius of the rotor blade in m, $V_w$ is the wind speed in m/s, and $C_p$ is the power coefficient.

The turbine characteristics defines the value of $C_p$, which is given by Equation (2 and 3):

$$C_p (\lambda, \beta) = c_1 \left( \frac{c_2 - c_3 \beta - c_4}{\lambda} \right) e^{\frac{-c_5}{\lambda}} + c_6 \lambda$$  \hspace{1cm} (2)

and

$$I = \frac{I}{\lambda} - \frac{0.035}{\lambda - 0.08 \beta - \beta^2 + 1}$$  \hspace{1cm} (3)

Here, $c_1$ to $c_6$ are the wind turbine characteristic coefficients: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$.

![Figure 3. $C_p - \lambda$ characteristic of wind turbine at different pitch angles.](image)

![Figure 4. Power characteristic of wind turbine ($\beta = 0^\circ$).](image)

Figure 3 shows the wind turbine $C_p - \lambda$ characteristic at different pitch angles ($\beta$). It shows that for $\beta = 0^\circ$; at $\lambda = 8.1$, it gives the optimal $C_p (C_{p, opt} = 0.48)$. Hence, $\lambda = 8.1$ is taken as a
corresponding optimal value ($\lambda_{opt}$). Figure 4 shows the wind turbine power characteristic for $\beta = 0^\circ$, at different wind speeds ($V_w$). At $V_w = 12$ m/sec the maximum turbine power output (1 pu) is achieved with the rotational speed of 1 pu.

To obtain Maximum Power Point Tracking (MPPT), it is preferred to measure turbine rotor speed ($\omega$) instead of wind speed ($V_w$). And with this measured turbine rotor speed ($\omega$), maximum power ($P_{mppt}$) is obtained by Equation (4).

$$P_{mppt} = 0.5\rho R^2 \left( \frac{\omega \lambda}{\lambda_{opt}} \right)^3 C_{P_{opt}}$$ (4)  

4. Control Scheme of VS-PMSG Based WECS

The block diagram of the control scheme is shown in Figure 5 for VS-PMSG based WECS. Here, PMSG is directly coupled with a wind turbine, so it avoids problems accompanying gear drive. The output of PMSG is given to the back-to-back converter; comprising Stator Side Converter (SSC), DC-link and Grid Side Converter (GSC). These SSC and GSC are voltage source converters, which are based on 2-levels of IGBT and connected through a DC-link circuit. The DC-link circuit is comprising a capacitor ($C_{dc}$) and chopper in series with resistance. SSC and GSC are controlled by their respective controllers. The output of back-to-back converter is given to PCC via inductive-filter and transformer.

**Figure 5.** Block diagram of control scheme for VS-PMSG based WECS.

The function of SSC is to convert 3-phase AC-voltage of PMSG into DC-voltage in accordance with the stator-side controller. The inputs for the stator-side controller are turbine rotor speed ($\omega$) and 3-phase currents and voltages at PMSG stator terminal. The output of stator side controller is the voltage references, which is given to SSC through the Pulse Wave Modulation (PWM).

**Figure 6.** Stator side controller scheme.

Figure 6 shows the stator-side controller scheme. It mainly controls active and reactive power outputs ($P_s, Q_s$) of PMSG. Here, the d-q rotating reference frame is used to design current control loop. The rotor angle position ($\theta$) is found from turbine rotor speed ($\omega$) for conversion amongst abc and dq variables. Here, d-axis current ($I_{sd}$) controls active power ($P_s$) and q-axis current ($I_{sq}$) controls reactive power ($Q_s$) of PMSG. To have u.p.f. operation, the reference value of reactive power ($Q_s^*$) is fixed to zero. The reference value of active power ($P_{ref}$) is obtained by means of MPPT method as illustrated in Figure 4, which is kept within rated power of PMSG. So as to improve control scheme tracking ability; cross-couplings ($I_{sd}\omega, I_{sq}\omega, \omega\psi_m$) are compensated in the current controller of Figure 6. Lastly, d-q voltage reference ($V_{sd}^*$ and $V_{sq}^*$) of current controller is obtained; which is converted into a-b-c 3-phase reference voltage ($V_{a}^*, V_{b}^*, V_{c}^*$). This 3-phase voltage references ($V_{a}^*, V_{b}^*, V_{c}^*$) controls the stator currents through modulation.

The function of GSC is to convert DC-link voltage into 3-phase AC-voltage of the grid frequency. The voltage across DC-link capacitor ($V_{dc}$), grid-current and grid-voltage are inputs for the grid-side controller. The output of GSC is voltage reference for modulation and a trigger command. This trigger command activates the chopper at the time of power unbalance amongst GSC and SSC during a fault condition, for the protection of DC-link circuit.

**Figure 7.** Grid side controller scheme.
Figure 7 shows the grid-side controller scheme. Here, the d-q rotating reference frame is employed in synchronism of grid-side voltage at PCC. The grid-side phase angle ($\theta_g$) is extracted by means of Phase Locked Loop (PLL) block available in MATLAB Simulink. Park transformation is used to transform the 3-phase grid voltage ($V_{ga}, V_{gb}, V_{gc}$) and current ($I_{ga}, I_{gb}, I_{gc}$) into d-q rotating reference frame voltage ($V_{gd}, V_{gq}$) and current ($I_{gd}, I_{gq}$) respectively. Here, $V_{gq}$ is set to zero and $V_{gd}$ is kept constant; so that, d-axis current ($I_{gd}$) controls active power ($P_g$) and q-axis current ($I_{gq}$) controls reactive power ($Q_g$) supplied to the grid separately. For injecting the active-power produced by PMSG into the grid, DC-link capacitor voltage ($V_{dc}$) is upheld to a constant value. Here, DC-voltage controller (PI-5) generates reference signal of d-axis grid-current ($I_{gd}^*$) and the grid terminal voltage ($V_g$) is set to 1 pu in order to get the q-axis grid-current reference signal ($I_{gq}^*$). At the output of current controller; the cross couplings $I_{gd}\omega_g L_g$ and $I_{gq}\omega_g L_g$ are compensated, so as to improve tracking ability of control scheme. The dq-axis grid-voltage references ($V_{gd}^*$ and $V_{gq}^*$) are converted into 3-phase grid-voltage references ($V_{ga}^*, V_{gb}^*, V_{gc}^*$) by dq to abc transformation. These $V_{ga}^*, V_{gb}^*$ and $V_{gc}^*$ are the reference signals for modulation. Here, THIPWM method of modulation is used, which maximize the fundamental component of output voltage without over-modulation. For the better control of the dq-axis current loop scheme, ANFIS-PI controller is anticipated in this work. In Section 5, the control strategy of ANFIS-PI controller is described. Fault detector gets activated as a result of grid voltage less than 0.9 pu, which gives a trigger command to activate DC-link protection. Simultaneously, on activation of fault detector; it also resets PI-5 to stop injecting active power into the grid, so as to maximize reactive power support.

5. ANFIS-PI Controller Design

Figure 8 shows the ANFIS-PI controller scheme for the d-axis current. ANFIS controller alters PI parameters ($K_p$, $K_i$) in accordance with the change in power system operating condition at the time of disturbance. ANFIS is the fusion of neural network with fuzzy inference system. Fuzzy logic is a branch of artificial intelligence, characterized by fuzzification, defuzzification and rule base. Fuzzy logic deals with linguistic variables and neural network. Requires input and output database for training. Generally, for linear database back propagation network is used and for nonlinear database multilayer feed forward neural network is preferred. In this simulation, we have used multilayer feedforward neural network with hybrid training algorithm and number of epochs as 100.

ANFIS model structure of the single input and the single output is shown in Figure 9. The variables for input Membership Function (MF) are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) as fuzzy subsets. Here, error ($e$) / change of error ($de$) is the input and output is the desired control signal.

![ANFIS model structure](image)

Figure 9. ANFIS model structure.

Figure 10 shows the input ($e/de$) membership function. Here, three triangular Membership Functions (MFs) as low, medium and high are considered. After selection of a proper MF for input, the rule base is created and IF...THEN logic is used to create rule base as shown in Table 2.
Table 2. IF...THEN Logic for Rule Base.

<table>
<thead>
<tr>
<th>IF input is</th>
<th>THEN output is</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>MF-1</td>
</tr>
<tr>
<td>NS</td>
<td>MF-2</td>
</tr>
<tr>
<td>Z</td>
<td>MF-3</td>
</tr>
<tr>
<td>PS</td>
<td>MF-4</td>
</tr>
<tr>
<td>PB</td>
<td>MF-5</td>
</tr>
</tbody>
</table>

Inference is applied to continue with centroid method of defuzzification. After defuzzification, the crisp value is obtained as output. In neural network, weight is updated as per the data rule and training continues till the error becomes zero. Selection of the proper MF will result into the zero error in less number of iterations.

6. Simulation Results

As shown in Figure 2, MATLAB simulation of the proposed model system is performed by considering a symmetrical 3-line to ground fault (3LG) on a transmission line. The simulation criteria for the proposed model system are given in Table 3. Simulation results give the comparison between a conventional PI controller scheme and the proposed ANFIS-PI controller scheme of GSC. Figures 11, 12, 13, 14 and 15 show the MATLAB simulation results.

Table 3. Simulation Criteria.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Criteria</th>
<th>Set Value of Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fault occurs at:</td>
<td>0.1 sec.</td>
</tr>
<tr>
<td>2</td>
<td>Circuit Breakers (CBs) of the faulted line opens at:</td>
<td>0.2 sec.</td>
</tr>
<tr>
<td>3</td>
<td>CBs of the faulted line recloses at:</td>
<td>1.0 sec.</td>
</tr>
<tr>
<td>4</td>
<td>Total time of simulation:</td>
<td>5.0 sec.</td>
</tr>
<tr>
<td>5</td>
<td>Wind speed of both the wind generators:</td>
<td>12 m/sec.</td>
</tr>
</tbody>
</table>
Figure 11 and 12 show the active power output of WF-1 and WF-2 respectively. Here, the active power output of both the wind farms quickly settles to their rated value on reclosing of the CBs. Figure 13 and 14 show the reactive power output of WF-1 and WF-2 respectively. Here, the reactive power requirement of WF-1 is supplied by the WF-2 during the fault. This results in the quick return of the PCC terminal voltage at the rated value, which can be observed in Figure 15. Finally; from Figures 11 to 15, it can be seen that the stability performance of the whole wind farm is enhanced in case of the proposed ANFIS-PI controller scheme compared to the conventional PI controller scheme of VS-PMSG based WECS.

7. Conclusion

The combined installation of VS-PMSG based WECS in close proximity of a FS-SCIG based WECS for improving LVRT capability of the FS-SCIG based WECS in addition to that of its own; seems to be a cost-effective method, as it need not have any additional installation of FACTS devices. Slight modifications in the GSC control scheme of VS-PMSG based WECS results into a coordinated control scheme. MATLAB simulation results of the conventional PI controller based coordinated control scheme are compared with that of the proposed ANFIS-PI controller based coordinated control scheme. The ANFIS-PI controller combines the ANFIS logic to the conventional PI controller, so as to have online fine-tuned of the PI gain parameters in accordance with the variations in system parameters during the fault. From the analysis of simulation results, it has been perceived that; ANFIS-PI controller scheme gives better outcomes compared to the conventional PI controller scheme to improve LVRT capability of the whole wind farm during the fault. Analysis of the prototype hardware model of the proposed simulation work is the future scope of research.

8. References

ANFIS-PI Controller based Coordinated Control Scheme of Variable Speed PMSG based WECS to Improve LVRT Capability of Wind Farm Comprising Fixed Speed SCIG based WECS


