An Adaptive Neural Network Based Energy Storage Control for Operation Enhancement of a Multi-Generator AC and Wind Power System

A.H.M.A. Rahim, S.A. Al-Baiyat

Department of Electrical Engineering King Fahd University of Petroleum & Minerals Dhahran, Saudi Arabia

Abstract: Increased wind penetration to conventional power systems sometimes bring operational problems which have to be properly addressed. Wound-rotor type induction generators are known to aid the damping of conventional power systems but suffer from the drawback that they are sensitive to low grid voltages and also to sudden and large changes in the system. Installation of additional energy storage (ES) device is gaining acceptance as tools for performance improvement of wind systems. Online adaptive neural network (NN) control a capacitor ES device for a multi-generator power system with mixed AC and doubly fed induction generator (DFIG) has been investigated in this work. The NN controller employing radial basis function computes the network weights in time domain, contrary to classical methods which use offline training of input output data for generation of the weights. Tests carried out on the asynchronous-synchronous system demonstrate that the proposed adaptive NN controller can restore satisfactory operation following grid faults and other severe disturbance conditions. The adaptive radial basis function NN control also helps to stabilize the AC system oscillations following the disturbance. The proposed controller algorithm is simple and hence will be easy to implement.

Key words: Adaptive neural network control, Wind generators, Multi-generator power system, Energy storage device, Radial basis function network

INTRODUCTION

With increased number of wind generators getting connected to power systems, it is likely that its impact on operation of the systems will be significant. This will be particularly so when large amount of power is transmitted over weaker lines (Koch et al., 2003). Compared to other variable speed systems, the advantages of the DFIG is its economic viability in terms of converter power handling, reduced losses, real and reactive power control capabilities, etc. (Lin et al., 2011a; Mohseni and Islam, 2012). Additionally, they can contribute to improve the damping of the electromechanical oscillations emanating from the synchronous machines in the system (Mendonca et al., 2007). Since the DFIG stator windings connect to the grid directly it makes the machine vulnerable to grid disturbances and low voltage conditions on the grid (Odeku et al., 2012). Controlled power electronic converters in the rotor circuit makes the DFIG behave like an inverter, inertia of which has virtually no coupling with the rest of the generator system. Hence with increased wind penetration the effective system inertia is decreased and it can affect reliability of the system significantly when subjected to severe disturbances (Gautam et al., 2009; Campos-Ganoa et al., 2013).

Under grid faults or severe low voltage conditions, the generator power cannot get past the faulted point. This causes over current in both stator and rotor circuits and also over-voltage in the DC link capacitor (Elsheikh et al., 2013; Yang et al., 2012). The machine behaves like a classical induction machine receiving reactive power from the depressed grid (Pannell et al., 2010). Various controls for grid fault ride through have been suggested. These include improvements with a circuit comprising of rectifier and IGBT on the rotor side with an inductor in parallel with it, current controlled voltage source inverter, voltage restorer connected between the generator and the grid (Vinodkumar and Selvan, 2011; Muyeen et al., 2011; Hu et al. 2011). A superconducting fault current limiter and series anti-parallel thyristors at the stator terminals have been shown to be useful (Elsheikh et al., 2013; Park et al. 2010). More advanced methods of control of both grid side and rotor side converters to reduce current inrush are available in the literature (Gautam et al., 2009; Rahimi and Pariani, 2010).

Energy storage (ES) devices used for LVRT are static var compensators (Amaris and Alonso, 2011), battery energy storage (Mendis et al., 2012; Ganti et al., 2012), supercapacitor (Qu and Qiao, 2011), SMES (Yunus et al., 2012), etc. Some of these which have the capability of supplying reactive as well as real power have the added advantage of providing damping to the system while providing voltage support. Effectiveness of these devices for leveling wind power fluctuations as well as low voltage ride-through has been demonstrated. The controls in most of these applications are generally derived through linear models or through heuristic methods. Considering the erratic nature of wind speed the use of intelligent control strategies have been recommended in
the literature (Lu et al., 2007). Neural network (NN) based control design provide an excellent platform because it can tackle the wind speed randomness as well as model nonlinearity. Application of NN to wind system study has, generally, been insignificant. Betzel (Batzel and Lee et al., 2000) used neural network control for rotor angle estimation in PMSG systems. A combination of sliding mode and radial basis function networks was employed for pitch control in (Lin et al., 2011b). Classical neural network control employs control determination from fixed weights obtained by training pre-specified input-output data. An adaptive NN control which can be realized online and adapted in time domain would be the most desirable feature.

Control of a power system with synchronous and asynchronous doubly fed generator through online NN control of capacitor ES is considered in this work. Update of the radial basis function neural network (RBFNN) weights is carried out adaptively in time domain. Section 2 gives the asynchronous DFIG and synchronous machine models and their integration procedure. The energy storage controller model is given in section 3. Section 4 develops the RBFNN controller. The neural network controller presented is tested in section 5 with conclusions drawn in section 6.

System Representation:

The multimachine AC power system considered in Fig. 2 consists of synchronous generators, transformers, load and its own transmission network. The wind generation is represented through an equivalent DFIG with two controlled converters in the rotor circuit. A capacitor energy storage device capable of responding to momentary emergency conditions is connected at the generator terminals. The model of the asynchronous and synchronous generators and the procedure of their dynamic integration are outlined below.

![Fig. 1: The multimachine power system with wind generation](image)

### 2.1 Asynchronous and Synchronous Generator Models:

For integrating the dynamics of the asynchronous wind generator with those of the synchronous machines in the multimachine system, their voltage current equations are expressed in the same form. Neglecting the stator transients of the induction generator, the voltage current flux relationships are written in terms of two differential equations,

\[
\begin{align*}
\dot{e}_d' &= -\frac{1}{T_s} [e_d' - (x_s - x_m)\psi_{qf}] + x_m e_q' + \frac{x_m}{x_r + x_m} \omega \psi_{e} \\
\dot{e}_q' &= -\frac{1}{T_s} [e_q' + (x_s - x_m)\psi_{df}] - x_m e_d' + \frac{x_m}{x_r + x_m} \omega \psi_{ed}
\end{align*}
\]

Here, \( e_d' = -\frac{x_m}{x_r + x_m} \psi_{qf}, \quad e_q' = \frac{x_m}{x_r + x_m} \psi_{df}, \quad x_1 = x_s - \frac{x_m^2}{x_r} \)

The voltage current relationships of the stator circuit are,

\[
\begin{align*}
V_{gd} &= -r_d i_{dh} + x_d i_{dq} + e_d' \\
V_{gs} &= -r_s i_{sh} + x_s i_{sd} + e_q'
\end{align*}
\]
The synchronous generator voltage current relations in the rotor and stator circuit, expressed through the standard 2-axes theory, are (Anderson and Fouad, 2003),

\[
\begin{align*}
\dot{e}_q &= \frac{1}{T_{do}} \left[ E_{do} - e_q' - (x''_d - x''_q) i_{gy} \right] \\
\dot{e}_d &= \frac{1}{T_{dq}} \left[ -e_d' + (x'_q - x'_d) i_{gy} \right] \\
V_{gd} &= -r_d i_{gd} + x'_d i_{gy} + e_d' \\
V_{gy} &= -r_d i_{gy} - x'_d i_{gd} + \dot{e}_q
\end{align*}
\]  

(3)

The additional dynamical equations of the synchronous generators are the swing equation and exciter voltage equation which are written as,

\[
\begin{align*}
\frac{1}{2H} \frac{d^2}{dt^2} \delta &= \frac{1}{2H} \left[ P_m - P_e - P_D \right] \\
\dot{E}_{sd} &= \frac{1}{T_s} \left[ K_s (V_{ref} - V_r) - E_{sd} \right]
\end{align*}
\]  

(5)

(6)

The mechanical power input \( P_m \) comes from the wind turbine and is given as,

\[ P_m = K_W C_p V_c^3 \]  

(7)

where, \( K_w \) is a constant depending on the dimensions of turbine, density of air, etc; power coefficient \( C_p \) depends on the ratio between turbine speed and wind velocity \( V_w \). The electrical power output is written as,

\[ P_e = x_m i_q i_{ds} = x_m i_d i_{qs} \]  

(8)

The turbine-generator rotor dynamics is expressed in terms of the following equations,

\[
\begin{align*}
2H_t \frac{d}{dt} \frac{d}{dt} \alpha_t &= P_m - K_{sh} \theta_{sh} - D_t \Delta \theta_t \\
2H_g \frac{d}{dt} \frac{d}{dt} \theta_r &= K_{sh} \theta_{sh} - P_e - D_g \Delta \theta_r \\
\frac{d}{dt} \theta_r &= \omega_0 (\alpha_t - \omega_r)
\end{align*}
\]  

(9)

(10)

(11)

The voltage and current \( (E_c, I_c) \) of the stator side converter VSC-G relates to the generator stator voltage \( V_s \) in per unit system as (Rahim and Habiballah, 2011),

\[ V_c = E_c + I_c R_c + \frac{1}{\omega_0} \frac{d \psi_c}{dt} \]  

(12)

Relationship (12) is broken up into two first order equation along d and q axes. Considering the DC coupling capacitor to be lossless, the capacitor voltage in the converter is derived by equating the power on the two sides of the capacitor and is written as,

\[ CV_c \frac{dV_c}{dt} = P_{gc} + P_{rc} \]  

(13)

2.2 Integration of Asynchronous and Synchronous System Models

In AC power system modeling the dynamics of each synchronous machine is expressed in terms of its own synchronously rotating d-q frames which relate to network frame (D-Q) variables through (24),

\[ [F]_{DQ} = [T][F]_{dq} \]  

(14)

The transformation matrix \( T \) is,
\[ T = \text{diag}[e^{j(\delta - \pi/2)}] = \text{diag}[\text{rot}(\delta_1), \text{rot}(\delta_2), \ldots, \text{rot}(\delta_G)] \]

\[ \text{rot}(\delta) = \begin{bmatrix} \sin \delta & \cos \delta \\ -\cos \delta & \sin \delta \end{bmatrix} \]  

A choice of induction generator angle given by the relationship fits the above transformation, 
\[ \delta_{ig} = \pi/2 + \theta_{ig} \]

If the transient variation in terminal voltage phase angle (\( \theta_{ig} \)) is ignored, \( \delta_{ig} \) remains constant. The voltage and current of the network relates to the reduced network admittance matrix \( Y_{\text{red}} \) as,
\[ I_{dq} = T^{-1} Y_{\text{red}} V_{dq} \]

\( Y_{\text{red}} \) includes all the loads represented by constant impedances. The stator voltage–current equations for the asynchronous and synchronous generators (2) and (4) are written in the general form,
\[ V_{dq} = [Z_g V_{dq} + E_{dq}] \]

Substituting (17) into (18), the non-state generator currents in terms of machine internal voltages are,
\[ I_{dq} = [I - Y_{m} Z_g]^{-1} Y_{m} E_{dq} \]

Expression (19) is substituted in (1) and (3) to get a closed form state representation for the integrated power system.

The Energy Storage Controller:

The energy storage device considered in this study consists of an energy capacitor connected to the DFIG terminal through a buck-boost (BB) converter and a VSC. Control of BB converter voltage allows power to flow in both directions. The VSC voltage magnitude controls the reactive flow to the grid. The circuit arrangement of the ES device is given in Fig. 2.

![Fig. 2: The energy storage control system](image)

For VSC voltage \( V_{sv} = m_{sv} V_{dc} \angle \psi_{sv} + \theta_{sv} \) and the generator terminal \( V_{g} = V_{g} \angle \theta_{g} \), control of voltage magnitude \( m_{sv} V_{dc} \) and phase angle \( \psi_{sv} \) can control reactive and real power. Real power exchange between the ES capacitor and the grid is executed by the BB converter voltage. The normalized voltage–current relationship at the VSC output terminal in terms of direct and quadrature axes components are, 
\[ \frac{di_{svd}}{dt} = \frac{a_0}{L_{svd}} [-R_{sv} i_{svd} + \omega L_{sv} i_{svq} + m_{sv} V_{dc} \cos(\psi_{sv} + \theta_{sv}) - V_{svd}] \]  

\[ \frac{di_{svq}}{dt} = \frac{a_0}{L_{svq}} [-\omega L_{sv} i_{svd} + R_{sv} i_{svq} + m_{sv} V_{dc} \sin(\psi_{sv} + \theta_{sv}) - V_{svq}] \]  

As in (13), the DC capacitor voltage in the ES device can be expanded in the form 
\[ \frac{dV_{dc}}{dt} = \frac{-m_{sv} [i_{svd} \cos(\psi_{sv} + \theta_{sv}) + i_{svq} \sin(\psi_{sv} + \theta_{sv})] + I_{ces}}{C_{dc}} \]  

The current supplied by the storage capacitor \( I_{es} \) relates to its voltage \( V_{es} \) though,
Combing equations (1, 3, 5, 6, 9, 10, 11, 12, 13, 20, 21, 22, 23) the state model for the multi-generator power system and ES controller is,
\[ \dot{x} = f(x, u) \]
\[ y = g(x, u) \]  
(24)

The input \( u \) to the system are \([m_v \, \psi_s]\) and \( y \) is the selected output vector.

**Adaptive Rbfnn Control Strategy:**

In classical NN applications, the network weights are calculated offline through training of a large number of input-output data (Kamalasadan and Gandakly, 2007). In adaptive online training, the weights are generated in time domain, the initial weights normally being selected at random. However, for unstable systems or systems prone to be driven to unstable regime care should be taken to initialize the control. Wind generation systems with randomly varying wind speeds fall into this classification. A possible approach for such systems is to start with initial weights from classical method of training (Suresh, 2007), or to include a stabilizing control initially which will be taken over by the neural network as the training progresses (Hagan et al., 2002). This article proposes an adaptive radial basis function network controller on the basis of latter concept.

![Fig. 3: The adaptive neural network controller structure](image)

The adaptive control strategy generates input \( u=(u_1 \, u_2 \ldots u_m) \) to the composite wind power system model, shown in Fig. 3, from a comparison of its output \( y \) with the reference or target value \( r \). There are two components to each input, the neural network output \( (u_{nn}) \) and the stabilizing circuit output \( (u_s) \). From the expanded view of the RBF neural network shown in Fig. 4, the neural output \( z \) is the sum of the signals from all the hidden nodes and is written as,
\[ Z(t_k) = W(t_k)^T \Phi(t_k) \]  
(25)

where, \( W(t_k) \) and \( \Phi(t_k) \) are the weights and basis functions at time sample \( t_k \).

\[ \Phi(t_k) = [\phi_1(t_k) \, \phi_2(t_k) \ldots \ldots \phi_p(t_k)]^T \]  
(26)

Usually, function \( (k) \) is chosen to be a Gaussian written as,
\[ \phi_i(t_k) = \exp(-\|r(t_k) - \beta_i\|^2 / \gamma_i^2) \]  
(27)

where, \( \beta_i \) and \( \gamma_i \) are the center and spread of the \( i^{th} \) unit, respectively. Considering the saturated output of the neural network to be a tangent sigmoid function having symmetric peak value of \( \rho \) and slope \( \delta \), the \( i^{th} \) input to the plant can be expressed as,
$$u_i(t_k) = \rho \frac{e^{\delta z_i(t_k)} - 1}{e^{\delta z_i(t_k)} + 1} = \rho \frac{e^{\delta w_i^T \phi(t_k)} - 1}{e^{\delta w_i^T \phi(t_k)} + 1} \quad (28)$$

**Fig. 4:** Structure of radial basis function NN

The weights of the RBF network is based by minimizing the mean-squared-error (MSE) written as,

$$E = e^T (t_k) e(t_k); \quad e(k) = r(t_k) - y(t_k) \quad (29)$$

Using the gradient descent technique, the update weight for the $i^{th}$ node is,

$$w_i(t_k + 1) = w_i(t_k) - \eta \frac{\partial E}{\partial w_i} \quad (30)$$

The slope of the the error function is,

$$\frac{\partial E}{\partial w_i} = -2e^T (t_k) \frac{\partial e(t_k)}{\partial w_i} = -2e^T (t_k) \frac{\partial y(t_k)}{\partial w_i} \quad (31)$$

Discretizing plant equations (24) at each time sample $t_k$ and linearizing we get,

$$x(t_k + 1) = A(t_k)x(t_k) + B(t_k)u(t_k) \quad (32)$$

Substituting (32) in (31),

$$\frac{\partial E}{\partial w_i} = -2e^T (t_k) \frac{\partial [C(t_k)x(t_k) + D(t_k)u(t_k)]}{\partial w_i}$$

$$= -2e^T (t_k) \frac{\partial [C(t_k)A(t_k)x(t_k - 1) + B(t_k)u(t_k - 1) + D(t_k)u(t_k)]}{\partial w_i} \quad (33)$$

By chain rule, the expression for gradient considering the dependence of $x(k)$ on previous $m$ samples of control is,

$$\frac{\partial E}{\partial w_i} = -2e^T (t_k) \frac{\partial [CA^m x(t_k - m) + \sum_{s=1}^{m} [CA^{s-1} Bu(t_k - s)] + Du(t_k)]}{\partial w_i} \quad (34)$$

From (28),

$$\frac{\partial u_i(t_k)}{\partial w_i} = \rho \frac{2\delta \phi(t_k) e^{\delta w_i^T \phi(t_k)}}{[e^{\delta w_i^T \phi(t_k)} + 1]^2} \quad (35)$$

Generally, inclusion of terms for $m \geq 2$ does not give significant improvement on controller performance (Al-Duwaish and Rizvi, 2011). Substitution of (35) in (34) gives the weight update relationship at every time sample $(t_k + 1)$ as,
\[
\begin{align*}
  w_i(t_k+1) &= w_i(t_k) + 2\eta e_{i}^T(t_k)\{CAB \frac{2\delta\phi(t_k-2)e^{\delta\phi(t_k-2)}}{[e^{\delta\phi(t_k-2)} + 1]^2} \\
  &+ CB \frac{2\delta\phi(t_k-1)e^{\delta\phi(t_k-1)}}{[e^{\delta\phi(t_k-1)} + 1]^2} + D \frac{2\delta\phi(t_k)e^{\delta\phi(t_k)}}{[e^{\delta\phi(t_k)} + 1]^2}\}
\end{align*}
\] (36)

Testing The Adaptive Controller:
The 10-bus, 4-machine, wind power system of Fig.1 consists of three AC generators connected at bus 1, 2 and 3. The equivalent doubly fed induction generator connected at bus 4 supplies 0.8 pu power. The terminal voltage of the DFIG is 1.02 at steady slip of -5%. The proposed adaptive radial basis function energy storage control was tested with two different types of large disturbances—input torque pulse to the shaft simulating wind gusts and grid faults.

Fig. 5: Speed variation of DFIG with the adaptive energy storage control for a torque pulse of 0.3 pu for 0.5s. The steady reference value is shown by the dotted line.

Fig. 6: Sum-squared-error E corresponding to disturbance of Fig.5. The outputs tracked are the terminal voltage and generator speed.
Figs. 5-9 show the responses of the multimachine power system with the energy storage control for a 40% torque pulse for 1s. Fig. 5 gives the induction generator speed with the proposed online NN control and compares it with the reference value and also the response without any control. Since the generator is on heavy load, a sudden large gust drives the system unstable in the zero damping case. The proposed controller, however, lets the generator ride through this gust and normal condition is restored in less than 3s. Comparison with the reference value shows that the overshoot is very small and the control provides extremely good damping to the system. The two output signals tracked in the adaptive control design are the DFIG terminal voltage and its speed. Fig. 6 shows the maximum value of SSE is less than 0.005.

Fig. 7: Comparison of power angle of synchronous generator at bus #3 for the torque pulse disturbance on the DFIG

Fig. 8: Voltage variation at generator #2 terminal for the input torque pulse on the induction generator
The energy storage control located at the induction generator terminal not only helps efficient transfer of energy to the grid by improving the damping profile, it also enhances the transient stability behavior of the synchronous system. From the power angle plot of synchronous machine #3 (Fig.7), it can be observed that the wind gust on the doubly fed generator creates large electromechanical oscillations in the synchronous system. Also, the sudden variations in wind system can inject harmonics into the AC system causing distortions and collapses in voltages as shown in Fig. 8. The proposed adaptive control tracks the doubly fed wind generator outputs to pre-disturbance condition helping restore the AC system variables to their normal operating levels. The improvement in recovery of DFIG voltage and in the damping profile is achieved by the reactive and real power supplied by the storage system (Fig.9).

The effectiveness of the adaptive NN control was tested by applying three phase faults in the vicinity of DFIG terminals. For a 500ms fault on bus #10, Figs. 10-13 show the transient responses of the asynchronous-synchronous system. Fig. 10 shows the grid fault causes breakdown of the generator terminal voltage making the machine slip away very fast (Fig.11). The grid fault and resulting collapse in the DFIG voltage upsets the power balance in the synchronous system. Fig. 12 shows that under the low voltage condition, the synchronous generator experiences large swings and even tries to enter the motoring region. With the proposed adaptive control of the storage system, the generator terminal voltage quickly recovers to the pre-fault level in a few seconds. The machine speed stabilizes and so does the synchronous generator oscillations. Fig.13 shows that recovery of the system to normal operation is achieved with reasonably small control effort.
Fig. 11: Induction generator slip variation for a 500ms fault on bus #10

Fig. 12: Rotor angle variation of generator #2 for 500ms grid fault

Fig. 13: Variation of the controls ($m$ and $\varphi$) for the 500ms grid fault
Conclusions:
An efficient adaptive energy storage control strategy for improving the performance of a multimachine system comprising of synchronous and asynchronous wind generator is presented. The controller design employs radial basis function neural network, weights of which are adapted in time domain so as to track the desired system output. Tests conducted show that with the proposed adaptive controller the doubly fed wind generator can easily ride through severe grid faults. The performance improvement is achieved by injection of both reactive and real power during the transient period. The injection of reactive power helps restore the system voltage quickly while the real power provides added damping. The proposed controller not only provides voltage support to the wind generator, it improves the stability of the synchronous machines as well. The adaptive strategy is computationally efficient since it does not require offline training as in conventional neural control. The controller algorithm presented is simple and is easy to implement.

ACKNOWLEDGEMENT

This study is part of KFUPM sponsored power systems research group project RG 1002. The support of the University is acknowledged.

List Of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>dq</td>
<td>Direct and quadrature axes</td>
</tr>
<tr>
<td>V_g</td>
<td>d-q values of induction generator voltage (V_g)</td>
</tr>
<tr>
<td>V_r</td>
<td>d-q values of IG rotor voltage (V_r)</td>
</tr>
<tr>
<td>r_s</td>
<td>IG stator resistance, reactance</td>
</tr>
<tr>
<td>x_s</td>
<td>IG rotor, mutual reactance</td>
</tr>
<tr>
<td>H, D</td>
<td>inertia and damping of synchronous generator</td>
</tr>
<tr>
<td>H_p, H_t</td>
<td>IG and turbine inertia</td>
</tr>
<tr>
<td>K</td>
<td>Stiffness constant and torsion angle of rotor shaft</td>
</tr>
<tr>
<td>D_r, D_i</td>
<td>damping of turbine and induction generator</td>
</tr>
<tr>
<td>x_s, x_q</td>
<td>Synchronous reactances of generator</td>
</tr>
<tr>
<td>X_r, X_q</td>
<td>Transient reactances of generator</td>
</tr>
<tr>
<td>T_d, T_q</td>
<td>Open-circuit field time constants of generator</td>
</tr>
<tr>
<td>V_s, r_s</td>
<td>Synchronous generator terminal voltage and stator resistance</td>
</tr>
<tr>
<td>K_A, T_A</td>
<td>Exciter system gain and time constant</td>
</tr>
<tr>
<td>V_m, V_n</td>
<td>Stator and rotor voltage of DFIG</td>
</tr>
<tr>
<td>P_m, P_e</td>
<td>mechanical power input, electrical power output</td>
</tr>
</tbody>
</table>

REFERENCES