On-Line ANN based Controller for Improving Transient Response of Grid-Connected DFIG-driven by Wind Turbine

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Abstract—The paper presents an application of on-line artificial neural network (ANN) for refining the transient performance of the doubly-fed induction generator (DFIG) operated by wind turbine energy system (WTES). The proposed on-line ANN is used to control the DFIG driven by WTES connected the electric grid via double transmutation lines. The on-line ANN used the back-propagation algorithm based on the gradient descent method to update the weights and biasing of the different layers of ANN. The objective function of the updating algorithm is to eliminate the system error. The system under study is simulated and tested using the SIMULINK package under different sever transient disturbances to validate the proposed controller. The simulation results depicted a better transient response of the overall system based on ANN in compared with the conventional PI controller.

Index Terms—On-Line ANN, DFIG, RSC, GSC, PI controller.

I. INTRODUCTION

Renewable energy has become the new direction for power generation to eliminate the global warming from the petroleum and coal usage. In 2016, the renewable energy around the world has covered almost two-thirds of net power capacity, with about 165 Giga-Watts (GW) coming online [1]. By 2022 renewable electricity capacity expected to increase by 43% equivalent one-third to over 8,000 terawatts per hour, which is considered half the current global coal capacity power which has taken 80 years to build [1].

During 2017, globally about 539,581 Mega-Watt capacity of wind power was added, lead to the increase of the total capacity which was almost 487,657 MW in 2016 [2-3]. This capacity of wind turbine considered the largest number ever installed through one year [3]. Wind energy is considered the cheapest commonly used clean energy, as the technology growth development, and the cost of maintenance become cheaper [3].

The widely used wind turbine configuration is the three-bladed horizontal axis, different combinations can be used of generator, drive train configuration, power control and rotational speed [4-6].

The wind speed can be either fixed or variable. In the past, using the Squirrel Cage Induction Generator (SCIG) was the most frequent means for the fixed speed wind turbine (FSWT) power generation. The FSWT disadvantage is that when the wind speed varies it is incapable of extracting the maximum power [4-7].

Due to the FSWT disadvantage, the industry technology has been taken towards the variable speed wind turbines (VSWTs). They have many advantages over the FSWT like efficiency improvement in wind speeds wide ranges, power quality improvement, etc. according to the power rating of the
converters, VSWTs can be divided according to its converters power rating into: DFIG and Direct Drive Synchronous Generator (DDSG). As the wind power, it’s high penetration increasing, DFIG become popular various other techniques of Wind Energy Conversion System (WECS) and plays a significant role in the stability of power systems, as well as the advancement of the transient performance of DFIG is growing progressively. Besides its converter lower cost, low power loss and higher efficiency [4-6].

Preceding researches have endeavoured to modify this by improving the control method like Proportional plus integral (PI) with fixed gain controller which considered the most commonly used in industrial applications for its easy design, robust performance, simple structure and cheap. In spite of, the advantages of the PI controller but the DFIG performance is still affected by the fine tuning of the PI controller gains, therefore, PI regulator will lose the flexibility at this time [8-9].

To optimize the performance of the system through the traditional trial and error for the PI controller much time will be consumed, and it will be inconvenient particularly when dealing with non-linear system [8-9]. So, many researches have been done to tune the PI parameters [10-12] through optimizing methods. Besides all these researches, but still the PI has some limitation such the parameters variation sensitivity and the dynamic systems non-linearity [13-14].

Nevertheless, the methods adopted simply modify the controller parameters at a single point of operation (fix optimal model) and the parameters are stable [15]. The controllers do not have the capacity to dynamically adjust the PI gain values consistent with the variance in the wind speed. This paper investigates the varying speed change with different operating modes at sever conditions through the adaptive neural network system. By changing the learning rate and adjusting the hidden layer’s number of neurons. The results of both PI and ANN controllers are then compared. The validity of the proposed model is designed through MATLAB/SIMULINK.

**II. DFIG BASED WIND TURBINE GENERATOR SYSTEM (WTGS)**

**A. WTGS**

A structure that extracts electrical energy from the incoming air stream’s mechanical kinetic energy is called the WTGS [16-17]. The typical wind turbine power-speed charactistics is shown in Figure 1. The relation between the wind speed passing through the rotor blade turbine and the maximum mechanical input power is as follows (1):

\[ P_{o_t} = \frac{1}{2} \rho \pi R^2 v^3 \omega C_P(\lambda, \beta) \]  \hspace{1cm} (1)

Where:

- \( P_{o_t} \) Wind turbine captured power
- \( \rho \) Air density
- \( R \) Rotor blade radius
- \( v_\omega \) Wind speed
- \( C_P \) Turbine Power coefficient, it is a function of the pitch angle ‘\( \beta \)’, and tip speed ratio ‘\( \lambda \)’. 
B. Double Fed Induction Generator

Today, more than 85% of the installed wind turbines employ DFIGs and the industrial commercial capacity has been increased towards 5MW [16-17]. As the global installed capacity of wind turbines are increasing as showing in Figure 2.

In Figure 3, the DFIG is linked to the grid through the rotor side converter (RSC) and the grid side converter (GSC). While the stator side is linked directly to the grid through a transformer, the RSC is linked using a power electronic interface converter, called as Back -to- Back Converter and fed by bi-directional Voltage Source Converter (VSC). The converters can control speed, frequency, torque, phase angles and rotor current. The DFIG can operate at a wide range ± 30% of synchronous speed; by that it gives the advantage to reduce the power fluctuation and regulate the reactive power. Unlike the stator, whose power supply is to the grid, the rotor side power is handled in both directions.

There are two different operating conditions, super-synchronous and Sub-Synchronous, the RSC and GSC in both operations are working vice-versa. In sub-synchronous, the RSC and the GSC each function as an inverter and a rectifier, respectively. Consequently, the power that is active passes from the grid’s side to that of the rotor. While the RSC functioning, during the super-synchronous condition, as a rectifier and the GSC works as an inverter. Therefore, it is allowing the flow of active power from the stator and rotor to the power grid. Figure 3 depicts the DFIG model block diagram-based wind turbine. More details about the Turbine parameters are given in Table [1].
Figure 3. DFIG model based wind turbine

Figure 4, shows the DFIG per-phase equivalent circuit [16-17]. The DFIG may be modelled in the synchronous reference frame as (2,3,4,5):

![DFIG per-phase equivalent circuit diagram]

where

- $I_s$: Stator Current
- $R_s$: Stator Resistance
- $X_s$: Stator Reactance
- $I_r$: Rotor Current
- $X_r$: Rotor Reactance
- $V_r$: Rotor Voltage
- $R_m$: Magnetizing Resistance
- $X_m$: Magnetizing Reactance
- $S$: Slip

Stator and Rotor Voltage

$$\begin{align*}
    v_{sd} &= -R_s i_{sd} - P \psi_{sd} + \omega_s \psi_{sq} \\
    v_{sq} &= -R_s i_{sq} - P \psi_{sq} - \omega_s \psi_{sd}
\end{align*}$$  \hfill (2)

$$\begin{align*}
    v_{rd} &= R_r i_{rd} + P \psi_{rd} + P \theta_s \psi_{rq} \\
    v_{rq} &= R_r i_{rq} + P \psi_{rq} + P \theta_s \psi_{rd}
\end{align*}$$  \hfill (3)

Stator and Rotor flux

$$\begin{align*}
    \psi_{sd} &= L_s i_{sd} - L_m i_{rd} \\
    \psi_{sq} &= L_s i_{sq} - L_m i_{rq}
\end{align*}$$  \hfill (4)
\[
\begin{align*}
\psi_{rd} &= L_r i_{rd} - L_m i_{sd} \\
\psi_{rq} &= L_r i_{rq} - L_m i_{sq}
\end{align*}
\]  

where

- \( L_s \) Stator Leakage inductance
- \( L_r \) Rotor Leakage inductance
- \( L_m \) Magnetizing inductance
- \( \omega_s \) Synchronous electrical speed
- \( \psi \) Flux Linkage
- \( \theta_s \) the rotor phase A-axis to the d-axis angle

### III. DFIG CONVERTER STRATEGY

DFIG power converter contains a back-to-back converter linking the rotor to the grid circuit, they usually consist of voltage source inverters with IGBTs equipped with freewheeling diodes as shown in Figure 5. By that way, a bi-directional power flow is enabled. The GSC output is equipped with an RL-filter to minimize the harmonics switching supplied to the grid.

![DFIG AC/DC/AC bidirectional power converter](image)

**Figure 5. DFIG AC/DC/AC bidirectional power converter**

#### A. Rotor Side Converter

The RSC scheme control contains two cascaded vector control one is employed in the regulation of the active and reactive powers \( P \) and \( Q \), respectively, and the other is to regulate the q-axis \( I_{qr} \) rotor current and d-axis \( I_{dr} \) rotor current. The outer loop via adjusting the DFIG rotor speed represents the first controller, \( P \) and \( Q \). However, the \( I_{dr} \) and \( I_{qr} \) controller are executed by the inner loop.

The reactive power and maximum slip control capability are affecting the RSC power size value. The rotor-side converter is a voltage source converter controlled current.

#### B. Grid Side Converter

The GSC power rating is chiefly based on the maximum slip power because it usually functions at a unity power factor to reduce the converter losses. Generally, the GSC is solely devoted to the DC-link voltage regulation. In case of a fault, the converter may be employed in sustaining grid reactive power. Also, the grid-side converter may be utilized in the enhancement of grid power quality selected as the real part of the imaginary d component and the bus bar voltage.

Also, the aim of the grid-side is the dc-link voltage regulation. A fast-inner current control loop composes GSC control, which regulates the grid filter current. In addition, a slower outer control loop is in charge of the dc-link voltage regulation. The inner current control loop’s reference frame shall be
aligned with the grid flux. Accordingly, the q and d constituents of the grid-filter current will control the active power and reactive powers, respectively, delivered from the converter. Hence, the q constituent of the grid-filter current will be affected by the outer dc-link voltage control loop.

The amount of energy stored in the dc-link capacitor is expressed by the following equation:

\[ E_c = \int P \, dt = \frac{1}{2} CV_{dc}^2 \]  
\[ P = P_r - P_g \]  

where

- \( P \) Net Power Flow into the capacitor
- \( C \) Capacitor DC link
- \( V_{dc} \) DC capacitor voltage
- \( P_r \) Inflow Rotor Power
- \( P_g \) Outflow Grid power
- \( E_c \) Capacitor Energy storage

IV. DFIG CONTROL STRATEGY

During studying and evaluating the system, two different controllers have been used, the first is the most used PI controller and the second is the proposed ANN controller. Figure 6, depicts the simple block diagram presentation of the PI controller for speed.

The wind energy extracted from the DFIG based wind turbine mainly depend on the control schemes by means of various orientation frames. Usually the DFIG functions in the Vector control mode-based PI controllers in the synchronous reference frame either stator voltage oriented (SVO) or the stator flux-oriented frames (SFO). Figure 7 shows the model of DFIG in the d-q frame with the IFOC.

\[ u(t) = K_p e(t) + K_i \int e(t) \, dt \]  

Where:

- \( u(t) \) Controller Output
- \( K_p \) Proportional Gain
- \( K_i \) Integral Gain
- \( e(t) \) Signal error

Figure 6. PI Controller block diagram
V. SYSTEM UNDER STUDY

The wind farm under study consists from DFIG driven from wind turbines, each turbine rated 1.5 MW, which make the total output 9 MW, connected to 25 KV distribution system, then it’s raised up to 120 KV across a double transmission line, each line is 30 Km connected with the grid. The line diagram in Figure 8, illustrates the system under study.

VI. SIMULATION RESULTS

Different case study has been executed to investigate the transient dynamic performance of the system being studied.

First Case:
The simulation of the first case is carried out when the DFIG connected to grid driven by wind turbine rotated by wind speed equals 15 m/s, then 3-phase short circuit occurs at 10.1 sec, followed by the automatic enclosure at 10.2 sec as aforementioned in Table [1]. In this case, the simulation results are presented in Figures (9 a, b and c).
Figure (9-a). Transient response of active power displayed for different values of proportional gains at load

Figure (9-b). Transient response of the reactive power

Figure (9-c). Depicts the transient response of the DC voltage
From Figures (9 a and c), the percentage over shoot (P.O.S) and the steady errors are varied when the \(K_p\) and \(K_i\), in the active power loop, have a different value. This is a normal conclusion with this type of controllers.

\[ \text{Figure 10. Transient response of the terminal voltage} \]

From Figures ((9 a, b, c), and 10) the best value of the \(K_p\) and \(K_i\) in the active power control loop are \(K_p = 1, K_i = 0.8\) which give almost the critical transient response in active power.

**Second Case:**

For the sake of confirming the validity of the controller, another simulation test is performed at different operating point condition. The system is tested with wind speed equal 10 m/sec, as given in Table [2], which delivered almost 50\% of the rated active power. Then the same disturbances described in the first case are executed. Figures (11 a, b, c and d) showing the simulation result of active power, Q, Vdc and terminal Voltage.

From these Figures, it appears that the PI controller with the same gain, in the full load condition as first case, couldn’t guarantee the same good performance regarding the P.O.S and steady state error in this case.

\[ \text{Figure (11-a). Active Power response at different operating point} \]
Therefore, the PI controller with fixed gains does not guarantee good transient response in a wide variety of operation conditions. Therefore, the ANN controller is introduced to overcome this problem.
VII. ARTIFICIAL NEURAL NETWORK

The online ANN model proposed in this research compromises from three layers. Firstly, the input layer which is of five input variables, the second is the hidden layer consists from a certain number of neurons \( N_{H\text{.Layer}} \). During the simulator program, different numbers of \( N_{H\text{.Layer}} \) were tested \( N_{H\text{.Layer}} \) equals 5, 6 and 8 neurons to select the best configuration. The third layer is the output layer with only one neuron.

Each neuron consists from activation function and biasing. In this paper, the tanh-sigmoid activation functions were used in this feed-forward ANN net. Sigmoid function predicts the probability and it’s used in this paper as an output activation function. The prediction probability falls only within range 0 and 1. Besides that, the Hyperbolic function was also used, to calculate gradients parameter, strengthen and smoothing the hidden layer. The Tanh function within range -1 and 1.

For sigmoid function, the equation can be described as following (9), and its shape shown in Figure 12.

\[
f(x) = \frac{1}{1 + e^{-x}}
\]

(9)

The activation derivative is:

\[
f'(x) = \frac{df}{dx} = f(x)(1 - f(x))
\]

(10)

Also, the equation describing the Hyperbolic function is given in equation (11), and its design shown in Figure 13.

\[
f(x) = \tanh(x) = \frac{2}{1 + e^{-2x}} - 1
\]

(11)

The activation derivative is:

\[
f'(x) = \frac{df}{dx} = 1 - f(x)^2
\]

(12)

As demonstrated in Figure 14, the flow of information of the ANN is in forward direction i.e. information moves from input layer, via different weight, to each neuron in the hidden layer. Then, the yield is transferred to the output neuron after multiplication of weights. Then a back-propagation algorithm is used to adaptive all linked layers weight and biasing [20-22] using the gradient descent method the objective function is to supress the I_d rotor side converter error.
In Figure 15, the single neuron output may be represented below (14)

\[
\begin{align*}
\text{Output} &= \text{activation function}\left(\sum_{i=1}^{n} \omega_{ij}x_i + \Theta_i\right) = f(a) \quad (13) \\
\text{where } a \text{ is Total Input} &= \sum_{i=1}^{n} \omega_{ij}x_i + \Theta_i \quad (14)
\end{align*}
\]

Where:
- \(\omega_{ij}\) synaptic weights
- \(\Theta_i\) external threshold, offset or bias

The ANN controllers may suffer from long training process and convergence time, even though they can lever the non-linearity features. Hence, the current paper proposes an adaptive ANN controller. The suggested On-ANN controller guarantees precise and fast dynamic responses with an outstanding steady-state operation as shown in the below results.

The third and fourth case evaluating the impact of the two types of controllers (PI with ANN), at different operating starting point at fully load which considered the normal operation and the other case at medium load by varying the wind speed with 3LG (Line-to-Ground) fault applied, the parameters values of each controller are shown in Table 2 [3].

**Third Case:**
The system is tested with wind speed equal 15 m/sec, which’s the full load operation rated 100% of the active power. Then the same disturbances described in the first case are executed. Figures (16 a, b, c and d) showing the simulation result of active power, Q, Vdc and terminal Voltage.
Fourth Case:
The system is tested with stepping down the wind speed to 10 m/sec, to be half the rated active power under severe condition has been executed. Figures (17 a, b, c and d) showing the simulation result of active power, Q, Vdc and terminal Voltage.
Figure (17-a). Active Power response with varying Controller

Figure (17-b). Reactive Power impact with varying controller

Figure (17-c). DC voltage impact with varying controller
The proposed On-ANN controller has been used to ameliorate the DFIG system’s transient stability during severe condition. The DFIG driven by WTES is tested using the conventional PI controller with fixed gains. Also, different operating condition has been implemented with changing the wind speed to show disturbance effect on the system. The simulation results have shown a better improvement in the transient response of the overall system based on ANN after comparing with the conventional PI controller.

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APPENDIX

Table 1. System Parameters

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Rated power windfarm (MW)                      | 9     |
| Frequency (Hz)                                 | 60    |
| DC bus voltage (V)                             | 1150  |
| Mechanical output power (MW)                   | 1.65  |
| Wind Speed (m/s)                               | 15    |
| Stator resistance (pu)                         | 0.023 |
| Rotor resistance referred to the stator (pu)   | 0.016 |
| Stator leakage inductance (pu)                 | 0.18  |
| Rotor leakage inductance referred to the stator (pu) | 0.16 |
| Magnetizing inductance (pu)                    | 2.9   |
| Fault Period (Seconds)                         | 10.1 – 10.3 |
| CB activation (Seconds)                        | 10.2 – 11 |

Table 2. PI controller parameters value

| Parameter                      | Value |
|--------------------------------|-------|
| $K_p$ - Rotor current regulator| 0.5   |
| $K_i$ - Rotor current regulator| 0.001 |
| $K_p1$ - Rotor current regulator| 0.5  |
| $K_i1$ - Rotor current regulator| 0.01 |
| $K_p$ - Vdc                    | 600   |
| $K_i$ - Vdc                    | 400   |

Table 3. ANN parameters

| Parameter                      | Value |
|--------------------------------|-------|
| No. of input neurons           | 5     |
| No. neurons of hidden layers   | 5     |
| Scale                          | 0.0001 |
| Learning Rate                  | 0.0001 |