ANFIS Based Neuro-Fuzzy Control of DFIG for Wind Power Generation in Standalone Mode

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***Abstract*—This paper presents an adaptive neuro-fuzzy controller (NFC) for doubly fed induction generator (DFIG) based wind energy conversion system (WECS) to operate under standalone mode. The NFC is developed based on adaptive-network-based fuzzy inference system (ANFIS) architecture since it has the unique advantage of fast convergence combining the robustness of fuzzy logic and flexibility of neural network algorithm. For the isolated operation of DFIG-WECS, ANFIS is designed for load side converter (LSC) control. The proposed scheme demonstrates improved dynamic performance under variable wind speed and load conditions by maintaining stable output voltage. The supply frequency to the load remains stable by virtue of precise control of LSC while turbine rotation varies with fluctuating wind speed. The flux alignment is ensured by the proportional-integral (PI) control of rotor side converter. The simulation results exhibit the controller's outstanding performance through its robust control over load-voltage and supply frequency under the variation of demand load power and wind speed.**

Keywords*— *Doubly-fed Induction Generator, Wind Energy, Standalone mode, Neuro-Fuzzy Controller.

I. INTRODUCTION

Now-a-days doubly fed induction generator has become popular for wind energy conversion system (WECS) due to its capability of wider speed range operation as compared to its counterparts [1]. Conventional squirrel cage asynchronous generators draw high magnetizing currents from the power grid. On the other hand, DFIG facilitates the use of low-power converters in grid-side/rotor-side, operation in sub-synchronous or super-synchronous modes and decoupled control of real and reactive powers. Depending on the demand, DFIG can either be operated as standalone (in remote area) or grid-connected mode (where existing grid is available). In standalone operation, the generator should have enough capacity to supply power to local base load and to the storage for backup. Due to the intermittent nature of wind flow, the wind generator can't sustain during isolated operation without the support of additional power sources. Various alternative energy sources such as flywheel based energy storage [2], turbine driven by water flow [3], hybrid energy storage supported by diesel engine [4], photovoltaic panel [5] have been chosen for standalone operation of DFIG driven WECS. However, the battery storage based standalone wind turbine power system gained popularity because of its ease of control and convenient storage facility [6-8]. The machine is equipped with power electronics interfaces to regulate voltage and frequency to handle the power variation from the energy source. So far, various control schemes have been proposed for the control operation of DFIG either feeding the grid-line or standalone load. Power control techniques such as vector control [9] , direct power control [10] have been proposed in literature to regulate the power output of DFIG for standalone mode under balanced and unbalanced condition. Unlike the numerous research attempts on grid-connected DFIG-WECS, only a handful articles have been found in standalone mode operation of DFIG in wind power islanding mode under variable speed condition [11-13]. In [14], a direct torque control scheme is proposed for dc voltage regulation of DFIG in SA mode. However, the model utilizes only PI controller and exhibit torque pulsation in its output. A PLL based angle loop control for improved frequency regulation has been proposed by Iwanski [13]. In another study, authors have proposed a direct voltage control based on negative-sequence compensation to support asymmetric loads [15]. However, the design haven't shown the performance of the wind power control under varying wind speed or applied torque. In Intelligent control algorithms such as neural network (NN), neuro-fuzzy control (NFC) or adaptive network-based fuzzy inference system (ANFIS) have not been thoroughly investigated yet for standalone operation of DFIG. Among various NFC schemes ANFIS provides adaptability on choosing the membership functions and fast convergence due to its hybrid learning. Moreover, ANFIS architecture has the distinguished feature of modeling a highly nonlinear system, as it combines the competence of fuzzy reasoning in handling uncertainties and learning aptitude of neural network from complex system [16]. Hence, ANFIS has been found a suitable candidate to cope with induction machine nonlinearities and uncertainties such as, variable wind speed, unbalanced load, fault conditions, etc. Therefore, the ANFIS based NFC technique is proposed for converter control in this paper. In this work, ANFIS based control scheme is developed for standalone operation mode of DFIG-WECS where the load side converter is driven by neuro-fuzzy network based control scheme. The proposed controller aims to regulate the frequency and the terminal voltage to a specified value. The sample input-output data for the training of ANFIS structure are taken from the transient response of the DFIG-WECS with the designed PI controller under variable demand power and fluctuating wind speed conditions. The Gaussian type of function is selected as membership function, and the combined back-propagation and

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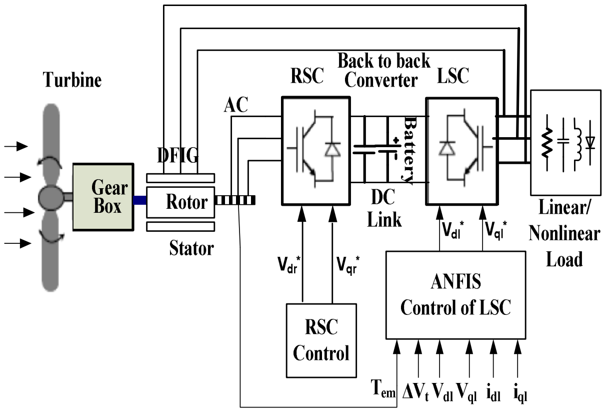

Fig. 1. Overall configuration of the ANFIS based DFIG-WECS

least square function algorithm is utilized to train the proposed ANFIS structure. The robustness of the controller is verified in simulation under changing conditions. The authors are currently developing the real-time experimental model of the proposed scheme.

The paper is organized as follows. Section II presents the configuration for the proposed scheme with required equation and nomenclature. The ANFIS structure with layer description and the converter control operations are also explained in the section with detail diagram. The simulation results are presented in section III. Conclusions are made in section IV.

II. PROPOSED DFIG-WECS CONFIGURATIONS FOR SA MODE

In DFIG based WECS, The wind turbine drives the generator and the conversion of rotational mechanical energy to electrical energy is performed by the generator. The stator of the generator is connected to the grid directly, while the rotor is interfaced with the grid through a power converter system with reduced power capacity [17]. A gear box is necessary to adjust the low speed of the turbine rotor to the high speed of the generator. The gear box is usually multi-staged to achieve the high conversion ratio to couple turbine shaft and rotor of the generator. Two back-to-back converters are connected at the rotor side and the grid side, which can be controlled independently. An isolated generation system is required when the users stay far away from the national supply grid. For a standalone application of WECS, the system needs to have sufficient storage capacity to handle power variations from the available wind energy source. Therefore, external storage device such as battery, fuel cells are connected along with the dc bus capacitor. In Fig. 1, standalone operation for DFIG based WECS is demonstrated. Table-I shows the specification of the wind turbine, DFIG and load parameters that have been utilized in simulation. In order to cope with induction machine nonlinearities and uncertainties in wind speed, and load conditions a novel ANFIS based NFC scheme is developed to control the converters for isolated operation of DFIG. The dynamic model of DFIG can be obtained from d-q axis voltage and flux equations [17] in synchronous rotating reference frame as shown in (1)-(8). The d-q transformation model can be obtained from the DFIG arbitrary reference frame model by replacing the arbitrary speed by the synchronous speed $_{s}$.

TABLE I. WIND TURBINE, DFIG AND LOAD PARAMETERS

Parameters	Value
Rated turbine power	2 MW
Pitch angle	0˚
Blade radius	15m
Rated generator power	2.5 MW
Rated slip	-0.1667
Grid voltage(rms)	690 V
Grid frequency	60 Hz
Number of pole pairs	2
Leakage resistance	2.9 mΩ
Leakage inductance	0.08 mH
Magnetizing inductance	2.5 mH
dc bus capacitance	150 mF
Load frequency	60 Hz
Rated Load Voltage(rms)	590 V

$$v_{ds} = R_s i_{ds} + p\psi_{ds} - \omega_s \psi_{qs} \quad (1)$$
$$v_{qs} = R_r i_{dr} + p\psi_{qs} + \omega_s \psi_{ds} \quad (2)$$
$$v_{dr} = R_r i_{dr} + p\psi_{dr} - (\omega_s - \omega_r)\psi_{qr} \quad (3)$$
$$v_{qr} = R_r i_{qr} + p\psi_{qr} + (\omega_s - \omega_r)\psi_{dr} \quad (4)$$

The d-q axis flux linkages can be related to the corresponding currents by the equations mentioned in (5)-(8),

$$\psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \quad (5)$$
$$\psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr} \quad (6)$$
$$\psi_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \quad (7)$$
$$\psi_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs} = L_r i_{qr} + L_m i_{qs} \quad (8)$$

where,
$v_{ds}, v_{qs}, v_{dr}, v_{qr}$—d-q axis stator and rotor voltages (V)
$i_{ds}, i_{qs}, i_{dr}, i_{qr}$— d-q axis stator and rotor currents (A)
$\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ – d-q axis stator and rotor flux-linkages (Wb)
R_s, R_r— stator and rotor winding resistances (Ω)
ω_s, ω_r—synchronous and rotor electrical angular speed (rad/s)
p —derivative operator *(p = d/dt).*
$L_s = L_{ls} + L_m$ —Stator self-inductance (H)
$L_r = L_{lr} + L_m$ —Rotor self-inductance (H)
L_{ls}, L_{lr}— Stator and rotor leakage inductances (H)
L_m— Magnetizing inductance (H)

A. Proposed ANFIS Structure

With linear controller design for DFIG-WECS, it is likely that the controller might need further adjustment before applying to real wind-turbine system. It is very difficult to obtain the perfect simulation model for a real DFIG-WECS as it contains several dynamics that are not fully known [18]. Adaptive neuro-fuzzy inference system consists of a fuzzy inference system whose membership functions can be reconstructed by using an authentic input-output data set. The parameter associated with the membership functions varies obtained by gradient descent algorithm [19]. ANFIS networks utilize a combination of least squares estimation and back propagation for membership function parameter estimation. The schematic of the proposed ANFIS architecture is shown in Fig. 2. The details of ANFIS structure can be found in [20]. In the proposed controller, a data driven designing algorithm for Takagi–Sugeno-Kang (TSK) fuzzy model has been introduced. The methodology generates the required reference voltages to drive the load side converter on the basis of input-output numerical data set to minimize the load voltage error function. This method utilizes the neuro-fuzzy model to adapt the parameter of the membership functions. After the gradient vector is determined, it utilizes one of its optimization techniques to adjust the parameters to reduce the error function defined as,

$$\mathrm{V_{err}} = \mathrm{V_x^{ref}} - \mathrm{V_x^{mes}} \tag{9}$$

where, $\mathrm{V_x^{ref}}$ is the reference d,q axis load side voltage used for training and $\mathrm{V_x^{mes}}$ is the measured reference voltages previous iteration step. The node functions of each layer are described as follows.

Layer 1: The first layer is also known as the fuzzification layer, a number of membership functions are assigned to each input. The Gaussian membership functions are used in the proposed method shown in Fig. 3. The equation for the Gaussian membership function can be expressed as

$$f(x) = e^{-\frac{(x-m_i)^2}{2\delta_i^{\,2}}} \tag{10}$$

where, x is the input for the layer, m_i and δ_i are the mean value and standard deviation of data respectively for the corresponding membership function.

Layer 2: In this layer, each node multiplies the entering signals and directs the output to the next level that represents the individual firing strength μ_i of a rule.

$$\mu_i = \mu_{A1}^{i}(x_1)\mu_{B1}^{i}(x_2)\mu_{C1}^{i}(x_3) \tag{11}$$

Layer 3: Each block in the third layer which is also known as normalization stage, estimates the proportion of the i-th rule firing strength ($\bar{\mu}_i$) to sum of the firing strength of all rules.

$$\bar{\mu}_1 = \frac{\mu_1}{\mu_1+\mu_2+\mu_3} \tag{12}$$

Layer 4: In this layer, the functional output (*f*$_i$) is calculated as the linear activation function.

$$\mathrm{f_i} = a_0^i + a_1^i x_j,\ \mathrm{i,j=1,2,3} \tag{13}$$

In this stage, the parameters a_o, a_1 are tuned as the function of input (X). These parameters are known as consequent parameters.

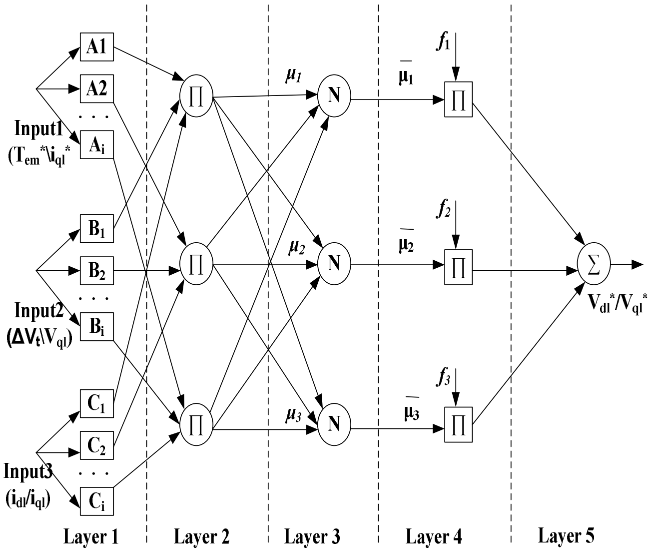

Fig. 2. Schematic of the proposed ANFIS architecture.

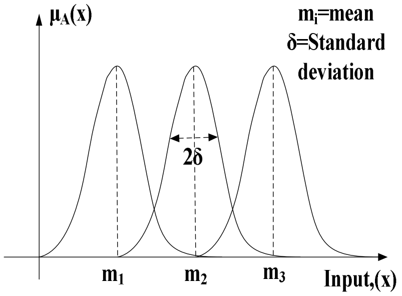

Fig. 3. Gaussian Membership Functions for Input Data.

Layer 5: The final layer is the output layer which computes the overall output by combining the incoming data.

$$V^{*} = \bar{\mu}_1 f_1 + \bar{\mu}_2 f_2 + \bar{\mu}_3 f_3 \tag{14}$$

B. Converter Control Operation in SA Mode

In standalone environment, intermittent wind speed and variable load power demand make the operation of wind-based power systems challenging to maintain constant output voltage and frequency of the DFIG. Battery storage system has been integrated parallel to dc link side to supply the demand in case of energy shortage and as energy storage in the case of excessive wind power generation. An energy management algorithm is required to maintain the demand – supply balance for the standalone system. The excessive energy is dissipated to dumping load if the storage unit gets saturated. For simplification of the control mechanism, it demanded power by the load unit is assumed to be same as the sum of the power generated by the turbine and the battery supply. The control strategies for the LSC and RSC are described in the following subsections for standalone mode of operation of DFIG.

1) *Proposed ANFIS based LSC control for SA mode*

In SA mode, the control complexity lies in the fact that stable grid voltages are not available. The output voltage and frequency have been controlled by the LSC.

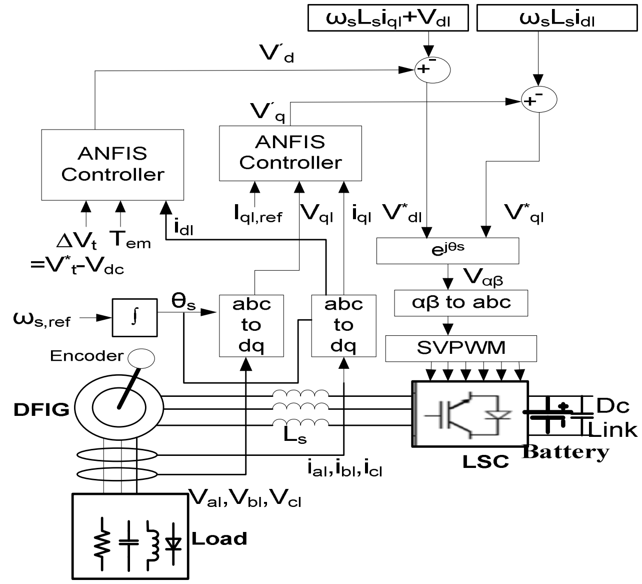

Fig: 4. Proposed ANFIS based LSC control for SA mode of DFIG

Figure 4 illustrates the LSC control arrangement for DFIG supplying power to linear and/or nonlinear loads. An ANFIS based on Takagi–Sugeno method having 3:3:9:12:1 architecture are used to generate the control d-axis voltage with electromechanical torque(T_{em}), d-axis load current (i_{dl}) and difference between desired terminal voltage and bus voltage ($V_{t,ref}$ -V_{dc}) as inputs and reference d-axis load voltage(V_{dl}^*) as output. The other ANFIS structure generates the q-axis reference load voltage, V_{ql}^* output by using actual q-axis load voltage (V_{ql}), actual and reference q-axis load current (i_{ql} and $i_{ql,ref}$) as inputs having similar structure with different number of nodes and training data pairs. The trial input-output data for the training of ANFIS structure are generated from the PI controlled converter based DFIG in standalone environment. The reference phase voltage for the load is selected as 590 V whereas, the stator flux position (θ_s) is derived from a free running integral of the stator frequency demand, ω_s^* (60 Hz).

$$\theta_s = \int \omega_s^* dt \qquad (15)$$

2) *Control of RSC in SA Mode*

While the LSC controls the load voltage and frequency, the RSC acts upon reference currents to maintain the stator flux orientation. With this indirect orientation scheme, the q-axis rotor current (i_{qr}) can no longer be used to control the generator torque; this is entirely appropriate for the standalone application in which the demand-load power and power-share of battery effectively determines the torque for a given shaft speed. It is also possible to control the magnetization of the machine by the variation of d-axis reference rotor current *($I_{dr,ref}$)* component as shown in Fig. 5. The RSC control configuration utilizes PI controllers to implement the proposed design. Typically, in autonomous operation of DFIG, the rotor side fully contributes to the magnetizing current component. Therefore, the stator flux is controlled using the q-axis load current i_{ql}. The reference q-axis rotor current, i_{qr}^* is controlled by i_{ql} which forces the orientation of the reference frame along the stator flux vector position. The reference current is obtained from (8) by assuming $\psi_{qr} = 0$ and $i_{ql} = i_{qs}$. The current is given by,

$$i_{qr}^* = -\frac{L_s}{L_m} i_{ql} \qquad (16)$$

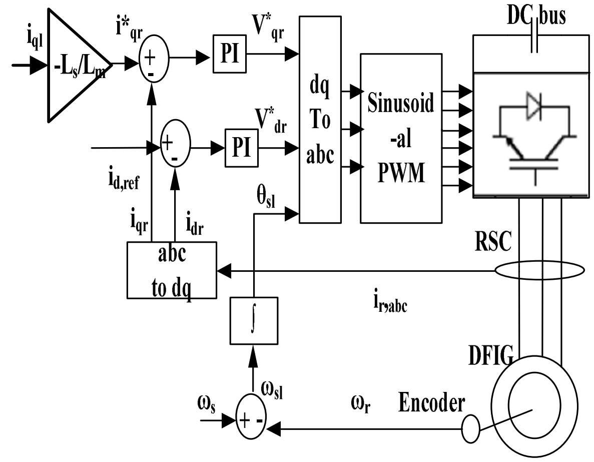

Fig. 5. RSC control scheme for SA mode of DFIG.

III. SIMULATION RESULTS

The performance of the proposed ANFIS controller based DFIG-WECS is investigated in simulation at different operating conditions such as variable wind speed, load variation for standalone mode. The target of the LSC control is to keep the output voltage and frequency of the DFIG to a steady level. For simplification of the control algorithm, it is assumed the load power demand is always less than the generated power of the wind turbine. Also filtering capacitors are required to eliminate the switching frequency harmonics produced by both the load-side and rotor-side converters. The capacitors also provide part of the reactive power needed for magnetization. For simplification of the proposed scheme, the filtering circuit is not shown in the control structure. Transient states caused by the rotor speed change and variation of load demand during supply of linear and nonlinear load have been presented in this section. Figure 6 illustrates the proficiency of the proposed ANFIS based LSC control scheme while there is a step increase of demand power from 0.2 MW to 0.3 MW at load end at t=0.5 sec (Fig. 6(a)).

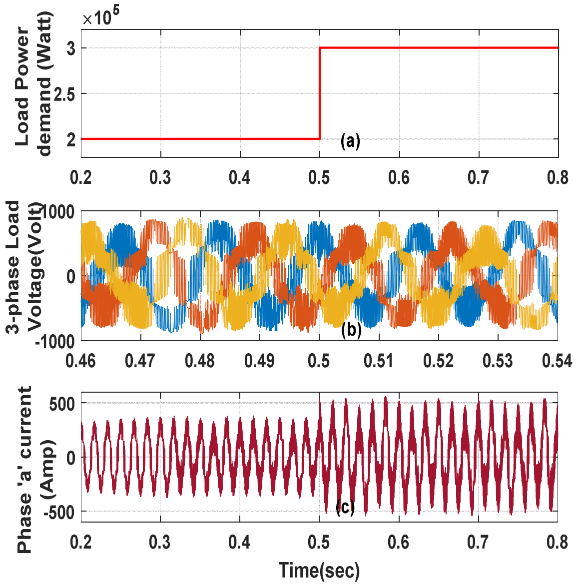

Fig. 6. Performance of the proposed ANFIS on SA mode for step increase in load demand: (a) Demand load power, (b) 3-phase voltage across load end, (c) 'a' phase load current.

The aim of the proposed controller is to keep the supply voltage fixed at 590 volt (rms) which is accomplished effectively even after sudden change of power demand by users (Fig. 6(b)). The voltage signal contains a number of harmonic components. It is possible to eliminate the harmonic components by adding active harmonic filters. The demand power is fulfilled by the current escalation from 370 Amp to 540 Amp as seen in phase 'a' load current graph (Fig. 6(c)). In addition, the output characteristics of the DFIG are tested for varying wind speed (Fig. 7(a)).The rotor speed and the dc-link voltage (Fig. 7(b) & 7(c)) follow the wind speed fluctuation smoothly to maintain the torque and stator power output at the desired level. In addition, the LSC controller ensures the stable output at the load end by maintaining the voltage roughly around 590 V and frequency at 60 Hz. Figures 7(d) & 7(e) delineate the results which confirm the efficacy of the ANFIS based control algorithm of LSC for DFIG operated WECS with isolated load.

Because of the learning capability of the implemented neuro-fuzzy algorithm, the proposed controller is capable of tracking the variation of wind turbine speed and fluctuation of demanded power.

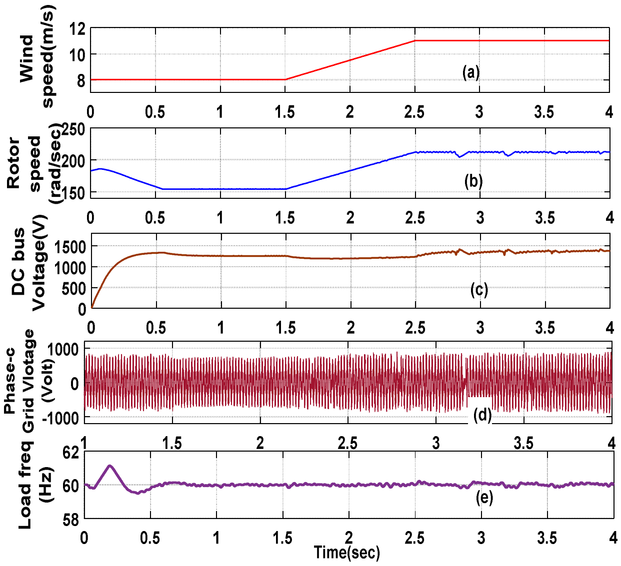

Fig. 7. Performance of the control system in SA mode: (a) Change in wind speed (b) Generator speed in rad/sec (c) DC bus voltage (d) Grid voltage of phase-c (Volt) (e) Frequency of Load voltage (Hz).

IV. CONCLUSION

A novel ANFIS based NFC scheme for DFIG operated WECS has been presented in this paper. The performance of the proposed controller has been investigated for isolated load under different dynamic operating conditions. The simulation results suggest that the LSC and GSC controller altogether contribute to real and reactive power control by adjusting the rotor speed and machine torque with the variation of wind speed. Also, the proposed controller is capable of maintaining constant voltage and frequency at the load end even after abrupt variation of the required power demand and wind speed. The inherent learning capability of the proposed controller ensures the adaptive compensation caused by the unpredictability of the whole system and nonlinearity of DFIG-WECS. The analysis of the proposed scheme suggests the superiority and robustness of the designed ANFIS architecture based controller in standalone operating mode of DFIG-WECS. The real-time laboratory model of the ANFIS controller based standalone DFIG-WECS is currently under experimentation.

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