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# An Adaptive Fuzzy-PD Inertial Control Strategy for a DFIG Wind Turbine for Frequency Support



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**ABSTRACT:** With increasing levels of wind generation in power systems, guaranteeing continuous power and system's safety is essential. Frequency control is critical which requires a supplementary inertial control strategy. Since wind power generation depends directly on wind conditions, this creates an immense challenge for a conventional inertial controller with parameters suitable for all power grid operations and wind speed conditions. Therefore, tuning the controller gains is absolutely critical for an integrated conventional/renewable power system. Here, a fuzzy-logic adaptive inertial controller scheme for online tuning of the proportional-derivative-type (PD) inertial controller parameters is proposed. The proposed controller adapts the control parameters of the supplementary inertial control of the doubly fed induction generator (DFIG) wind turbine so that with any disturbance such as load changes, the active power output can be controlled to mitigate the frequency deviation. Simulation results indicate that the proposed adaptive controller demonstrates a more consistent and robust response to load changes compared to a conventional controller with fixed parameters.

**Key words:** Wind energy generation; doubly-fed induction generator (DFIG); frequency control; kinetic energy; rate of change of frequency (RoCoF).

## 1. INTRODUCTION

The necessity and challenge of a reduction in CO<sub>2</sub> emissions due to its detrimental effect on environment, as well as insurance and dearth of sources such as fossil fuel, has led to several countries agreed to raise the penetration level of non-traditional and renewable generation sources. Wind energy, in particular, is considered to be a reliable renewable energy source for electricity production therefore replacing conventional generation from traditional thermal fuel supplies (gas, oil and coal) at a large scale. Although high-level of integration of alternate energy sources, particularly with an increase in the penetration of wind power into the normal grid, can be beneficial, it could have unexpected results which could counteract the reliability and the stability of current traditional power systems [1]. The use of the DFIG-based wind turbine generator (WTG) has grown rapidly since the turn of the 21<sup>st</sup> century. In a DFIG, the generator frequency can vary as the wind speed changes, which allows the WTG to operate at different wind speed independent of the frequency and voltage of the grid [2].

Nevertheless, when the number of DFIGs is increased in cumulative penetration and when connected to the power grid, the frequency stability of a power system may decline. System inertia is a key factor, in determining the sensitivity of the frequency to any imbalance between generation and load [3] as it affects the rate of change of frequency (RoCoF) after any frequency event. A reduction in system inertia will lead to a rapid drop in system frequency, thus affecting the RoCoF increasing the likelihood of potential system collapse

System frequency is controlled on a second-by-second basis by balancing the power supply and demand for electric

power systems. Traditional power plants with synchronous generation play an essential role in controlling the frequency, since they have a large inertia constant [4]. Usually wind turbines are designed to operate to increase their output power under various wind power conditions however, their active power is mainly determined by the wind speed. The rotor speed of a DFIG therefore is decoupled from the system frequency. Thus, DFIG active power output remains constant with any changes in the system frequency. As a result, the DFIG must not produce any additional rise in the active power output. Hence, in a power system with a high level of wind power penetration, and therefore reduced synchronous inertia, the system frequency acts as an indicator of any imbalance between generation and load following load disturbance or generator tripping, for example.

The effect of DFIG penetration in a power system has been investigated in [5-7]. It has been shown that without an additional supplementary control loop added to the DFIG controller, the control system acts against changes in the system frequency, therefore responding with a zero or negligible inertial response. In [7-12], the frequency support function of a WTG that uses inertial control temporarily releases the KE stored in the rotating mass of a WTG to improve the frequency nadir during the initial/transient stages of a disturbance.

A proportional-derivative (PD)-type controller is commonly used in power systems for frequency regulation.

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Although, this controller is simple and usually effective, its performance is typically limited by restrictions of traditional PD control due to guaranteed delivery of optimum performance [12-13]. In [14], a PD virtual inertial controller (VIC) was used in the active power control of DFIGs. It was demonstrated that with the proposed structure, the controller gain parameters of the PD-VIC could be tuned online to prevent the system frequency from falling too low while maintaining the rotor speed within an operating limit.

The impact of PD parameters has been investigated in [15] in order to compare, contrast and set a benchmark with the aim of developing an alternative control strategy which is able to enhance frequency control and effectively emulates inertia.

In [16], a releasable KE-based inertial control scheme for DFIG wind power plant was proposed that differentiates the DFIG's contribution depending on its releasable KE. The scheme adjusts the gains of the RoCoF and droop control loop in the DFIG controller depending on the rotor speed prior to a disturbance. The results demonstrated an improvement in the system frequency nadir compared to the conventional constant gain scheme.

In [17], a fuzzy logic controller for inertial control of WTGs is proposed. Simulation results noted that the proposed scheme can boost the frequency nadir following the decline of the system frequency as opposed to the conventional control scheme.

A novel adaptive VIC to boost both the frequency stability and inter-area oscillations is proposed in [18]. The gain of the suggested VIC is dynamically adjusted utilizing fuzzy logic with respect to inter-area oscillations. Several frequency events such as short circuit disturbance with load shedding and loss of generation are used to assess the control and efficiency performance of the adaptive fuzzy VIC. Simulation results displayed that the proposed fuzzy VIC scheme can provide improved performance than the traditional fixed gain VIC for both system frequency stability and the inter-area oscillations.

A fuzzy adaptive additional inertial control technique is given in [19] for frequency regulation to adjust the proportional and derivative constants adaptively based on the frequency deviation and the frequency deviation change rate under load disturbances or wind speed. The derivative and proportional constant values in traditional inertial control are adjusted by simulating the static characteristics and inertial response characteristics of the conventional synchronous generator. The proposed scheme is correlated with traditional additional inertial control strategy and kinetic energy (KE)-based gain. Simulation results note that the proposed scheme can provide additional frequency support during load disturbances successfully and also repress the frequency variation made by the wind speed fluctuation.

This paper proposes an adaptive-inertial control scheme for a DFIG WTG with partial scale frequency converter (Type C) using a fuzzy logic scheme for frequency regulation in power systems. A fuzzy logic-based adaptive control strategy is implemented here to obtain robust and accurate control performance as well as faster frequency response with stable system operation during the time of an

event. The proposed control automatically adjusts the DFIG controller parameters online so that the inertia from wind turbines can be utilised to decrease the change in frequency variation and therefore enhance the frequency nadir during the transient periods.

In this study, the impact of wind generation on electric power grids and networks with particular consideration of the effects on system frequency has been examined. The work has been analysed and discussed to identify the main problem caused by the integration of high levels of wind penetration and its direct impact on power system stability which affects reliability and the operational performance of power systems.

The performance of the proposed scheme is studied under various system conditions and compared with the widely used PID based control. The results indicate that the robustness of the adaptive controller to any load changes is greater than that of the conventional controller with fixed parameters. It is demonstrated that the active frequency response of the power grid with high wind power penetration can be significantly enhanced.

A frequency deviation loop (droop loop) has been chosen in this work since it allows total energy discharge. This control strategy has been developed to use different values of deviation loop gains, based on previous work in [20]. However, the frequency deviation gain value is varied online as a function of the power system frequency deviations. The gain of the RoCoF ( $K_p$ ) loop in the proposed scheme is maintained as constant while the droop frequency deviation loop gain ( $1/R$ ) changes automatically with time.

In addition, the proposed Adaptive Fuzzy-PD Inertial Control scheme is compared with the previous work in [20], which has been developed to utilise different values of the deviation for frequency regulation using variable gains in the frequency deviation loop for the inertial controller and loop control gains (active gains) based on change of frequency. The two approaches mentioned above preserve stable operation of a DFIG and increase the frequency nadir in comparison to conventional fixed gain schemes. It can therefore be concluded that by correct adjustment of inertial controller parameters the performance will be greatly improved. However, manual tuning is cumbersome and requires trial and error.

The results presented in this study compares the performance of the proposed fuzzy-based control under the same frequency event between the following four cases: DFIG without control, the proposed fuzzy-based control, DFIG with conventional fixed gain, and DFIG with active droop control.

All the results confirm the proposed Inertial Control strategy can improve the frequency nadir and guarantee steady operation of a DFIG.

Additionally, the proposed method requires no earlier knowledge or mathematical model of the system. Also please note that the frequency used in this paper is 60 Hz in order to make a fair comparison with the conventional inertial controller, which was implemented using the 60 Hz system.

The paper is organized in five sections. Section 2 provides some background on the conventional inertial

response of a DFIG. Section 3 explains the fuzzy logic system design and modelling. Next, the proposed control strategy is presented in Section 4 whilst Section 5 shows the simulations results and discussions. Finally, the conclusions that can be drawn from the analysis are provided in Section 6.

## 2. THE CONVENTIONAL INERTIAL CONTROL OF A DFIG

The DFIG is decoupled from the grid due to a back-to-back AC/DC/AC convertor. Consequently, the electronic convertor decouples the generator speed from grid frequency [21]. The power electronic convertor enables the DFIG to capture wind energy and reach the maximum efficiency over a wide range of wind speeds. DFIGs are adapted to constantly alter the rotational speed and therefore the active power of wind turbines at various wind speeds to enhance quality of supply and to regulate the active as well as the reactive power. However, due to the decoupling of the rotational speed from the grid frequency, the DFIG produces no response to changes in system frequency [5]. It is however possible for a wind turbine to contribute to the system inertia and support the frequency control by adding a supplementary inertial control. Enhancement of such a supplementary control for improved frequency support is the main subject of this paper.

This work assumes that the conventional inertial control scheme of each DFIG includes two control loops: 1) the RoCoF; and 2) frequency deviation loops. Both feedback schemes are utilized simultaneously to enhance the system frequency control of the DFIG as presented in [12], [22], [23]. The traditional inertial control scheme is shown in Fig. 1 wherein the inner control loop is the RoCoF loop ( $\Delta P_{in}$ ) whereas the outer one presents the frequency variation loop or droop-loop ( $\Delta P$ ).  $K$  and  $1/R$  are the gains of RoCoF and deviation loop, respectively.

From the figure,  $\Delta P_{in}$  can be written as (1),

$$\Delta P_{in} = -K \cdot f_{sys} \cdot \frac{df_{sys}}{dt} \tag{1}$$

where  $\Delta P_{in}$  and  $f_{sys}$  are represented in per unit and Hz respectively.

The control gain  $\Delta P$  mitigates the frequency deviation loop of a synchronous generator, which is shown as in (2).

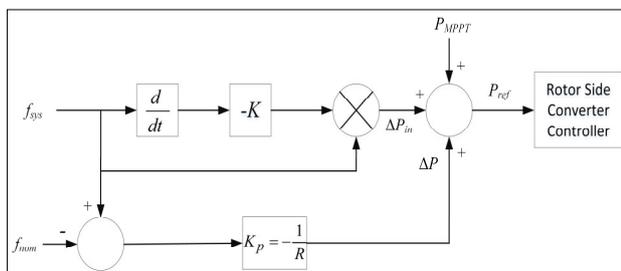


Fig. 1. Inertial controller schematic for the DFIG [11]

$f_{sys}, f_{nom}$  : system frequency and nominal frequency  
 $R$  : droop gain of the loop

$$\Delta P = -\frac{1}{R} (f_{sys} - f_{nom}) \tag{2}$$

where  $\Delta P$  and  $f_{nom}$  are represented in per unit and Hz respectively.

$\Delta P_m$  is dominant during the primary period of a frequency event due to a significant change in RoCoF; whereas  $\Delta P$  is dominant around system frequency rebound i.e. the frequency nadir.

The system inertial response is the decline in the rate of change of frequency attained once the stored KE is produced. The KE is the active power stored in the rotating mass of the generators presented by (3).

$$E = \frac{1}{2} J \omega_r^2 \tag{3}$$

where  $J$  is the inertia of the generator in  $Kg.m^2$  and  $\omega_r$  is its rotational speed in rad/s.

In conventional power systems, a constant inertia  $H$  in seconds as defined in (2) is the greatest amount of time the generator is able to produce a maximum output power from its own stored KE. Typically, this is in the range of 2-9 seconds [24].

$$H = \frac{J \omega_r^2}{2S} \tag{4}$$

where  $S$  is the nominal apparent power of the generator in MVA. Power imbalance is not a result of the moment of inertia however it does impact the system response to those transient events and the frequency control strategy utilised to improve these disturbances period. Prior to a disturbance,  $\Delta P_{ref} = P_{MPPT}$  when the power system frequency drops below its nominal value for any transient event such as sudden increase or decrease in load and/or demand, the inertial control loop (the RoCoF loop  $\Delta P_{in}$  and the frequency deviation loop  $\Delta P$ ) provides extra active power to the DFIG active power reference  $P_{ref}$  control loop (see Fig. 1). Thus,  $\Delta P_{ref}$  becomes positive increasing  $P_{ref}$  as a result thus reducing the rotational speed of the rotor  $\omega_r$  as given by Eq. (5), [24].

$$\begin{aligned} P_m - P_e \\ = P_m - (P_{MPPT} + \Delta P + \Delta P_{in}) = J \omega_r \frac{d\omega_r}{dt} \end{aligned} \tag{5}$$

where  $P_m, P_e, P_{MPPT}$  represents mechanical power electromagnetic power and maximum power point tracking (MPPT) respectively.

## 3. FUZZY-LOGIC DESIGN AND CONTROL SYSTEM

To release KE stored in rotating masses during an event and to regulate the frequency, researchers have proposed a number of methods. In [4, 7], the use of RoCoF as an input was used in the inertial control loop. In [9, 10, 12, 22, 23], both RoCoF and frequency deviation loops were utilised to enhance the frequency regulation of DFIG based on variations in system frequency. For example, the output active power of DFIG must respond efficiently through the additional inertial control. Although these inertial control schemes improve the system frequency, they generally employ constant loop gains, thus failing to take full

advantage of these controllers. In [25], it was determined that a higher gain improves the system frequency nadir, although this may result in over-deceleration of the rotor speed which may cause large WTG tripping, resulting in a decline in the frequency. Conversely, a small gain produces a minor enhancement in the system frequency nadir but guaranteeing stable operation of a WTG [25].

In [20], an active inertial control approach for the frequency deviation  $\Delta f$  loop for frequency regulation was presented. A frequency deviation loop was selected as it allows a greater total energy release [26]. This supplementary control scheme has been designed to utilise various values of the deviation loop gains based on the frequency deviation value. From the aforementioned, it can be concluded that substantial operation enhancements can be formed by suitable alterations of inertial controller parameters. However, manual tuning is challenging and requires trial and error. The use of fuzzy logic can offer an automatic way of detecting a frequency event thereby adjusting the gains online based on  $\Delta f$ .

This type of control helps in modelling complicated system behaviour, in which the direct relationship between system input and output cannot be easily modelled or expressed through analytical equations [27]. Moreover, the use of fuzzy-logic control (FLC) has become very popular recently because it can deal with approximate inputs [28]. Therefore, fuzzy logic controller can be used to regulate a DFIG wind turbine with acceptance of system nonlinearity.

Following on the earlier work of the authors in [20], fuzzy membership functions and rule bases can be designed to provide appropriate online adjustment of feedback gains (as opposed to manual tuning), thus providing frequency support automatically for different situations or conditions, for example, fluctuating wind speed. Frequency support can be divided into two groups: power reserve control and inertial control [29]. This work only focuses on inertial control to improve the system frequency nadir whilst guaranteeing steady operation of WTGs.

The design of the proposed fuzzy logic adaptive inertial control (FLAIC) for DFIGS is presented in the following section.

#### 4. FLAIC STRATEGY FOR EFFECTIVE INERTIAL CONTROL OF DFIGS

For a DFIG, the performance of the conventional PD controller is restricted in terms of both the frequency deviation loop (droop loop) gain,  $Kp$  and the RoCoF loop gain,  $Kd$  are constant. Since power systems are generally nonlinear, any alteration in the operating condition could cause performance degradation. In case of any variation in the power system frequency due to any mismatch between the generation against the load, the conventional inertial control changes the active power reference value  $P_{ref}$  to recover the grid frequency to the nominal value by releasing rotor KE [14]. Fig. 2 shows the block diagram of FLAIC. The adaptive fuzzy gains that are varied on-line make the system respond to parameter variations and load disturbance/frequency changes [30]. The proposed fuzzy logic-based scheme aims to release more KE in a wind power

plant by adjusting the controller parameters to achieve the optimal value of an active power reference  $P_{ref}$ .

The structure of the proposed FLAIC scheme is illustrated in Fig. 3, where the input signal is  $\Delta f$  and the output of the controller is the  $Kp$  gain. Fig. 4 shows the fuzzy sets and corresponding triangular membership functions (MF) of the input signal. The fuzzification part of the fuzzy logic controller, which uses three input membership functions signals (input signal to the FLAC controller), is the frequency deviation value which is the difference between the nominal frequency value  $f_{nom}$  and system frequency value  $f_{sys}$  ( $f_{nom} - f_{sys}$ ). The fuzzy membership functions (MFs) for input variables are triangular and the range of the MFs for the input of  $\Delta f$  are for negative values of the variables and have been chosen from  $-0.5\text{Hz} - 0\text{Hz}$  as the load disturbance (generation < load) event in this paper.

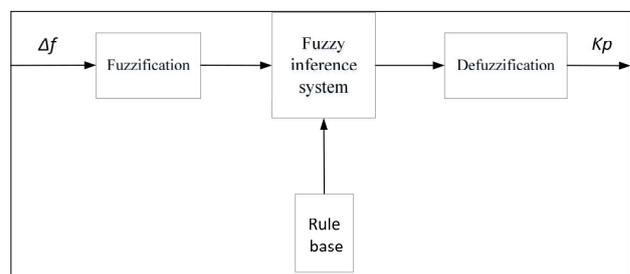


Fig. 2. Block diagram of a fuzzy inertial controller

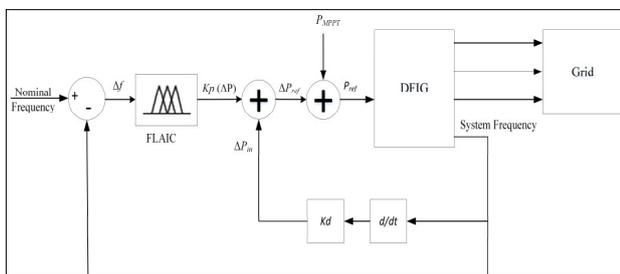
The semantic terms used for input variable membership functions are labelled as NB (Negative Big), NM (Negative Medium), and ZO (Nominal Value). In order to improve the frequency nadir resulting in a greater inertial response, the accelerating torque of the proposed controller should be cancelled so that the DFIG inertia response is restored because of the increment in the deceleration torque. Nevertheless, after the event, the proposed fuzzy controller will change the operating point of the DFIG wind turbine and will operate at a reduced speed. Therefore, the wind turbine will work away from the MPPT curve. The DFIG speed would require to return back to its optimal value during the tertiary response. Thus, an empirical determination is used to set the membership functions in order to enhance the performance of FLAIC controller, which is based on the power system frequency deviation value during the time. The output of the fuzzy logic is the value of  $Kp$  (0 - 50).

There are two MFs for the output variable, shown in Fig. 5, where the nominal value ( $Kp = 20$ ) and Big value ( $Kp = 30$ ). The proposed inertial response control loop (the output of the fuzzy controller) is the frequency deviation loop gain value  $Kp$  that computes the output of the droop loop or the frequency deviation loop  $\Delta P$ , which is the defuzzification part of the fuzzy controller. The output is defuzzified and applied to the main control system then added to the output active power reference produced via the RoCoF loop,  $\Delta P_{in}$  which provides extra active power  $\Delta P_{ref}$  to the DFIG wind turbine active power reference  $P_{ref}$ -control loop. The fuzzy control rule database consists of series IF- AND- THEN fuzzy logic condition sentences and the various rules are presented in Table 1.

**Table 1** Fuzzy Logic Rules for the Controller

$\Delta f$	NB	NM	ZO
$Kp$	Nominal	Big	Nominal

The result of the fuzzy logic is the value of  $Kp$ , and the fuzzy logic rules for the controller as follows: a large  $\Delta f$  results in a nominal value of  $Kp$ . If the value of  $\Delta f$  is medium, then  $Kp$  is large. When  $\Delta f$  is equal to zero,  $Kp$  should be 20 (nominal value). Based on work in [20], a frequency deviation loop (droop loop) has been selected as it permits entire power discharge [26]. In addition, the impact of this loop is sure and is not affected by frequency recovered noise incorporated within the measured of the system frequency [25]. This control strategy has been designed to utilise various values of frequency deviation loop gains, again based upon previous work in [20].



**Fig. 3.** Fuzzy logic- based adaptive inertial control of a DFIG

However, the frequency deviation gain value is changed online dependent on the power system frequency deviation values. The gain value of the RoCoF ( $Kd$ ) loop in the presented control is sustained whereas the frequency deviation loop gain  $Kp$  adapts automatically during the transient period, based on

the power system frequency deviation values. In this strategy, a fuzzy controller was developed to overcome the

limited contribution of the frequency deviation loop during the primary stage of a transient period. Therefore, the proposed controller actively alters  $Kp$  online based on frequency deviation values  $\Delta f$  to produce a value of  $\Delta P$  to mitigate the affect of disturbances. Therefore, the FLAIC technique produces a regulatory signal  $\Delta Kp$  to tune the parameters of the frequency deviation loop in the conventional inertial control using the fuzzy logic base rules which are designed to improve the controller performance and to avoid over- deceleration of the WTG.

The controller action can be expressed:

$$Kp = f(\Delta f) \tag{6}$$

$$\Delta P_{ref} = \Delta P + \Delta P_{in} \tag{7}$$

$$\Delta P_{ref} = Kp + Kd \frac{df}{dt} \tag{8}$$

$$\Delta P_{ref} = Kp(\Delta f) + Kd \frac{df}{dt} \tag{9}$$

$$P_{ref} = (P_{MPPT} + \Delta P + \Delta P_{in}) \tag{10}$$

$$P_{ref} = (P_{MPPT} + Kp(\Delta f) + Kd \frac{df}{dt}) \tag{11}$$

$$P_m - P_e = Jw_r \frac{dw_r}{dt} \tag{12}$$

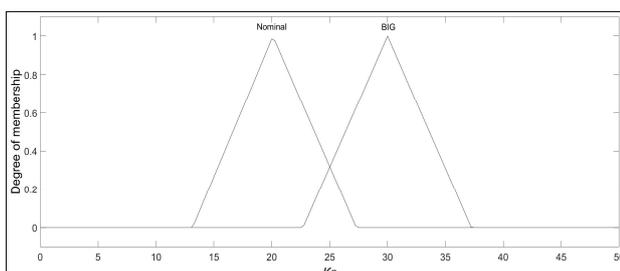
$$P_m - P_e = P_m - \left( P_{MPPT} + Kp(\Delta f) + Kd \frac{df}{dt} \right) = Jw_r \frac{dw_r}{dt} \tag{13}$$

Where  $Kp(\Delta f)$  represents the frequency deviation gain value ( $Kp$ ) which is a function of the frequency deviation ( $f_{sys} - f_{nom}$ ) respectively.

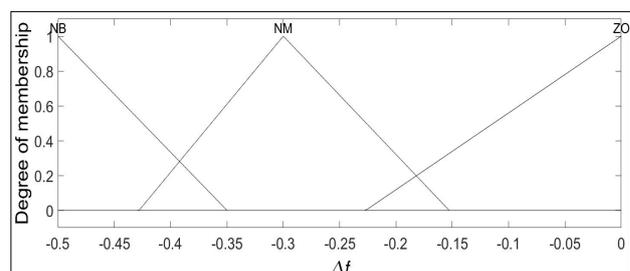
The nominal value of the frequency deviation loop gain was selected to be 20. This value is maintained when the disturbance starts at  $t = 50s$ . When the disturbance occurs, this adjustable gain control scheme value will dynamically

**Table 2** Inertial response, steady state error, frequency nadir and rotor speed value of a DFIG for different control strategy of frequency regulation

No	Wind Energy Penetration (%)	Control Scheme	Steady State Error (Hz)	Inertia Response (pu)	Frequency Nadir (Hz)	Rotor Speed (min value) (pu)
1	18.75	Conventional inertial control	-0.3514	0.7405	59.6486	1.1605
2	18.75	Active control	-0.3343	0.7686	59.6657	1.1594
3	18.75	Fuzzy logic control	-0.3235	0.7776	59.6765	1.1441
4	18.75	No control	-0.4459	N/A	59.5541	1.1998



**Fig. 4.** Membership function of the input variable



**Fig. 5.** Membership function of the output variable

responds to alterations in the power system to enhance system control and to tune its gain value to change conditions and knowledge acquired by the controller. Therefore, the FLAIC controller has the ability to respond to fluctuations in system frequency and improves the frequency nadir of the power system.

## 5. SIMULATION RESULTS AND DISCUSSIONS

### 5.1 The simulation system

Simulations have been evaluated in Matlab/Simulink environment to confirm the conventional inertial scheme and to verify the effectiveness of the proposed control strategy. The results also demonstrate the ability of the DFIG to simulate system inertia response in the event of any transient occasion such as an abrupt upsurge in load. The power system considered for this study consists of a four-machine power grid containing three traditional synchronous power generators (M1, M2, M3) are valued at 400 MW, 400 MW and 500 MW respectively, two combined loads (L1, L2) are rated at 800 MW each and a 200-unit DFIG-based wind farm rated at 300 MW (1.5 MW each). The wind speed is considered to be 12 m/s whereas the DFIG is originally under the MPPT control. In this work, only the improvement in system frequency nadir is simulated and discussed. The simulation is run for a maximum time of 100s to observe both the transient and steady-state effects. The power plant is assumed to be running in steady-state before the occurrence of disturbance at 50s.

### 5.2 Simulation results

#### 5.2.1 Case study 1 - Performance analysis of the proposed scheme

In this case study, Fig. 6 presents a comparison between the proposed fuzzy-based control with different strategies and cases under the same frequency event. Also, Table 2 demonstrate the steady state error as well as frequency nadir, whereas the inertial response to support the same level of frequency support (for the same load event) is compared for different strategies and cases. All the simulations have the same conditions, that is a step load increase of 10% pu at  $t = 50$ s and wind speed = 12 m/s. the effect of a sudden change in load is considered when the load is raised by 10% at  $t = 50$ s, as a result of an imbalance in the power system. It is assumed in this case that the nominal operating frequency is 60Hz. This causes a drop in the power system frequency, which is presented in Fig. 6(a) as there is no supplementary inertial control supplemented to the control loop of the power system, the mechanical rotor speed of modern converter controlled DFIG wind turbine is decoupled from the electrical frequency. Consequently, the DFIG presented no or negligible inertia and the power grid frequency abruptly declines to approximately 59.5541 Hz. However, the drop in system frequency was corrected by the synchronous generator although, the system frequency then rises to around 59.8398 Hz because of the integral gains of the speed controllers in the traditional synchronous generators. With no any supplementary inertial control on the DFIG based wind turbines, both the speed of the DFIG

and the DFIG active power output stays unchanged as shown in Figs. 6(b) and 6(c) respectively, with a high rate of change of frequency as depicted in Fig. 6(d). This is because the traditional synchronous generators raised their total active power output to maintain the impact of extra loading.

For the conventional inertial control, the initial PD controller gain parameters  $Kp$  and  $Kd$  are constant and set to  $Kp = 20$  and  $Kd = 10.08$ , respectively [15]. The power system is disturbed by adding a load disturbance of 10% of the total load. In real terms, the load is changed abruptly from 1600 MW to 1760 MW at 50s.

A supplementary inertial control is then added to the control loop of power system. It can be observed from Fig. 6 that once the drop in the power system frequency occurred, an extra power  $\Delta P_{ref}$  is added to the active power reference  $P_{ref}$  via raising the torque set points of the DFIG wind turbine therefore increasing the electromagnetic torque. As the wind speed is unchanged, the mechanical torque remains constant, while the rotor decelerates as given in the torque equation below, [24].

$$T_m - T_e = J \frac{dw_r}{dt} \quad (14)$$

Thus, KE will be released in this case. Fig. 6(a) demonstrates that the system frequency nadir is enhanced from 59.5541 to 59.6468 Hz, due to the abrupt rise in the electrical active output power. As the DFIG mechanical torque power is smaller than its electromagnetic torque power, the rotor speed will drop as seen in Fig. 6(b). In Fig. 6(c), the DFIG raises its output active power from 0.6482 pu to 0.74 pu. As observed, the frequency response has a significant decline without support from wind generation; the inertial scheme enhances the system frequency nadir whilst decreasing the RoCoF. The wind turbine will stall on the occasion that frequency continues to fall, and if the electromagnetic power endures larger than the mechanical power. Thus, in power systems, in case of any significant variations in system frequency, the DFIG output active power must be dynamically regulated to prevent wind turbine stalling.

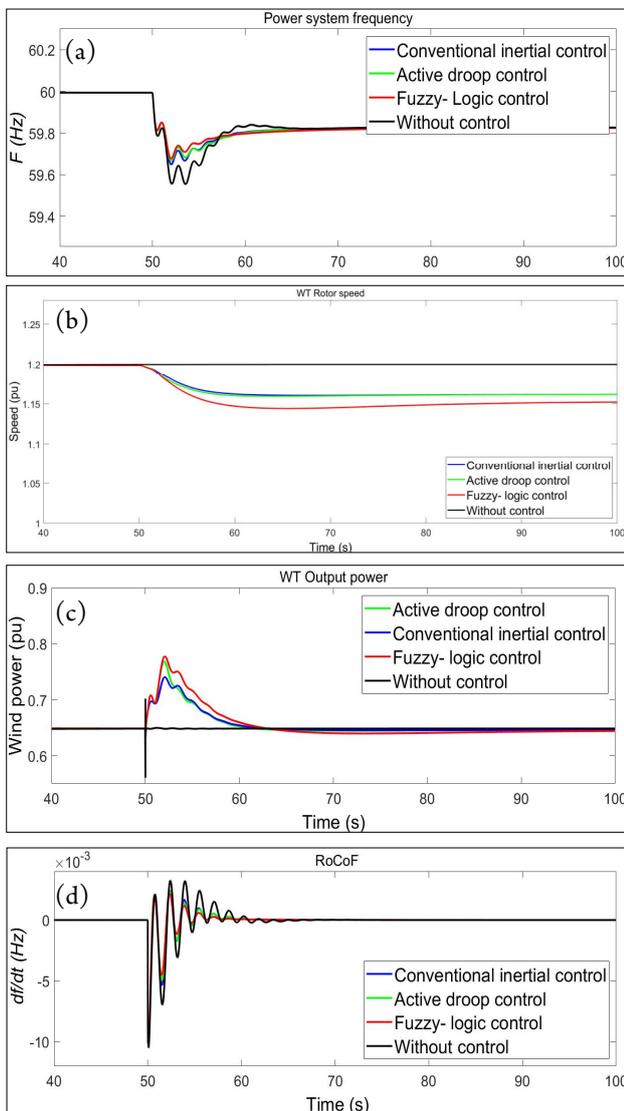
The effect of the proposed control block is investigated by simulating the drop in the power system frequency, the gain value of  $Kd$  will remain constant while the proposed control scheme adjusts the parameter  $Kp$  automatically based on the system's frequency response. Fig. 6(a) illustrates that the frequency nadir improves to 59.6765 Hz compared to 59.6486 Hz, in the case of a conventional inertial controller. Moreover, with the implementation of the proposed control scheme, the power system frequency exhibits less overshoot. The rotor speed will decrease more, see Fig. 6(b) and the DFIG wind turbine releases the KE to increase its output active power from 0.74 pu to 0.7776 pu as shown in 6(c).

The results additionally demonstrate that the proposed scheme has the ability to reduce the RoCoF as seen in Fig. 6 (d). The frequency nadir increases while the decline in the rate of change of frequency (RoCoF) is further enhanced. Fig. 7 illustrates the fuzzy output signal, which shows changes in  $Kp$  based on the system frequency deviation from its nominal value. During the steady state period, and if the

difference between system frequency and nominal frequency  $\Delta f$  is large,  $K_p$  remains at its nominal value of 20, whereas the proposed controller adapts the magnitude of  $K_p$  gradually when  $\Delta f$  is at its medium value based on the maximum acceptable deviation value for the system frequency during the disturbance event, as shown in Fig. 7. The range of the frequency deviation value is  $[-0.5\ 0]$ .

Table 2 shows the frequency profile with the proposed control performing better than the conventional inertial control. All parameters including the frequency nadir, steady state error, inertial response and rotor speed demonstrate improvements.

The proposed fuzzy logic-based control is also compared with the previous work in [20] where an active control strategy (based on manual tuning) was introduced for frequency control utilizing varying gains in the frequency deviation loop for the supplementary inertial scheme.



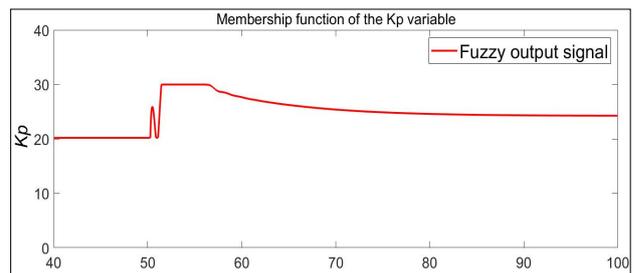
**Fig. 6.** Power sharing under frequency event for different control strategies (a) Power system frequency (b) rotor speed variation (c) DFIG active power output (d) RoCoF

Fig. 6 illustrates a comparison between an active strategy in [20] with the proposed control in this work. The system frequency nadir is enhanced from 59.6657 Hz to

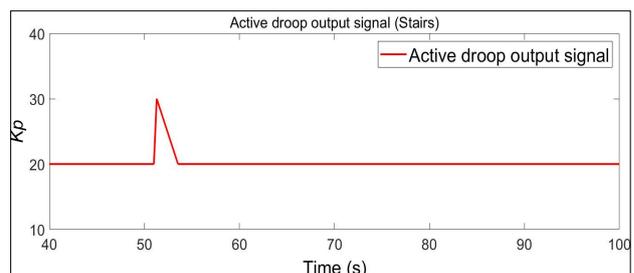
59.6765 Hz. Therefore, the frequency nadir of the proposed control is larger than that of an active control by 0.0108 Hz. Furthermore, in the situation of the suggested control, the frequency oscillation as well as overshoot are both improved, in comparison to an active control strategy as shown in Fig 6 (a). Thus, the wind turbine rotor speed will decline to a value inside the operating limit, therefore reducing further than the active control scheme reaching 1.1414 pu; however for the active controller scheme, the rotor speed changes to 1.1594 Pu as seen in Fig. 6(b). The inertial response of the supplementary scheme is greater than that of an active scheme by 0.0090 see Fig. 6(c). In addition, the RoCoF of the proposed scheme is shown to be better than that of an active controller as depicted in Fig 6 (d). The new controller approach is adept to deliver applicable frequency regulation whilst reducing the RoCoF. Fig 8 depicts the active control output signal of an adaptive gain, which was created to overcome the restricted contribution of frequency deviation loops throughout the primary stage of the transient period. Therefore, the proposed controller actively varies its gain value for the duration of the transient period based on the  $\Delta f$  to reach a large value of  $\Delta P$ . During the initial stage of an event the droop gain should be large and decrease its value with time to prevent over-deceleration of a WTG. The primary value of the droop gain is designed to be 20.

This value maintains constant once the event starts at  $t = 50$ s. At  $t = 51.3$ s, the frequency deviation loop gain value reaches 30 which is next gradually reduced along with time till it attains the primary gain value of 20 at  $t = 53.54$ s.

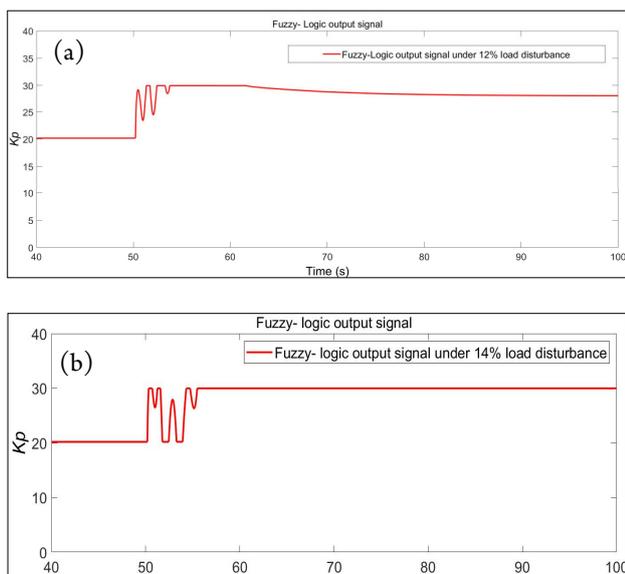
As shown in Fig 6(a) and Table 2, the system frequency nadir is greater for the proposed scheme whereas the steady state error and the overshoot parameters are also improved. This is due to a higher inertial response with the proposed scheme. The proposed FLAIC proposal be able to maintain the system frequency nadir and ensure stable operation of a DFIG by utilizing the variable gain control approach. It is therefore demonstrated that DFIG wind turbines can regulate system frequency and control system inertia.



**Fig. 7.** Fuzzy controller output showing  $K_p$  adaptation



**Fig. 8.** An active shaping function of the  $K_p$  variable



**Fig. 9.** Fuzzy controller output showing  $K_p$  adaptation for the proposed control under 12% and 14% load disturbance (a) Fuzzy controller output showing  $K_p$  adaptation under 12% load disturbance (b) Fuzzy controller output showing  $K_p$  adaptation under 14% load disturbance

*5.2.2 Case study 2 - The proposed inertial scheme performance under a different load disturbance*

In this case study, the system frequency event is created by adding a load disturbance between 5% and 23% of the existing nominal load. The fuzzy logic system proposed earlier is the same as use in Case study 1. Fig.9 (a) and 9 (b) illustrate typical outputs of the proposed fuzzy control scheme for a 12% and 14% increase in load, respectively. It can be seen that the controller parameter  $K_p$  is adaptively adjusted to respond to system frequency changes.

Fig. 10 illustrates the response of system frequency, inertial response, rotor speed and RoCoF under 5%, 10% and 14% load disturbances. These were acquired to verify system performance of the proposed scheme. For comparison, the system response of the conventional inertial control and the proposed scheme are shown in the same figure.

As shown, the frequency response of the fuzzy control (compared to the conventional control) was improved as shown in Fig.10 (a). Table 3 shows the frequency nadir for the conventional inertial control and the proposed scheme respectively for different amounts of load disturbance with the steady state frequency error, system inertial response, frequency nadir and the rotor speed for 10 altered values of load disturbance. In Fig.10 (a), the minimum frequency (see Table 3) is enhanced as the load value increases; the system frequency nadir improves and hence the system performance is shown in Table 3. Also, the rotor speed is within the secure operating range using the proposed controller, Fig.10 (b). Moreover, the total KE released is greater by as much as 7% as compared to that of the conventional control; however, it increases slightly as given in Table 3, Fig. 10(c). The steady state frequency error is less with the proposed control. The maximum RoCoF is similar for both schemes for all different values of load disturbance because the RoCoF loop gain in the proposed scheme is kept constant. The RoCoF for all the load variations is also depicted in Fig. 10(d).

From both Fig. 10 and Table 3, it can be detected that the proposed fuzzy-based scheme of the DFIG demonstrates better performance than the conventional control during any load disturbance event. Thus, the frequency regulation improves and the frequency nadir increases but RoCoF is unaffected, as explained above.

**Table 3** Steady state error, inertial response, frequency nadir and rotor speed values of the conventional control and the proposed scheme under different amount of load disturbances

No	Control Type	Load Disturbance (%)	Load Value (MW)	Steady State Frequency Error (Hz)	Inertia Response (pu)	Frequency Nadir (Hz)	Rotor Speed (min value) (pu)
1	Conventional	5	80	-0.1739	0.6538	59.8261	1.1795
	Fuzzy			-0.171	0.7001	59.829	1.1792
2	Conventional	10	160	-0.3514	0.7405	59.6486	1.1605
	Fuzzy			-0.3235	0.7776	59.6765	1.1441
3	Conventional	11	176	-0.3902	0.7508	59.6098	1.1567
	Fuzzy			-0.357	0.7892	59.643	1.136
4	Conventional	12	192	-0.4295	0.7613	59.5705	1.1529
	Fuzzy			-0.3984	0.786	59.6016	1.1281
5	Conventional	13	208	-0.4693	0.7718	59.5307	1.1491
	Fuzzy			-0.4454	0.7824	59.5546	1.1207
6	Conventional	14	224	-0.5092	0.7824	59.4908	1.1453
	Fuzzy			-0.4864	0.7826	59.5136	1.1144
7	Conventional	15	240	-0.5492	0.7929	59.4508	1.1415
	Fuzzy			-0.5258	0.787	59.4742	1.1081
8	Conventional	18	288	-0.6679	0.8243	59.3321	1.1303
	Fuzzy			-0.6272	0.8492	59.3728	1.0886
9	Conventional	20	320	-0.7457	0.8448	59.2543	1.123
	Fuzzy			-0.6941	0.8735	59.3059	1.0755
10	Conventional	23	368	-0.8625	0.8754	59.1375	1.1122
	Fuzzy			-0.8075	0.9124	59.1925	1.0625

To investigate the efficacy of the proposed scheme and to validate system performance, the system frequency, rotor speed response, inertial response and RoCoF under 12% load disturbance for three different approaches were analyzed and illustrated in Fig. 11. All simulation conditions are the same for all approaches, that is a load disturbance of 12% at  $t = 50$ s and wind speed = 12m/s. Fig. 9(a) depicts the fuzzy output signal for the proposed scheme; the frequency deviation gain is repeatedly tuned online to respond to system frequency deviation to enhance the system performance of the power scheme in comparison to 59.5911Hz and 59.5705Hz in the case of the adaptive and conventional control, respectively. The frequency nadir is positively enhanced and drops to 59.6016Hz for the proposed scheme, Fig. 11(a).

The rotor speed response decreases in the case of the proposed scheme and is preserved under the operating range as shown in Fig. 11(b). The total KE released is identical for the conventional and active schemes and smaller than the proposed scheme until  $t = 51$ s.

The output active power are 0.7613 pu, 0.786 pu and 0.795 pu for the conventional, FLAIC and active schemes respectively. However, the proposed scheme provides additional inertial response than the other two approaches for a longer period of time as shown in Fig. 11(c). Also, the results demonstrate that the proposed scheme has a very small impact on the RoCoF. The frequency falls at a same peak rate of -0.0121 Hz/s for the three approaches. However, during recovery period, frequency oscillations are lower and have a faster settling time as compared to those for the conventional and active schemes, as seen in Fig. 11(d).

5.2.3 Case study 3 - Frequency response with increasing levels of wind penetration

a. Inertial response and the RoCoF in power system with different levels of wind Penetration

Most large-scale wind turbines that have been integrated into power systems are DFIGs.. In this case, the first assumption is that the WTGs supply no inertial response. Therefore, with an increase in the installations of DFIG based wind turbine displacing traditional power plants, which have the capability of providing an inertial response. However, the changes in system frequency due to the fluctuations of wind turbine generator causes a series of problems such as increasing the RoCoF and reduction of the overall inertial response.

The power system in this chosen case is assumed to be in steady state before the occurrence of a load disturbance event on the system. At 50s, similar to the previous cases, the load is raised from 1600 MW to 1760 MW. The power system frequency and the peak rate of change of frequency (RoCoF) for different levels of wind penetration are simulated and illustrated in two scenarios, as shown in Figs. 12, 13, 14 and 15.

(i) DFIG without an inertial response

In the base case, when no wind power is being produced, the frequency nadir drops to 59.6683 Hz as shown in Fig. 12.

When the wind turbine generators increase the wind power penetration to 18% and 25% of output power, the

frequency nadir is 59.5541 Hz and 59.5353 Hz respectively, (see Fig. 12). In the same figure it is apparent that the frequency nadir declines further to 59.4987 Hz as the power generated by WTGs is increased to 35% of output power. The impact of the reduction in the system inertia due to an increase in the penetration of wind generation is also illustrated in Fig. 13. When the system inertia is reduced, the peak RoCoF increases from -0.0106 Hz/s for no wind generation to -0.112 Hz/s when the wind penetration is 50% of output power. In the case of wind turbines producing no inertia, any contribution of the wind generation into the system has a negative influence on the system frequency nadir. As the level of wind penetration increases, the drop in the system frequency will rise. From Fig. 12 and Fig. 13 it is apparent that a significant increase in the frequency deviation and RoCoF can be critically important as this can lead to additional losses of generated power, thus increasing the risk of a potential system breakdown, [2].

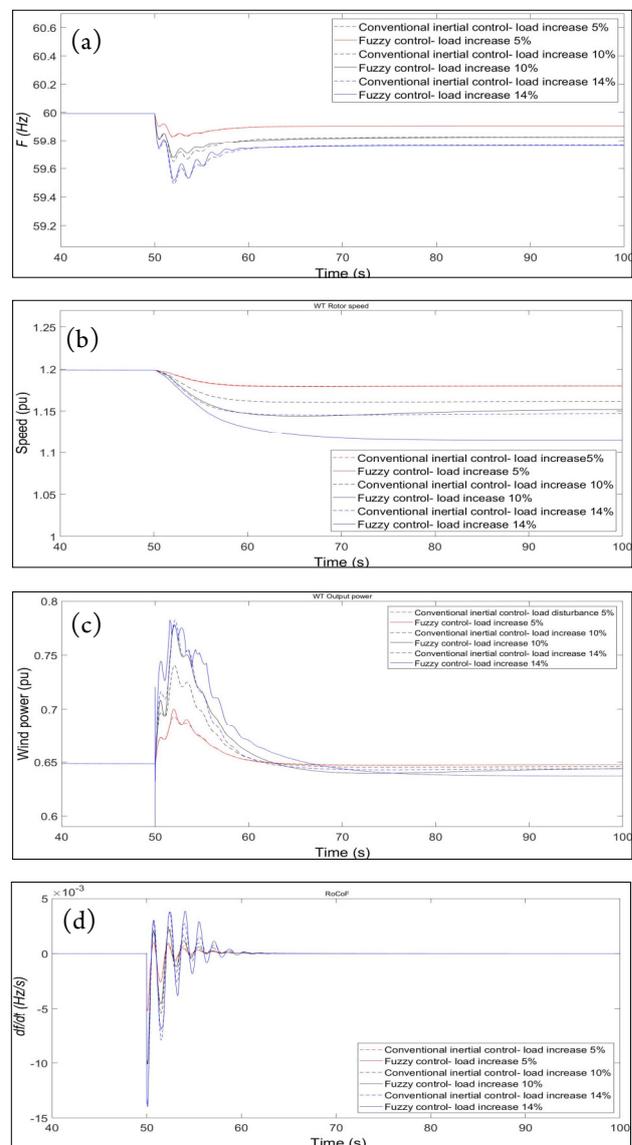
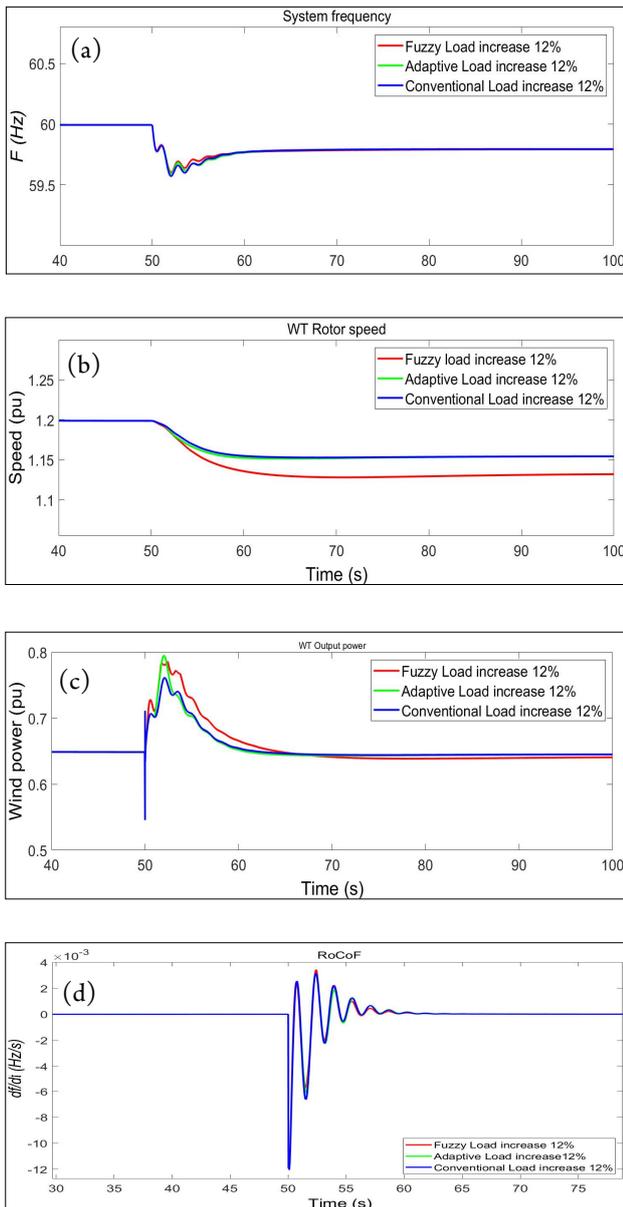


Fig. 10. Frequency response, rotor speed response and inertial response for the conventional control and the proposed scheme under different amount of load disturbances (a) Power system frequency (b) Rotor speed variation (c) DFIC active power output (d) RoCoF



**Fig. 11.** Power system frequency response for a load disturbance for different cases under the same amount of load disturbance (a) Power system frequency (b) Rotor speed variation (c) DFIC active power output (d) RoCoF

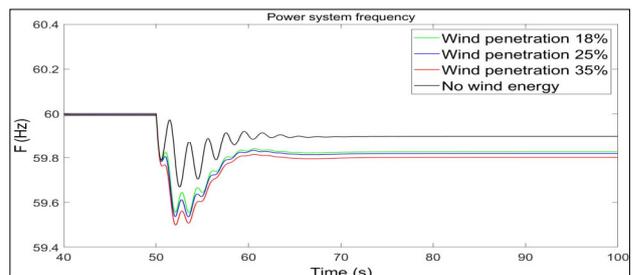
(ii) DFIG with an inertial response

In this scenario, it is assumed that all DFIG wind turbines provide an inertial response as suggested in [15]. When no output power is being produced by DFIG wind turbines, the system frequency nadir drops to 59.6672 Hz. The augmented load is then recompensed via the traditional synchronous generator with its associated inertia as shown in Fig. 14. Therefore, when the wind turbines generate 18% of the total output power, the system frequency nadir drops to 59.6552 Hz.

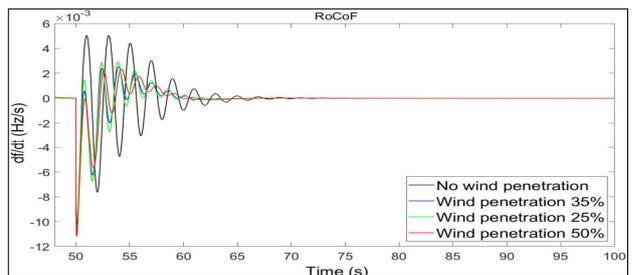
As such, DFIG output power displaces only a small fraction of the conventional generation with its combined inertia while the DFIG wind turbines still provide the full inertial response. When DFIG wind turbines produces 25% of the total output power, the system frequency nadir falls greater and reached 59.6331 Hz. At a wind power penetra-

tion of 35% of the full output power, the nadir has dropped further to 59.5954 Hz, (see Fig. 14).

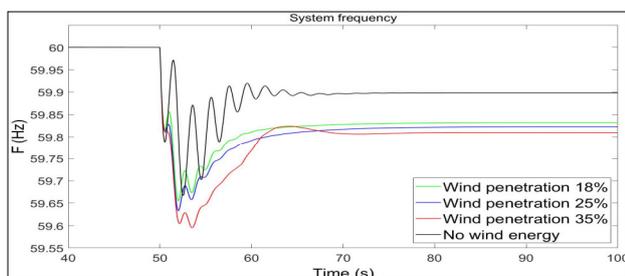
Fig.15 depicts the maximum RoCoF at different levels of wind penetration producing an inertial response. It is apparent that when the wind penetration is 25% of the total output, the RoCoF is  $-0.0102$  Hz/s, compared to  $-0.0106$  Hz/s for the case when DFIG wind turbines provide no wind power. The peak RoCoF is  $-0.0104$  Hz/s, when the wind turbines produced 35% of the total output power. At a wind penetration of 50% of the total output power, the peak RoCoF also maintains approximately the same value reaching  $-0.0107$  Hz/s. From the results in Fig. 12 to Fig. 15, it can be observed that in the case of wind turbines producing no inertia, any wind power connected to the system has a negative effect on the frequency nadir, and this disadvantage will be equivalent to the amount of wind power being produced. Nevertheless, if the wind plants are assumed to supply an inertial response, it benefits the supplementary inertial response. The primary RoCoF with increasing wind power penetration for the scenarios with an inertial response provided by the wind plants, at which the frequency drops will not be affected. In addition, the system frequency nadir and the RoCoF for the scenario with and without an inertial response is nearly the same when no wind generation is connected to the system. If the wind generators provide an inertial response, the additional inertial contribution improves the system frequency nadir. The increasing amount of wind generation is combined with the further decline in the frequency nadir. The RoCoF with increasing levels of wind penetration for the case with an inertial response are almost the same. Therefore, from the results above, it can be observed that the additional inertial response will improve the frequency deviation although this will not impact on the maximum RoCoF. Additional inertia, derived from flywheel technology, for example, is necessary to decrease the initial RoCoF [31].



**Fig. 12.** Power system frequency with wind turbines producing no inertial response



**Fig. 13.** RoCoF for a 10% load disturbance with wind turbines producing no inertial response

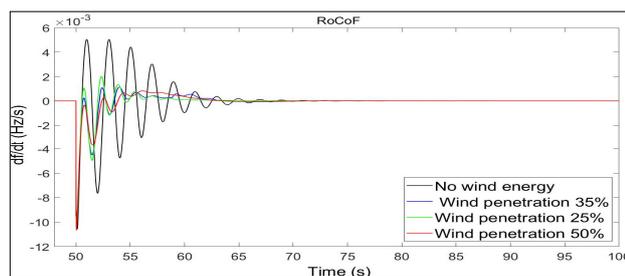


**Fig. 14.** Power system frequency with wind turbines producing an inertial response

*b. Performance of the Proposed Scheme with Higher Penetration Levels of Wind Generation*

A DFIG operating at a higher rotor speed is capable of reaching optimal efficiency for a diverse range of windspeeds, so it is modified to vary the wind turbine rotor speed continuously and thus the DFIG active power output at various wind speeds.

Therefore, a DFIG contains more releasable KE than operating in a lower rotor speed region [24]. In order to verify the effectiveness of the proposed scheme of the DFIG wind system in case of higher levels of wind penetration, a simulation study has been performed using a 45% of the rated output power generated by the DFIG wind turbines.



**Fig. 15.** RoCoF for a 10% load disturbance with wind turbines producing an inertial response

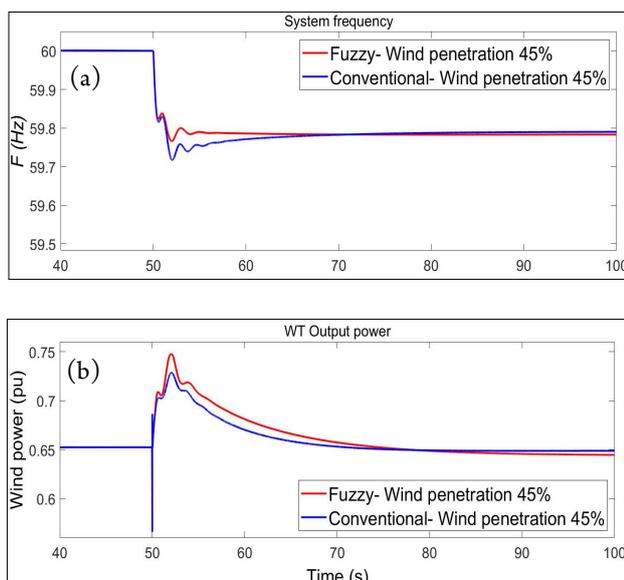
Fig. 16(a) represents the power system frequency under the event of the load disturbance at  $t = 50s$ . The system frequency nadir is improved from 59.7168 Hz in the case of the conventional inertial control to 59.766 Hz for the proposed scheme. The rotor speed decreases further whilst the wind turbine releases further KE as depicted in Fig. 16 (b); however the RoCoF is nearly the same.

Table 4 presents the numerical results of the comparison between the conventional inertial control and the proposed scheme. The proposed scheme effectively improved the system frequency nadir, as the former controller uses the  $\Delta f$  frequency deviation loop ( $f_{nom} - f_{sys}$ ) as the input to the fuzzy controller due to the fact that more total energy is discharged by using the frequency deviation loop for frequency regulation. Another advantage of the proposed scheme is that during the recovery period, frequency overshoot and oscillations are managed, compared to that of the conventional scheme (Fig. 16(a)). The maximum RoCoF is equivalent to that of the conventional controller since the RoCoF loop gain is maintained whilst the  $\Delta f$  loop uses a variable gain. To improve the maximum RoCoF, its loop gain needs to be further tuned. Although correlated to the conventional controller, the frequency improvement is accompanied by faster settling times of frequency oscillations to the steady-state error values (see Table 4).

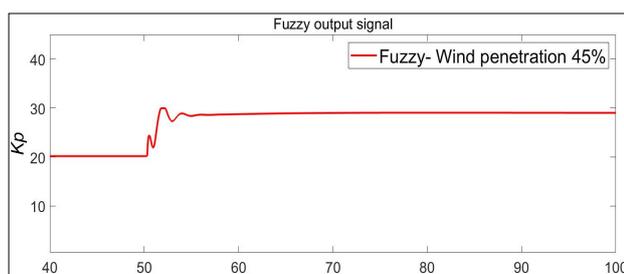
Fig. 17 depicts the fuzzy-logic output signal for the proposed controller. During the steady state period,  $Kp$  was 20; however, the controller was automatically adjusted once the disturbance occurred. The value of  $Kp$  was constantly tweaked according to system changes in order to improve the system performance. It can be observed from the results that the proposed controller effectively enhances the frequency nadir but reduces the RoCoF marginally and does not have a great effect on it.

**Table 4** Steady state error, inertial response, frequency nadir and rotor speed values of the conventional scheme and the proposed scheme for different levels of wind penetration

No	Control Type	Wind Penetration (%)	Wind Energy Value (MW)	Steady State Frequency Error (Hz)	Inertia Response (pu)	Frequency Nadir (Hz)	Rotor Speed (min value) (pu)
1	Conventional	5	80	-0.3691	0.7483	59.6309	1.167
	Fuzzy			-0.3593	0.7927	59.6407	1.154
2	Conventional	10	160	-0.37	0.7504	59.63	1.1644
	Fuzzy			-0.3518	0.7935	59.6482	1.1504
3	Conventional	15	240	-0.3677	0.7494	59.6323	1.1613
	Fuzzy			-0.3421	0.7935	59.6579	1.1452
4	Conventional	18	288	-0.3564	0.7479	59.6436	1.161
	Fuzzy			-0.328	0.7854	59.672	1.1449
5	Conventional	25	400	-0.3375	0.7434	59.6625	1.159
	Fuzzy			-0.3024	0.7758	59.6976	1.1412
6	Conventional	35	560	-0.2892	0.7313	59.7108	1.1627
	Fuzzy			-0.2523	0.7566	59.7477	1.151
7	Conventional	45	720	-0.2832	0.7286	59.7168	1.1533
	Fuzzy			-0.234	0.7478	59.766	1.1273



**Fig. 16.** Response of a DFIG for the proposed scheme to a drop in network frequency with higher penetration levels of wind generation (a) Power system frequency (b) DFIG active power output



**Fig. 17.** Fuzzy controller output showing  $K_p$  adaptation with 45% wind penetration

## 6. CONCLUSION

This paper introduces a fuzzy logic adaptive controller scheme for DFIG wind turbine for online tuning of the PD type inertial controller parameters. With the proposed structure and tuning algorithms, the gain parameters of the frequency deviation loop (droop loop) of the supplementary inertial controller of the DFIG wind turbine can be tuned online and adapted automatically to avoid the system frequency from falling too low, while maintaining the rotor speed within a safe operating range. Therefore, the active power output of the DFIG can be controlled and the frequency variation due to load changes can be restrained.

The frequency deviation loop is used as the input signal of the proposed fuzzy control, which determines a new value of  $K_p$  depending on the input range. Two scenarios are investigated and analysed, in which all, or none of wind turbines provide an inertial response with varying levels of wind penetration after a frequency transient. In the case of wind turbines providing no inertial response, a significant increase in the frequency deviation is observed whilst the frequency nadir declines further as the level of wind penetration increases.

Conversely, wind turbines capable of providing an inertial response can contribute to system inertia, thus enhancing the system frequency response. The simulation and results exemplify and validate the effectiveness of the proposed controller parameter tuning method. The proposed scheme demonstrates that an adaptive controller can actively respond to the frequency variation of power system to enhance control performance in comparison with a conventional inertial controller widely used in power systems. Moreover, the robustness of the proposed control is greater than that of the traditional inertial scheme, as evidenced by results and analyses presented herein.

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