An Analytical method for detecting instability in grid-connected doubly-fed induction generator

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Abstract
Doubly-fed induction generator (DFIG) is among the most attractive technologies in wind farms. As the penetration of wind power into the grid has increased in recent years, protecting of wind farm's generators against grid disturbances has become a major issue for the power system industry. Transient instability (TI) is among the most frequent phenomena due to severe grid disturbances. This phenomenon might cause significant damages to network equipment. In DFIG based wind turbine (WT), when the crowbar circuit is activated, the rotor winding is short-circuited and the power converter is blocked. At this moment, the DFIG operational mode is temporarily changed to squirrel-cage induction generator (SCIG). This lead to reactive power absorption and voltage drop, that might cause electromechanical oscillations and unstable condition. This study presents an analytical method for detection TI of a grid-connected DFIG based on analysis of angular velocity and acceleration data, which are readily obtained from locally measured quantities. This technique works on a setting-free manner, i.e. revising would not be required even when the network configuration changes, which is a favourable feature in protective relaying. The performance of the proposed method is verified using MATLAB/Simulink. Simulation results prove the method's reliability and simplicity.

1 | INTRODUCTION

Reducing fossil fuels, rising greenhouse gases and global warming are among the most important challenges the governments are facing in recent years. These environmental concerns attract more attention to renewable energy resources. The global wind energy council predicts that about 50% of the world’s power consumption will be provided by renewable energies by 2050. It is also reported that the European Union plans to reduce greenhouse gas emissions to about 80% below 1990 levels by 2050, focusing on renewable energy resources [1]. Among various renewable resources, wind energy has developed rapidly throughout the world because of such benefits as cleanliness, availability and affordability [1]. In the last decades, wind farms widely employed a variety of technologies for converting wind power to electricity. Doubly-fed induction generator (DFIG) is among the most well-known technologies used in wind power plants. The main advantages of DFIG are independent control of active and reactive power, improving power quality, its ability to keep the output frequency constant while working at different wind speeds, lower mechanical stresses than fixed-speed wind generators and using smaller and cheaper power converter in comparison with other employed technologies [2, 3].

Like other grid-connected generators, DFIGs are inherently susceptible to network severe disturbances. These disturbances might be caused by such reasons as short-circuit, load shedding and so on [4]. Thus, it is quite obvious that DFIG based wind turbines (WTs) need specific protection circuits to protect them against grid faults [5–8]. In this regard, various protection systems are proposed in recent years, that the crowbar circuit is the most commonly used protection schemes in the
wind farms [5]. During network faults, the rotor winding and the power converter are protected by crowbar circuit against excessive over-voltages and over-currents. As the network voltage drops, the crowbar circuit turns on and detaches the power converter from the rotor slip-ring. Subsequently, rotor windings are short-circuited through the crowbar resistors, and finally, the rotor current is bypassed. Hence, there is no control on both delivered active and reactive powers and the DFIG operational mode temporarily changes to squirrel-cage induction generator (SCIG) [5, 6]. Under this transient condition, the equilibrium between mechanical and electrical energy is lost, which results in electromechanical oscillations and acceleration of the rotor [6]. These oscillations might cause the unstable condition, and therefore the DFIG must be tripped off from the network [8]. Accordingly, accurate detection of transient instability (TI) in grid-connected DFIG based WTs can be considered a major concern in wind power plants.

Due to the high installation of conventional power plants in power systems, most of existing TI detection studies have focused on synchronous generators (SGs). So, it is worthwhile to review some of them. In literature, the use of the angular velocity and acceleration data obtained from various parameters of electric machines are suggested in refs. [9–11]. Ref. [9] has used direct measurement of the rotor’s angular velocity to identify the unstable condition. For this purpose, sensors are inserted inside the machine to measure the required data. Considering the cons of the utilised approach, it has some drawbacks such as the use of sensors, special circuits and the synchronous measurement of data. Additionally, angular velocity measurement is affected by the torsional oscillations of the rotor that challenges this technique. In ref. [10], the author has used the frequency deviation of the measured voltage from the generator terminals. Then the angular velocity and acceleration are taken from the voltage phasor. However, it is worth noting that the switching transients in the power grid will affect the measured voltage. In order to improve the previous method, magnetic flux is offered in ref. [11]. The main principle of this method arises from the fact that since electrical machines have high magnetic characteristics, they are not affected by switching transients. Despite the fact that another advantage of this technique is its fast performance in detecting instability, it is of crucial importance to note that the magnetic flux measurement is difficult and sensors should be mounted inside the machine.

On the other hand, the merit of using active power for detecting TI of grid-connected generators has already been proven [12–14]. For example, many articles use the equal area criterion (EAC) method for detecting instability in SGs. The EAC method is actually a benchmark of how long the SG can withstand severe disturbances and then return to its stable condition after the fault clearance. It should be noted that in this method, the active power versus power angle profile of the SG is used along with the swing equation to calculate the machine’s stability boundary and the critical clearing time [12]. In ref. [13], this technique was implemented on a multi-machine system between the state of Georgia and Florida in the United States. However, determining the power angle of the generators had its own problems and required extensive system stability studies and a lot of communication tools. To overcome the problems associated with the power angle measurement, ref. [14] proposes the power-time curve instead of that mentioned in the previous method. Although this detection technique is simple, the identification process here is graphically performed by a point-by-point examination, which can relatively prolong the decision time.

So far, there are a few studies on transient stability assessment of the DFIG [12]. In ref. [15] a comparative study is carried out between DFIG’s transient behaviour and that of other generators used in power systems such as SCIG and SG. This paper has used the transient stability index (TSI) based on the transient energy function (TEF). However, because of its complex calculations of critical energy, it is difficult to implement this approach on a multi-machine system with a detailed model of equipment [15, 16]. In ref. [12], an EAC’s equivalent is suggested for stability assessment and critical clearing time determination for induction generators such as DFIG. According to this research, the implementation of EAC used in transient stability studies of SGs is not suitable for DFIGs. Its main reason is lack of connection between the mechanical angle of the DFIG and the electrical angle between the DFIG and the network.

This paper proposes a new setting-free identification method for detecting instability in grid-connected DFIG based WTs using local variables. The aim of proposing a setting-free method is the independence of the decision-making criterion from network configuration, equivalent machine parameters and even the fault clearing time. This means no revision is needed from one network to another network, which is an interesting feature in protective relaying. The angular velocity and acceleration data are simply obtained from the generator output voltages and currents to identify the unstable condition. The main advantages of this method are its independence upon the fault clearing time and network configuration. In brief, the main contributions of this study are as below:

- Developing a TI detection algorithm suitable for grid-connected DFIG based on analysis of three-phase active power which avoids complex system studies and extensive offline calculations.
- Propose an approach which would be applied directly to a multi-machine power system without any network reduction.
- Developing a setting-free technique based on only the local electrical quantities accessible at the generator terminal and therefore abstains from the need for any extra measurement devices.

The performance of the proposed algorithm is tested on both a single-machine infinite bus (SMIB) model and a three-machine infinite bus (TMIB) test system using MATLAB/simulink software. The simulation is carried out for a variety of scenarios. Simulation results show the satisfactory and reliable performance of this method under various pre-fault slips, load conditions etc.
2 WIND TURBINE-GENERATOR SYSTEM MODELLING

In the following section, the model of the WT-generator system for transient stability studies is expressed.

2.1 Wind turbine modelling

The most important issue in WT modelling is to calculate the amount of power received from the wind. It is clearly understandable that there is a direct relationship between wind power and its velocity. In a region, the wind speed constantly changes during the day, which can affect the power extracted from the wind. Even though various mathematical models of WTs are presented so far, simplified WT models are usually used to study the electrical behaviour of WT systems. A simple and typical mathematical formula to express the mechanical power received by a WT can be calculated as follows [7, 17]:

\[ P_m = \frac{\rho}{2} \pi r^2 v_w C_p(\gamma, \beta), \]

where \( P_m \) is the absorbed power by the turbine (W), \( \rho \) is the air density (kg m\(^{-3}\)), \( r \) denotes the radius of the area covered by the blades (m), \( v_w \) is the wind speed (m s\(^{-1}\)) and \( C_p \) is the power coefficient which is a function of both tip-speed ratio \( \gamma \) and blade pitch angle \( \beta \). It is defined as below [17, 18]:

\[ C_p(\gamma, \beta) = \frac{1}{2} (\gamma - 0.022\gamma^2 - 5.6)e^{-0.17\gamma}, \]

\( \gamma = \frac{v_r}{v_w}. \)

where \( v_r \) is the angular velocity of the turbine.

The mathematical model of the drive train can be obtained by the following differential equation [17, 19, 20]:

\[ \frac{d^2 \delta}{dt^2} = \frac{w_0}{2H}(P_m - P_c), \]

\[ = \frac{\pi f_0}{H}(P_m - P_c). \]

In Equation (4), \( H \) stands for the generator inertia constant, \( \delta \) is the rotor angle, \( w_0 \) is the nominal angular velocity of the network and \( P_c \) is the electrical output power.

2.2 Dynamic modelling of healthy doubly-fed induction generator

In the literature, there are many research works on the dynamic modelling of DFIG [17, 21]. Most of them have used the rotating reference frame theory with Park and Clarke transformations.

Assuming the balanced performance of the generator, since DFIG can be considered as a kind of traditional wound rotor induction machine (WRIM) with non-zero rotor voltage, its full-order dynamic model in \( d-q \) synchronously rotating reference frame can be expressed as below [21]:

\[ V_{dq} = R_i i_{dq} + \frac{d\lambda_{dq}}{dt} - w_s \lambda_{ds}, \]

\[ V_{qs} = R_i i_{qs} + \frac{d\lambda_{qs}}{dt} + w_s \lambda_{ds}, \]

\[ V_{dr} = R_i i_{dr} + \frac{d\lambda_{dr}}{dt} - (w_e - w_s) \lambda_{dq}, \]

\[ V_{qr} = R_i i_{qr} + \frac{d\lambda_{qr}}{dt} + (w_e - w_s) \lambda_{ds}. \]

where the subscripts \( s \) and \( r \) represent the variables of stator and rotor sides, \( R \) is the resistance, \( V \) and \( i \) are voltage and current, respectively, and \( w \) is the angular velocity. \( \lambda \) is the magnetic flux linkage of its related equations can be written as follows:

\[ \lambda_{ds} = L_s i_{ds} + L_m i_{dr}, \]

\[ \lambda_{qs} = L_s i_{qs} + L_m i_{qr}, \]

\[ \lambda_{dr} = L_s i_{dr} + L_m i_{ds}, \]

\[ \lambda_{qr} = L_s i_{qr} + L_m i_{qs}, \]

\[ L_s = L_m + L_{dr}, \]

\[ L_q = L_m + L_{qr}, \]

where \( L_m \) denotes the magnetising inductance, \( L_s \) and \( L_q \) are the rotor and stator inductances, \( L_{dr} \) and \( L_{qr} \) are also the rotor and stator leakage inductances. The electrical output power and reactive power at the stator terminal might also be calculated as [22]:

\[ P_e = \frac{3}{2} L_m V_e i_{qr}, \]

\[ Q_e = \frac{3}{2} V_e \left( \frac{L_m}{L_s} i_{dr} - \frac{V_e}{\omega_s L_m} \right). \]

where \( \rho \) is the number of pole pairs.

2.3 Power converter modelling

As mentioned earlier, DFIG is a WRIM connected to the grid via a step-up transformer, and its rotor winding is fed by an AC/DC/AC power converter that also connects to the grid. General configuration of a grid-connected DFIG is depicted in Figure 1(a). Various types of power converters used in DFIGs are reviewed in ref. [23]. The most commonly used power converter in the wind power industry is the back-to-back converter. This converter is employed to control the active and reactive power...
power independently and to keep the output frequency constant in a relatively high slip (about ± 0.3 of the nominal speed) [24].

As shown in Figure 1(a), this power converter consists of two main parts, the rotor side converter (RSC) and the grid side converter (GSC). Each part comprises of a bi-directional full-bridge converter with six controllable switches. These two parts are connected together through the DC-link capacitor [23]. This capacitor is used to smooth out the voltage variations [7]. The RSC regulates both the active and reactive power independently. The task of the GSC is to maintain the DC-link voltage constant. Furthermore, the balance of exchanging reactive power between both sides of the DC-link capacitor is ensured by the GSC. It is worth saying that to achieve these aims, the vector control method is used [24]. The general control scheme of the RSC and GSC are shown in Figsue 1b and 1c, respectively.

2.4 | Crowbar protection circuit

As stated previously, DFIG based WTIs are relatively high sensitive to severe grid disturbances. Therefore, special methods are used to protect them against excessive over-voltages and over-currents that might occur due to high transient voltage drops at the point of common coupling (PCC) [6]. Some of these methods are investigated in ref. [5]. In the wind power industry, the most famous solution to ride-through severe grid disturbances is the crowbar protection circuit. As shown in Figure 1(a), the crowbar circuit consists of a number of resistors connected to the rotor slip rings through a set of power electronic switches to protect the rotor winding as well as RSC, when needed [5, 6]. Its operating principle is that when the rotor current exceeds a predetermined threshold value, the crowbar circuit is activated to disconnect the power converter.
FIGURE 2  Doubly-fed induction generator. (a) Transient response of doubly-fed induction generator’s rotor speed and active power during grid faults for stable and unstable conditions with the presence of crowbar circuit, (b) power versus rotor speed curve for stable condition and (c) power versus rotor speed curve for unstable condition [12].

from the generator and short-circuit the rotor winding through the crowbar resistors.

Thus, increasing the rotor resistance can confine inrush currents and prevents damage to both the power converter and windings [5].

3  POWER VERSUS ROTOR SPEED CURVE AND STABILITY MARGIN

Assuming the wind speed is constant during network faults, due to their short period of time. Hence, the mechanical input power $P_m$ is fairly assumed constant. When the crowbar circuit is actuated, the power converter is separated from the DFIG and evidently, there will be no control over active and reactive powers. In this transient circumstance, the generator operational mode is temporarily changed to SCIG [5, 6]. Referring to Equation (12), there is a direct relationship between electrical power and the voltage at the stator terminal.

Therefore, during grid faults and voltage drop in the PCC, the electrical power decreases, while the mechanical input power remains constant. Hence, the equilibrium between electrical and mechanical powers will be lost. This inequality causes the power oscillation and acceleration of the rotor (see Figure 2(a)). If the rotor speed exceeds a certain margin, which is called the critical speed, the DFIG must be tripped off from the grid [8]. To
simplify the concept of the critical speed of the generator, its power versus rotor speed curve can be assisted. To obtain the power versus rotor speed curve of electric machines, steady-state equations are used. These mathematical equations are obtained in refs. [12, 25]. The power versus rotor speed curve for both stable and unstable operating conditions is depicted in Figure 2(b,c). For better illustration, the electrical and mechanical powers are multiplied by minus one (−1). According to Figure 2(b,c), it can be seen that there are two points where electrical and mechanical powers are equal (i.e. points S and U). At point S, the generator operates as stable in which the rotor speed is normal (i.e. \( w_o \)). Whereas, point U represents the unstable equilibrium point. The rotor speed at this point is called the critical speed (i.e. \( w_c \)) [12, 25].

In Figure 2(b), when a severe fault occurs in the power network, it leads to voltage drop and severe electrical power reduction based on Equation (12). Thus, the machine operating point is moved to point O. Under this condition, the rotor speed increases according to Equation (4). When the fault is cleared (i.e. \( t_o \)), the generator operates as stable in which the rotor speed is normal (i.e. \( w_o \)). At this moment, since the rate of change in velocity is greater than zero (i.e. \( P_m - P_e < 0 \)), the rotor speed decelerates. So, the generator finally returns back to the stable point S.

Turning to the other side, in Figure 2(c), at the instant of fault occurrence and electrical power reduction to near zero, the generator operating point reaches point C. At this moment, since the rate of change in velocity is lower than zero (i.e. \( P_m - P_e < 0 \)), the rotor speed accelerates. So, the unstable state will happen [26, 27].

### 4 | PROPOSED METHOD

The following section explains how angular velocity and acceleration can be calculated from the local variables and applied as an appropriate criterion for determining TI.

#### 4.1 | Calculation of angular velocity and angular acceleration

Since the suggested technique is based on the analysis of angular velocity and acceleration data for TI identification, this subsection is dedicated to explain an appropriate way for calculating these data using electrical power.

A sampling frequency of 1 kHz is adequate for the presented method. It is worth highlighting that in case of the unstable state, the power swing is not damped out after the fault clearance, whereas in case of the stable state, the power swing subsides after a while (see Figure 2(a)). Accordingly, it can be clearly stated that the stable and unstable conditions are reflected in the DFIG’s output power. In other words, that is why this parameter can be suggested as a proper quantity for the proposed method.

Furthermore, the electrical power is a local variable and its measurement from the machine terminal can be easily done. Thus, the application of the proposed algorithm would be relatively simple in practice. The electrical output power at any instant can be computed readily using three-phase currents and voltages [28]:

\[
P_e = V_a^* I_a^* + V_b^* I_b^* + V_c^* I_c^*. \tag{14}
\]

where superscript \( n \) denotes the number of each sample. \( V_a^* \) and \( I_a^* \) are the phase voltages and currents (\( x = a, b \) or \( c \)), respectively. Considering the dynamic equation of the drive train governed by Equation (4), and taking an integration over a very short interval of time yields:

\[
\int_{t^-}^{t^+} \frac{d\delta(t)}{dt} \, dt = \frac{\pi f_0}{H} \int_{t^-}^{t^+} (P_m - P_e) \, dt. \tag{15}
\]

\[
\frac{d\delta(t)}{dt} \bigg|_{t^+}^{t^-} = \frac{d\delta(t)}{dt} \bigg|_{t^+}^{t^-} + \frac{\pi f_0}{H} \int_{t^-}^{t^+} (P_m - P_e) \, dt. \tag{16}
\]

Considering the short integration interval, the right-hand side of Equation (15) would be approximated by the trapezoidal rule as below:

\[
\int_{t^-}^{t^+} (P_m - P_e) \, dt = \frac{(P_m - P_e)^{t^+} - (P_m - P_e)^{t^-}}{2} \Delta t. \tag{17}
\]

As just mentioned, the value of \( P_m \) is assumed constant during the calculation. Therefore, Equation (17) can be redefined as below:

\[
\int_{t^-}^{t^+} (P_m - P_e) \, dt = \frac{(2P_m - P_e)^{t^+} - (P_m - P_e)^{t^-}}{2} \Delta t. \tag{18}
\]

By substituting Equation (18) in Equation (16) in the discrete time domain, its corresponding equation can be written as:

\[
\frac{\Delta\delta^n}{\Delta t} = \frac{\Delta\delta^{n-1}}{\Delta t} + \frac{\pi f_0}{2Hf} \left[ (2P_m - P_e)^n - (P_m - P_e)^{n-1} \right] \Delta t. \tag{19}
\]

In Equation (19), \( \Delta t \) stands for the sampling time interval. The sequential change in rotor angle for \( n \)th sample can be explained as:

\[
\Delta\delta^n = \Delta\delta^{n-1} + \frac{\pi f_0}{2Hf} \left[ (2P_m - P_e)^n - (P_m - P_e)^{n-1} \right] \Delta t^2. \tag{20}
\]

With respect to Equation (20), the rotor angle at each sampling instant can be given as:

\[
\delta^n = \Delta\delta^n + \delta^{n-1}. \tag{21}
\]

In the next step, the angular velocity can be calculated by taking the derivative of the rotor angle in the discrete
time domain:

\[ \omega_p^n = \frac{\delta^n - \delta^{n-1}}{\Delta t} = \frac{\Delta \delta^n}{\Delta t}. \]  (22)

Taking the derivative of angular velocity yields:

\[ a_p^n = \frac{\omega_p^n - \omega_p^{n-1}}{\Delta t}. \]  (23)

where \( a_p \) is the angular acceleration. The subscript \( p \) denotes the electrical power because the angular velocity and acceleration are locally extracted by measuring the electrical power at the machine terminal.

As a consequence of Equations (22) and (23), at each sampling instant, the value of \( \omega_p \) and \( a_p \) can be computed concerning the value of the rotor angle at the previous sampling instants.

At the beginning of the sampling process, it makes sense to assume that the value of \( \Delta \delta \) in the previous sample is zero (i.e. \( \Delta \delta^{n-1} = 0 \)). Under normal condition, there exists an equilibrium between mechanical and electrical power (i.e. \( P_m = P_e \)). Consequently, the value of \([2P_m-P_e] = (P_e)^{n-1}\) in Equation (20) will be zero, which means that the rotor angle does not undergo any variations. Subsequently, the value of \( \omega_p^n \) and \( a_p^n \) in Equations (22) and (23) will also be equal to zero, respectively. During transient perturbations, the equilibrium between mechanical and electrical power is collapsed (i.e. \( P_m \neq P_e \)). Hence, the value of \( \Delta \delta^n \), \( \omega_p^n \) and \( a_p^n \) in Equations (20), (22) and (23) will deviate from zero. This is confirmed in the simulation study in Section 5.

Finally, transferring Equations (22) and (23) in the continuous time domain yields:

\[ \dot{\omega}_p = \frac{d\delta(t)}{dt}, \]  (24)

\[ a_p = \frac{d^2\delta(t)}{dt^2}. \]

According to Equations (4) and (24), it is obvious that there exists a relationship between the dynamic behaviour of the DFIG and that of \( \omega_p \) and \( a_p \) obtained from the generator terminal. In other words, the behaviour of \( \omega_p \) and \( a_p \) can be affected by DFIG’s transient conditions. Therefore, with the help of a suitable study of the behaviour of these two parameters, it is attainable to achieve a proper criterion for distinguishing the TI. This is addressed in the next section.

4.2 Proposed algorithm

As just explained, after the disturbance clearance, if the rotor speed does not exceed the critical speed, the generator remains stable and experiences damped power fluctuation. Otherwise, the generator will become unstable and power fluctuation will not be damped out. This subsection explains how \( \omega_p \) and \( a_p \) can participate to differentiate between stable and unstable conditions.

Figure 3(a,b) show the behaviour of the DFIG on power versus rotor speed curve under stable and unstable conditions, respectively. Figure 3(c,d) illustrate the trajectory of angular acceleration versus angular velocity extracted from \( \dot{P}_a \) corresponding to Figure 3(a,b), respectively. Considering Equations (4) and (24), Table 1 represents a detailed explanation of the relationship between the location of different operating points on the power versus rotor speed curve and \( a_p \) versus \( \omega_p \) trajectory.

As shown in Table 1, during unstable condition, when the generator operating point passes the unstable equilibrium point (i.e. point U), the sign of \( a_p \) changes from negative to positive, while \( \omega_p \) remains greater than zero. Comparing stable and unstable conditions in Table 1, it can be found out that the aforementioned sequential changes in \( a_p \) and \( \omega_p \) are observed only in the unstable condition. Accordingly, these changes can be used as a suitable criterion for detecting TI. In other words, the following criterion must be met to detect TI.

\[ \begin{align*}
    a_p^{n-1} &< 0 & \& a_p^n > 0 \\
    \& \& \omega_p^n > 0
\end{align*} \Rightarrow \text{Unstable condition.} \]  (25)

The main logic of the proposed detection algorithm is summarised in a flowchart as illustrated in Figure 4(a).

5 | SIMULATION AND PERFORMANCE EVALUATION

In this section, the performance of the proposed detection algorithm is evaluated on both SMIB and TMIB configurations.

Conventionally, a wind farm that is integrated into the grid consists of several generators. However, since a multi-machine system can be computationally reduced into a single-machine equivalent system with equivalent parameters, the use of SMIB configuration in stability studies of the grid-connected DFIG is commonplace by researchers [6, 7, 16, 29]. The calculation of this procedure is presented in ref. [17]. Figure 4(b) shows the general configuration of the simulated SMIB model. The simulation is conducted utilising MATLAB/Simulink software.

This SMIB system consists of a 1.5 MW DFIG based WT connected to the power grid via two 25 kV transmission lines of 30 km in length. The nominal frequency of the network is 60 Hz. The main parameters of the simulated model are presented in Appendix [6].

The severity of network disturbances on the DFIG depends on such factors as the type of the fault, fault duration, DFIG’s pre-fault slip, the inertia constant of the generator and loading condition [5, 16]. Hence, these factors are considered for this case study.

A disturbance is made by applying the three-phase to ground fault at \( t = 5 \) s at the middle of one of those transmission lines. Before continuing, it is worth to discuss why symmetrical faults, for example, three-phase fault, is used to verify the proposed
FIGURE 3  Behaviour of the doubly-fed induction generator under stable and unstable conditions. (a) Power-rotor speed curve in case of stable behaviour, (b) power-rotor speed curve in case of unstable behaviour, (c) trajectory of $a_p$ versus $w_p$ of $P_e$ in case of stable behaviour and (d) trajectory of $a_p$ versus $w_p$ of $P_e$ in case of unstable behaviour.

TABLE 1  Detailed description of the relationship between the location of different operating points on the Power-rotor speed curve and the $a_p$-$w_p$ trajectory under both stable and unstable conditions

| Location | Stable condition | Unstable condition |
|----------|-----------------|-------------------|
|          | Angular velocity and acceleration of the rotor angle ($\delta$) | Angular velocity and acceleration of the rotor angle ($\delta$) |
| s        | $P_m = P_e$     | $P_m = P_e$       |
|          | $\dot{\delta}(t)/dt = 0$ | $\dot{\delta}(t)/dt = 0$ |
|          | $\ddot{\delta}(t)/dt^2 = 0$ | $\ddot{\delta}(t)/dt^2 = 0$ |
|          | $w_e = 0$       | $w_e = 0$         |
|          | $a_p = 0$       | $a_p = 0$         |
| e        | $P_m < P_e$     | $P_m < P_e$       |
|          | $\dot{\delta}(t)/dt > 0$ | $\dot{\delta}(t)/dt > 0$ |
|          | $\ddot{\delta}(t)/dt^2 < 0$ | $\ddot{\delta}(t)/dt^2 < 0$ |
|          | $w_e > 0$       | $w_e > 0$         |
|          | $a_p < 0$       | $a_p < 0$         |
| f        | $P_m < P_e$     | $P_m < P_e$       |
|          | $\dot{\delta}(t)/dt < 0$ | $\dot{\delta}(t)/dt < 0$ |
|          | $\ddot{\delta}(t)/dt^2 < 0$ | $\ddot{\delta}(t)/dt^2 < 0$ |
|          | $w_e < 0$       | $w_e < 0$         |
|          | $a_p < 0$       | $a_p < 0$         |
| g        | $P_m < P_e$     | $P_m > P_e$       |
|          | $\dot{\delta}(t)/dt < 0$ | $\dot{\delta}(t)/dt > 0$ |
|          | $\ddot{\delta}(t)/dt^2 > 0$ | $\ddot{\delta}(t)/dt^2 > 0$ |
|          | $w_e < 0$       | $w_e > 0$         |
|          | $a_p < 0$       | $a_p > 0$         |
| h        | $P_m > P_e$     | $P_m > P_e$       |
|          | $\dot{\delta}(t)/dt < 0$ | $\dot{\delta}(t)/dt > 0$ |
|          | $\ddot{\delta}(t)/dt^2 > 0$ | $\ddot{\delta}(t)/dt^2 > 0$ |
|          | $w_e < 0$       | $w_e > 0$         |
|          | $a_p < 0$       | $a_p > 0$         |
| k        | $P_m < P_e$     | $P_m < P_e$       |
|          | $\dot{\delta}(t)/dt > 0$ | $\dot{\delta}(t)/dt > 0$ |
|          | $\ddot{\delta}(t)/dt^2 < 0$ | $\ddot{\delta}(t)/dt^2 < 0$ |
|          | $w_e > 0$       | $w_e < 0$         |
|          | $a_p < 0$       | $a_p < 0$         |
| s        | $P_m = P_e$     | $P_m = P_e$       |
|          | $\dot{\delta}(t)/dt = 0$ | $\dot{\delta}(t)/dt = 0$ |
|          | $\ddot{\delta}(t)/dt^2 = 0$ | $\ddot{\delta}(t)/dt^2 = 0$ |
|          | $w_e = 0$       | $w_e = 0$         |
|          | $a_p = 0$       | $a_p = 0$         |

method. Symmetrical faults are more serious than asymmetrical faults because they cause a more intense voltage drop in the generator terminals and further reduction in electrical power. This would mean a sharp collapse of the balance between electrical and mechanical power and increasing the probability of the generator’s instability. Therefore, although they are less likely to occur, this simulation uses a three-phase to ground fault to create disturbance in the power system.

To evaluate the performance of the proposed approach, the results of 14 different simulation cases are summarised in Table 2. In addition, it should be stated that the DFIG capability curve is utilised to extract operating loading points for a fairly wide range of slips (i.e. $\pm 0.25$ of the synchronous speed) [29, 30].

It is worth mentioning that when the wind speed is low, the rotor speed would be lower than the synchronous speed and
### TABLE 2  Performance of the proposed detection method on SMIB configuration

| Case no. | Loading points P+jQ (p.u.) | Pre-fault slip (%) | Fault duration time (s) | Detection time (s) | DFIG operational state |
|----------|-----------------------------|--------------------|-------------------------|--------------------|------------------------|
| 1        | 0.05+j0.80                  | 25                 | 0.15                    | 0.231              | Stable (Sub-synchronous)|
|          |                             |                    |                         | 0.200              |                        |
| 2        | 0.05-j0.30                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.261              |                        |
|          |                             |                    |                         | 0.260              |                        |
| 3        | 0.25+j0.20                  | 11.50              | 0.15                    | Stable             |                        |
|          |                             |                    |                         | 0.259              |                        |
|          |                             |                    |                         | 0.255              |                        |
| 4        | 0.25-j0.01                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.252              |                        |
|          |                             |                    |                         | 0.253              |                        |
| 5        | 0.30+j0.55                  | 9.50               | 0.15                    | Stable             |                        |
|          |                             |                    |                         | 0.254              |                        |
|          |                             |                    |                         | 0.264              |                        |
| 6        | 0.30-j0.20                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.257              |                        |
|          |                             |                    |                         | 0.253              |                        |
| 7        | 0.50+j0.63                  | 1.30               | 0.15                    | Stable             |                        |
|          |                             |                    |                         | 0.256              |                        |
|          |                             |                    |                         | 0.251              |                        |
| 8        | 0.50-j0.80                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.253              |                        |
|          |                             |                    |                         | 0.257              |                        |
| 9        | 0.75+j0.49                  | -9.30              | 0.15                    | Stable             | Super-synchronous      |
|          |                             |                    |                         | 0.254              |                        |
|          |                             |                    |                         | 0.258              |                        |
| 10       | 0.75-j0.04                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.264              |                        |
|          |                             |                    |                         | 0.282              |                        |
| 11       | 0.90+j0.33                  | -17                | 0.15                    | Stable             |                        |
|          |                             |                    |                         | 0.224              |                        |
|          |                             |                    |                         | 0.217              |                        |
| 12       | 0.90-j0.20                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.247              |                        |
|          |                             |                    |                         | 0.246              |                        |
| 13       | 1.00+j0.50                  | -25                | 0.15                    | Stable             |                        |
|          |                             |                    |                         | 0.243              |                        |
|          |                             |                    |                         | 0.244              |                        |
| 14       | 1.00-j0.05                  | 0.15               |                         | Stable             |                        |
|          |                             |                    |                         | 0.255              |                        |
|          |                             |                    |                         | 0.253              |                        |
the rotor windings absorb energy from the grid. This situation is called the sub-synchronous state.

On the other hand, when the wind speed is high, the rotor speed would be greater than the synchronous speed and the rotor windings will feed out energy to the grid. This situation is called the super-synchronous state.

In this simulation, after \( t = 5.15 \) s the generator experiences the stable condition, while after \( t = 5.30 \) s and \( t = 5.40 \) s, it is unstable. According to Table 2, it can be found out that the suggested method has almost acceptable performance in various load levels. Additionally, it can be seen that in the case of the unstable state, detection time changes slightly with different loading points.

Figure 5(a) illustrates the terminal voltage response to the three-phase to ground disturbance under stable state during case 8. Figure 5(b,c) also depict the behaviour of the DC-link voltage and the rotor current with the presence and absence of the crowbar circuit, respectively.

As it can be seen in Figure 5(b,c), disconnecting the power converter from the DFIG and increasing the rotor resistance by the crowbar resistors, reduces the DC-link voltage from 1.36\( \text{p.u.} \) to 1.12\( \text{p.u.} \), which indicates the FRT capability improvement of the generator.

Figure 6(a) shows the behaviour of \( \omega_p \) and \( a_p \) under normal operation, during case 8. Referring to Figure 6(a), it is obvious that both quantities have no variations.

The angular acceleration and angular velocity extracted from \( P_e \) for the stable and unstable conditions during case 8 are depicted in Figure 6(b,c), respectively. As shown in Figure 6(b), under stable condition with the fault duration time of 0.15 s, when \( a_p \) changes the sign from negative to positive, the value of \( \omega_p \) is less than zero, which is in accordance with the theoretical description given in Table 1. Hence, it can be said that the proposed method successfully identified the stable condition.

Figure 6(c) indicates the behaviour of \( \omega_p \) and \( a_p \) under a first-swing unstable condition in which the fault lasts for 0.40 s. It can be seen that after the fault clearance, when \( a_p \) changes the sign from negative to positive, the sign of \( \omega_p \) is positive, which is also in accordance with the theoretical description given in Table 1. Hence, it seems possible that the proposed method successfully identified instability as well as a stable condition. In this situation, the grid-connected DFIG must be tripped off from the power network.
FIGURE 5  Impact of crowbar circuit on FRT capability of the doubly-fed induction generator under stable state during case 8 on single-machine infinite bus configuration. (a) Voltage drop in the point of common coupling, (b) DC-link voltage with the presence and absence of the crowbar circuit and (c) rotor current with the presence and absence of the crowbar circuit.

In order to show the similarity in characteristics, a simulation test is carried out considering three different inertia constants. Figure 6(d) shows the active power variations for 2, 3 and 4 s inertia constants of the DFIG at case 12, under stable condition. This figure shows that the active power has a similar pattern in all different inertia constants. Nevertheless, it can be found out that higher fluctuation occurs in case of the smaller value of inertia constant.

This is due to this fact that during network disturbances, when the balance between the electrical and mechanical power is disrupted, the smaller value of inertia constant leads to faster acceleration of the rotor [15].

However, to study the impact of inertia constant on the proposed method, three different values of DFIG’s inertia constants are listed in Table 3. The DFIG based WT is connected to light and heavy loads and the three-phase to ground fault is cleared at \( t = 5.40 \) s to create an unstable condition.

According to Table 3, it can be clearly seen that the detection time changes slightly under various loading levels. However, the recommended method can correctly identify the DFIG’s condition at the different values of inertia constants. Further investigations are also made to evaluate the effectiveness of the proposed algorithm on a multi-machine power system.

For this purpose, a TMIB model is considered. This configuration is shown in Figure 4(c). The parameters of TMIB model are mentioned in the Appendix. This model consists of a 1.5 MW DFIG based WT connected to the power grid at Bus 1 along with two SGs which are integrated into the power grid at Buses 2 and 3, respectively. A three-phase to ground fault is applied at Bus 1 and is cleared after 0.40 s. The DFIG based WT is tested under light and heavy loads and various pre-fault slips. Table 4 represents the results of these simulation cases. According to this table, it can be seen that although the detection time changes slightly with different loading levels, the multi-machine
FIGURE 6  Impact of normal, stable and unstable conditions on the 1.5 MW doubly-fed induction generator during case 8 on single-machine infinite bus configuration. (a) \( \omega_p \) and \( \alpha_p \) for normal operation, (b) \( \omega_p \) and \( \alpha_p \) for stable oscillation, (c) \( \omega_p \) and \( \alpha_p \) for unstable oscillation and (d) behaviour of the active power for three different inertia constants under stable operation.
TABLE 3 Performance of the proposed detection method for different inertia constants of DFIG on a SMIB power system

| Inertia cons. H (s) | Fault duration time = 0.40 s | Pre-fault slip, 25 % | Loading point (p.u.) | Detection time (s) | Loading point (p.u.) | Detection time (s) |
|--------------------|-------------------------------|----------------------|----------------------|-------------------|----------------------|-------------------|
|                    |                               | L1 0.05+0.80         | 0.261                | L11 0.90+0.33     | 0.296                |
|                    |                               | L2 0.05-j0.30        | 0.260                | L12 0.90-j0.20    | 0.282                |
|                    |                               | L3 0.05+0.80         | 0.264                | L13 0.90-j0.20    | 0.267                |
|                    |                               | L4 0.05-j0.30        | 0.272                |                   |                      |

TABLE 4 Performance of the proposed detection method on TMIB configuration

| Case No. | Loading points P+jQ (p.u.) | Pre-fault slip (%) | Detection time (s) | DFIG operational state |
|----------|----------------------------|--------------------|--------------------|------------------------|
| 1        | 0.05+0.80                  | 25                 | 0.351              | Sub synchronous        |
| 2        | 0.05-j0.30                 |                    | 0.425              |                        |
| 5        | 0.30+0.55                  | 9.50               | 0.362              |                        |
| 6        | 0.30-j0.20                 |                    | 0.340              |                        |
| 11       | 0.90+0.33                  | -17                | 0.347              | Super synchronous      |
| 12       | 0.90-j0.20                 |                    | 0.339              |                        |
| 13       | 1.00+0.50                  | -25                | 0.323              |                        |
| 14       | 1.00-j0.05                 |                    | 0.326              |                        |

power system slightly extends the operating time of this method, in comparison with SMIB configuration (see Tables 2 and 4). However, the proposed algorithm could successfully identify the unstable condition.

For further explanation, Figure 7(a,b) illustrate the rotor speed and active power of the simulated DFIG in the TMIB test system under stable and unstable conditions, respectively. As shown in Figure 7(c), in case of stable condition in which the active power oscillation is damped out after the fault and the over-speed situation does not happen, the proposed detection algorithm could successfully identify this condition in a multi-machine configuration.

On the other hand, according to Figure 7(d), in case of the unstable condition in which the stability is lost after the inception of the three-phase to ground fault, the proposed detection algorithm could correctly identify this condition within 0.339 s.

6 | COMPARATIVE ANALYSIS

In this section, a comparative study is made between the proposed method and other methods recommended in refs. [16, 19]. Critical clearing time assessment is one of the well-known methods for specifying the stability margin of the grid-connected generators. The critical clearing time is the maximum time duration which a disturbance can be applied before the DFIG passes the critical speed [27]. In ref. [10], the critical clearing time for a DFIG is calculated based on the steady-state and swing equations of the generator.

\[

\tau_{\text{crit}} = \frac{H}{a_p} \times \frac{b_p}{a_p} \times f_m \left( 2 + \frac{b_p}{a_p} \right).
\]

(26)

where

\[

\begin{align*}
  a_p &= P_m (R_{Th}^2 + X_{Th}^2) + R_i |V_{Th}|^2 + K_1 R_{Th} + X_{Th} K_2, \\
  b_p &= 2P_m R_{Th} R_i - R_{Th} K_1 - X_{Th} K_2 - R_i |V_{Th}|^2 - R_{Th} K_1 - |V_i|^2, \\
  c_p &= P_m R_{Th}^2 + R_{Th} |V_i|^2 + R_i K_1, \\
  K_1 &= V_{dr} V_{dTh} + V_{qr} V_{qTh}, \\
  K_2 &= V_{dr} V_{dqTh} - V_{qr} V_{dTh}.
\end{align*}
\]

(27)
FIGURE 7  Impact of stable and unstable conditions on the 1.5 MW doubly-fed induction generator during case 12 on three-machine infinite bus configuration. Fault cleared after 0.15s and 0.4s to create stable and unstable conditions, respectively. (a) Rotor speed and active power of the generator for stable operation, (b) rotor speed and active power of the generator for unstable operation, (c) $\omega_p$ and $a_p$ for stable operation and (d) $\omega_p$ and $a_p$ for unstable operation

where subscript Th stands for the Thevenin variables (see Figure 8(a)). Referring to Equations (26) and (27), it is worth highlighting that the value of $t_{crit}$ depends on the Thevenin variables seen from points A and B of the grid-connected DFIG [27]. For better illustration, Figure 8(b) reveals the impact of different Thevenin variables on the power versus rotor speed curve and its related critical clearing time. Consequently, it can be figured out that when the network parameters change, the value of $t_{crit}$ must be re-calculated, which is a cumbersome and time-consuming task.

Another criterion that is used to detect instability in the generator is called TSI [19]. This EAC-based index is obtained by calculating the TEF and defined as follows:

$$\text{TSI} = \frac{E_{cr} - E_{cl}}{E_{cr}} \times 100\%.$$  

(28)

If the critical energy of the generator ($E_{cr}$) is greater than its total transient energy ($E_{cl}$), the TSI value is greater than zero, which means that the system has maintained its stability and if the TSI is negative, the system has reached an unstable state. However, this method also requires extensive system stability studies for finding the settings and their complexity increases when applied to multi-machine networks. Additionally, EAC-based technique is suitable for a SMIB system and fails to give efficient results for large scale power systems [4]. Furthermore, as stated before, the implementation of EAC used in transient stability studies of SGs is not suitable for DFIGs. Moreover, because of its complex calculations of critical energy, it is difficult to implement this approach on a multi-machine system with a detailed model of equipment.

Whereas, simulation results show that the proposed setting-free approach has acceptable performance in different power system configurations. In other words, no re-calculation is required by changing the configuration of the network. Therefore, it can be pointed out that its usage is easier than the recommended method in ref. [16], especially for a multi-machine power system.

7 | CONCLUSION

This paper presented a new method for detecting an unstable condition in a grid-connected DFIG. The identification process has been based on the analysis of the angular velocity and acceleration data obtained from locally measured quantities. Simulation results demonstrate the successful performance of the proposed algorithm not only on a SMIB power system but also on a multi-machine power system under various situations. The most important benefits of the presented approach are its independence from the fault clearing instant and self-tuning feature, which means there is no need to re-adjust the relay’s settings when the power system configuration changes. In addition, the performance of this method is not affected by different values of DFIG’s inertia constants, loading levels, pre-fault slips etc. Moreover, electrical power can be locally measured from the machine terminal, which makes its application rather straightforward.
FIGURE 8 Grid-connected doubly-fed induction generator. (a) Reduced equivalent circuit of a grid-connected doubly-fed induction generator [11] and (b) impact of different Thevenin variables on the power versus rotor speed curve and critical clearing time.

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### APPENDIX

See Tables A.1–A.3.

#### TABLE A.1 SMIB parameters

| Parameters         | Values                  |
|--------------------|-------------------------|
| Transformers       |                         |
| DFIG rating        | 1.5 MW, 575 V, 60 Hz    |
| Inertia constant   | 0.685 s                 |
| Transmission line  |                         |
| T-I                | 1.75 MVA, 575V/25 kV\(0.00174+0.05p.u.,\) |
| T-II               | 47 MVA, 25 kV/120 kV\(0.00534+0.16p.u.,\) |
| Other generators   |                         |
| Length             | 30 km                   |
| Positive and zero sequence resistances | 0.1153, 0.413 Ω km⁻¹ |
| Positive and zero sequence inductances | 1.05, 3.32 mH km⁻¹ |
| Positive and zero sequence capacitances | 11.33, 5.01 nF km⁻¹ |
| Infinite bus voltage | 1 p.u.                |
| Inertia constant   | 2, 3, 4 s               |

#### TABLE A.2 TMIB parameters

| Parameters          | Values                  |
|--------------------|-------------------------|
| Generator-1 rating  | 1.67 MVA, 575 V, \(H = 0.685\) s |
| Generator-2 rating  | 555 MVA, 25 kV, \(H = 3.5\) s |
| Generator-3 rating  | 66 MVA, 25 kV, \(H = 4.29\) s |
| \(Z_1\)             | \(0.048 + j0.48\) Ω |
| \(Z_2\)             | \(0.00576 + j0.573\) Ω |
| \(Z_3\)             | \(0.0288 + j0.288\) Ω |
| \(Z_4\)             | \(0.0576 + j0.576\) Ω |
| \(Z_5\)             | \(0.0142 + j0.142\) Ω |
| \(Z_6\)             | \(0.0192 + j0.192\) Ω |
| \(Z_7\)             | \(j0.0957\) Ω          |

#### TABLE A.3 Parameters of the utilised wind turbine and DFIG [6]

| Parameters                  | Values |
|-----------------------------|--------|
| **Wind turbine**             |        |
| Power                       | 1.5 (MW) |
| Blade radius(\(r\))         | 3.24 (m) |
| Rated speed                 | 11 (m s⁻¹) |
| Cut in wind speed           | 6 (m s⁻¹) |
| Cut out wind speed          | 30 (m s⁻¹) |
| Air density (\(\rho\))      | 1.225 (kg.m⁻²) |
| Maximum power coefficient (\(C_{\text{pm}}\)) | 0.24 |
| **DFIG**                    |        |
| Power                       | 1.67 (MVA) |
| Stator voltage              | 575 (V) |
| Nominal frequency           | 60 (Hz) |
| Stator resistance (\(R_s\)) | 0.023 (p.u.) |
| Rotor resistance (\(R_r\))  | 0.016 (p.u.) |
| Stator inductance (\(L_s\)) | 0.18 (p.u.) |
| Rotor inductance (\(L_r\))  | 0.16 (p.u.) |
| Mutual inductance (\(L_m\)) | 2.9 (p.u.) |
| Pole pairs                  | 3      |

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