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Power System Stability Studies Considering High Penetration of Grid Connected Doubly-Fed Induction Generators

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ABSTRACT Doubly-Fed Induction Generator (DFIG) is one of the preferred wind turbine generators which commonly utilized nowadays due to its advantages as compared with fixed speed generators. In spite of the well coverage of stability issues in conventional power systems, no sufficient analysis is carried out for recognizing the power system stability issues when large wind farms are interconnected into the system grid. This highlights the importance of the present research, which visualize the essence of the power system stability problem when large amounts of wind power are penetrated in its grid. This paper investigates the stability of the power system, focusing on voltage, angle, and frequency, while considering high levels of DFIG wind turbine integration. The study examines various scenarios that could influence system stability, including short circuit faults, power penetration ratios, and islanding effects. From the obtained results, DFIGs offer significant advantages in modern wind power systems, particularly in terms of fault tolerance and grid support. The study highlights that DFIGs allow for longer critical clearing times and better fault handling compared to FSIGs. However, they present challenges for power system frequency stability, emphasizing the need for advanced control strategies. Despite these challenges, DFIGs are suitable for isolated and hybrid systems, demonstrating their versatility in renewable energy applications. Effective grid integration and control are essential for ensuring the reliable operation of DFIG-based systems.

INDEX TERMS Crowbar, Fault Ride-Through, Grid code, Rotor angle stability, Rotor protection circuits, voltage instability,

I. INTRODUCTION

Energy consumption in countries always reflects the extent of their progress and prosperity of the industrial and commercial sectors and thus economic growth. The rate at which the electricity being consumed often reflects the level of prosperity that it could achieve. What distinguishes electrical energy is the possibility of generation from multiple sources, including traditional ones that rely on fossil fuels and renewable ones, which support the environment by reducing thermal emissions as well as reducing the costs of electricity production in the long term. Fig.1 shows the development over the previous years of electrical power generation sources and the percentage of power generated by each type, which illustrates the global trend of relying on renewable energy sources to generate continuous electrical energy during the past years. Clearly, from this figure, the renewable sector participates by about 28% of total energy generation with additional 15.7% from hydropower energy, while decrease in the energy generated from fossil fuels sources is continues. [1], [2]

Wind energy is one of the most promising renewable energy sources and has continued to increase the rate of reliance on it in generating electrical energy over the past years.

Electrical power can be extracted from wind power using either fixed or variable speed generators. The basic difference between the two types appears clearly in the amount of power generated with a change in wind speed, as the latter type allows obtaining electrical power even with wind speeds lower and greater than the rated speeds. Variable-speed systems offer enhanced aerodynamic efficiency, lower mechanical stresses, and reduced noise levels. Several types of generators can be utilized in variable-speed wind turbines, with Doubly-Fed Induction Generators (DFIGs) being one of the most widely used.

DFIGs have emerged as the preferred choice for modern wind farms. The DFIG design for variable-speed wind turbines allows for precise control of both active and reactive power, which is crucial for grid integration. Additionally, the vector control of DFIGs enables the decoupling of active and reactive power, providing more effective and independent control over these parameters. [2]

With the large-scale penetration of the wind farm equipped with the DFIGs into power systems different challenges of power system stability is raised, therefore it is of critical importance to investigate the influence of DFIGs on the power system voltage, angle and frequency stability. [2], [3] This paper introduces a complete stability study of the power system considering all scenarios that may affect the power system angle, or frequency, or voltage stability, such as, short circuit faults, penetration power ratio and islanding.

II. CONFIGURATION OF THE DFIG

The DFIG (Doubly-Fed Induction Generator) is a variable-speed wind turbine generator that primarily consists of a wound rotor induction machine, which is directly connected to the grid through the stator. The rotor is linked to the grid via a variable-frequency AC/DC/AC converter (VFC). The configuration of the DFIG is depicted in Fig. 2. The mechanical shaft of the DFIG is connected to both a high-speed and a low-speed shaft, which are driven by the wind turbine blades. This setup enables the DFIG to maintain a constant voltage and frequency when connected to the grid, across a wide range of rotor speeds, from sub-synchronous to super-synchronous.

As the rotor speed of the DFIG varies from sub-synchronous to super-synchronous speeds, the power flow between the rotor and the grid changes. The control circuits are responsible for managing the power flow between the rotor circuit and the grid, both in terms of magnitude and direction, as well as controlling the stator's output power. The Variable Frequency Converter (VFC) consists of two four-quadrant Insulated-Gate Bipolar Transistor (IGBT) Pulse Width Modulation (PWM) converters, connected back-to-back by a DC-link capacitor. This four-quadrant AC-to-AC converter allows for fully decoupled control of the generator's active and reactive power outputs. Additionally, the variable-frequency rotor voltage enables adjustment of the rotor speed to optimize the operating point at any given wind speed, implementing maximum power point tracking. Therefore, the Rotor Side Converter (RSC) and the Grid Side Converter (GSC) with a shared DC-link allow the wind turbine generator to operate efficiently across a broad range of rotor speeds, from sub-synchronous to super-synchronous, unlike traditional induction machines.

The control circuits for the Rotor Side Converter (RSC) and the Grid Side Converter (GSC) are illustrated in Fig. 3. The RSC control system includes two primary control loops: one for managing active power (P) and the other for reactive power (Q). The GSC plays a crucial role in maintaining a constant DC-link voltage across the capacitor, regardless of the magnitude or direction of the rotor power. Additionally, the GSC is responsible for controlling the reactive power output, particularly during grid disturbances, to ensure system stability and smooth operation.

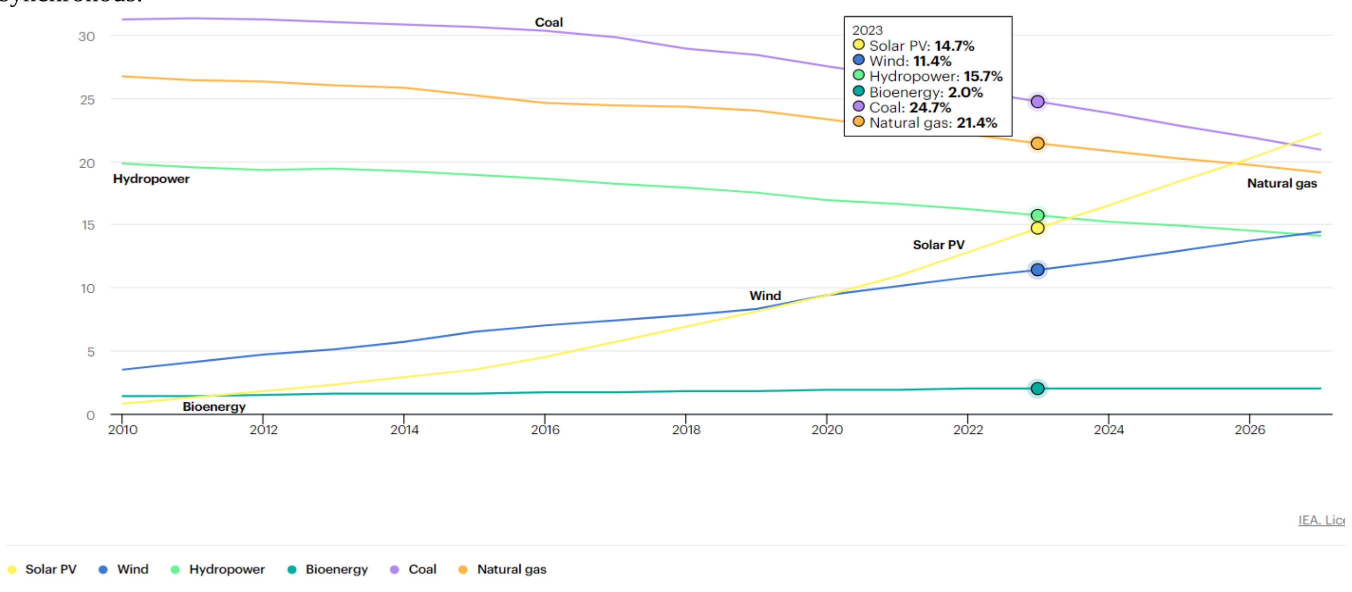

Fig. 1 Global energy generation [1]

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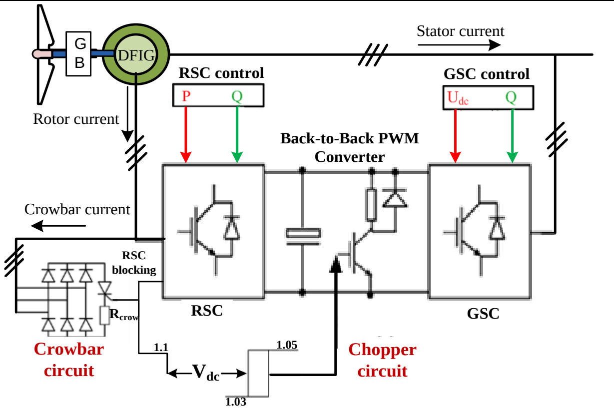

Fig. 2 Configuration of double fed induction generator-based wind turbine [3]

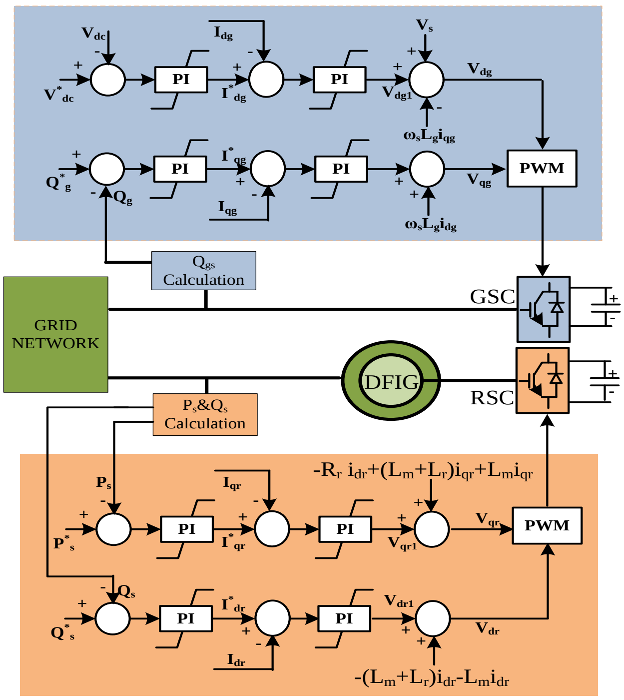

Fig. 3 Basic control loops for the RSC and GSC [3]

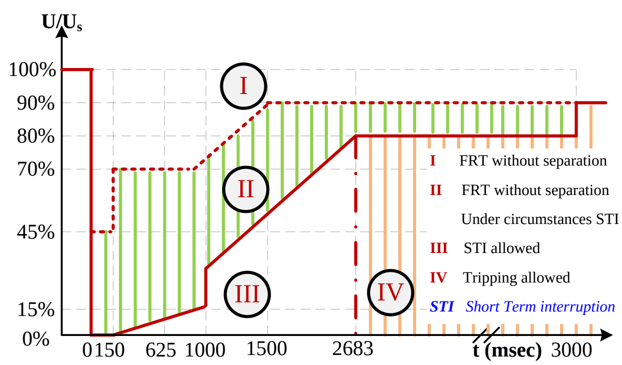

Fig. 4 Fault Ride Through capability of wind farm power station

III. GRID CODE REQUIREMENTS

It can be said that, the electrical power networks, despite design precautions, are exposed to a number of electrical and non-electrical faults, which have an impact on the stability of the network, continuity of operation, maintaining connection of loads, and continued feeding of loads with the appropriate quality. Therefore, it is necessary to have a grid codes regulating the operation of electrical systems to ensure this. With the beginning of the renewable resources integration to grids, such as wind energy, and with its small percentage in the beginning, it was easier to completely disconnect the wind turbines from the network in the event of malfunctions in the feeding system.

Wind turbines are typically recommended to be disconnected from the grid when their terminal voltage falls below 80% of its nominal value. While this may be acceptable during periods of low power generation, as wind energy penetration into electrical power systems has increased, it has become unacceptable to disconnect turbines even when voltage drops to these levels. As a result, modern grid codes now require wind farms, especially those connected to high-voltage (HV) grids, to remain connected and withstand voltage dips to a certain percentage of the nominal voltage, sometimes even down to 0%, for a specified duration. These requirements are referred to as Fault Ride-Through (FRT) or Low Voltage Ride-Through (LVRT) capabilities, and they are typically characterized by voltage vs. time profiles, as shown in Fig. 4.

During a grid disturbance, the rotor current of the DFIG increases, often reaching 2-3 times its nominal value. To meet the primary objective of FRT-ensuring the wind turbine remains connected to the grid without damaging the machine-the rotor side converter must be protected to handle the increased current and maintain stable operation. This protection prevents potential damage to the system and ensures the continued integration of wind energy into the power grid even during fault conditions.

Rotor protection can be implemented through two primary protection methods. The first method is the crowbar protection circuit, which includes a three-phase diode bridge to rectify the rotor currents. It also features a single thyristor connected in series with a resistor (R_{crow}). The thyristor is triggered by the DC voltage, which must exceed 110% of the nominal DC voltage, as illustrated in Fig. 2. This mechanism helps protect the rotor by limiting excessive current during fault conditions. The second method is the chopper protection circuit, which consists of a resistor connected in series with a controlled switch, such as an IGBT (Insulated Gate Bipolar Transistor), as shown in Fig. 2. The chopper is activated when the DC voltage rises above 1.05 times its nominal value and remains active until the voltage drops to 1.03 times its

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nominal value. The chopper circuit helps to stabilize the system by dissipating energy and controlling the voltage during fault conditions, ensuring the DFIG operates safely within its limits [4-7].

IV. POWER SYSTEM STABILITY STUDIES CONSIDERING THE DFIG WIND TURBINE

The system stability computation considering the DFIG will be carried out in this paper for the considered 5-machine 16-bus power system, shown in Fig. 5.

The stability computations are carried out using the MATLAB-Simulink library. Different case studies are suggested to cover most of the system stability issues, which are described in the following subsections. For all the following cases the DFIG is protected with the chopper and crowbar protection circuit, which are triggered as mentioned earlier.

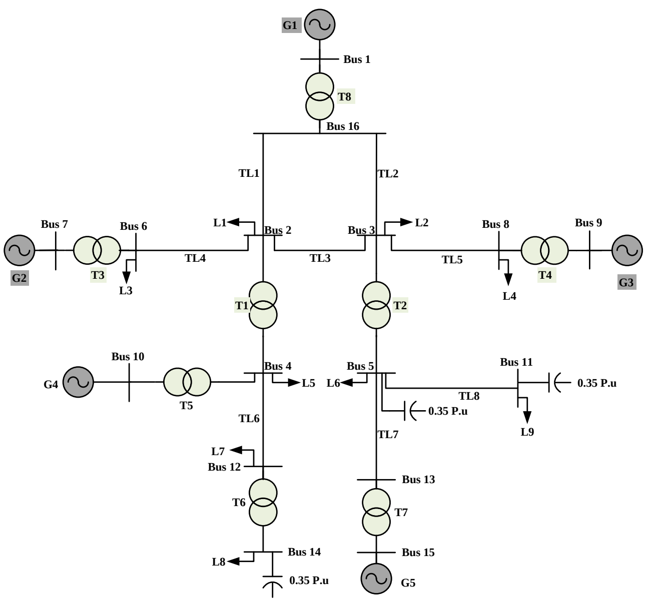
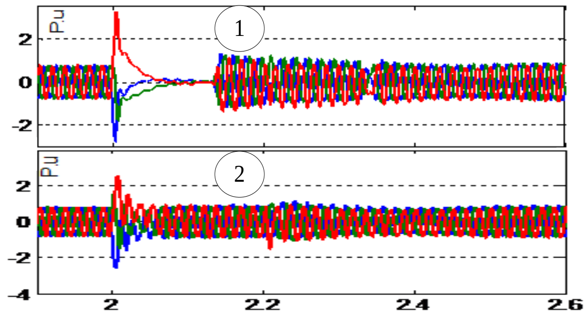


Fig.5 The considered 5-machine 16-bus power system

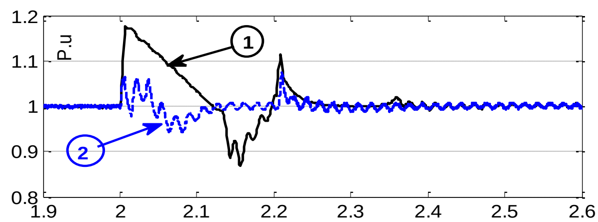
A. Fault Rid Through Capability of the DFIG.

To assess the fault ride-through capability of the DFIG, it is assumed that the synchronous generator at bus 9 (G_3) is replaced with a DFIG, which maintains the same output active power. A three-phase short circuit fault is simulated at bus 3, occurring at t = 2 seconds and cleared after 0.2 seconds. The performance of the DFIG, equipped either with a crowbar or a chopper circuit, is depicted in Fig. 6. The chopper circuit helps the DFIG maintain stable operation during the fault, while the crowbar provides protection by limiting the rotor current, but it may lead to higher reactive power consumption during and after the fault. The figure demonstrates how these protection systems impact the system's stability and the DFIG's ability to withstand the fault without compromising its performance.

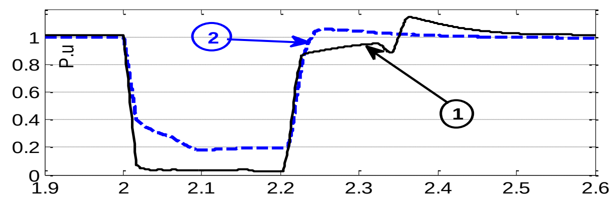
The chopper mechanism helps protect the rotor winding while allowing the DFIG to continue operating at variable speed during a fault. In contrast, when the crowbar is activated, it effectively converts the DFIG into a Fixed-Speed Induction Generator (FSIG), leading to a significant consumption of reactive power both during and after the fault. As a result, the DFIG with the chopper system maintains a more stable terminal voltage compared to the system that relies on the crowbar. The chopper's ability to regulate power flow ensures better voltage stability during fault conditions, while the crowbar's reaction to the fault induces higher reactive power demand and causes more substantial voltage deviations.



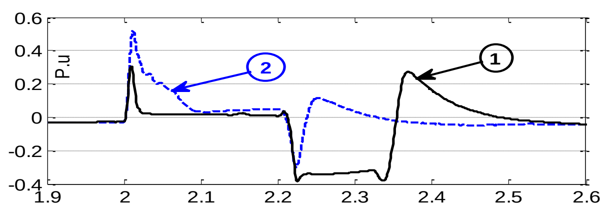
a) The DFIG stator current



b) The DFIG DC-link voltage



c) The DFIG terminal voltage



d) The DFIG output reactive power

Fig. 6 Response of the DFIG during grid disturbance (1- The DFIG is equipped with crowbar protection circuit 2- The DFIG is equipped with chopper protection circuit)

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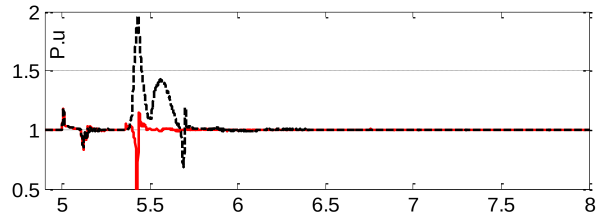
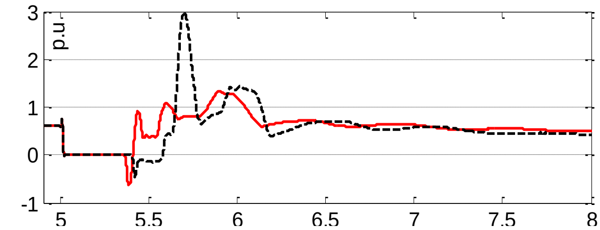
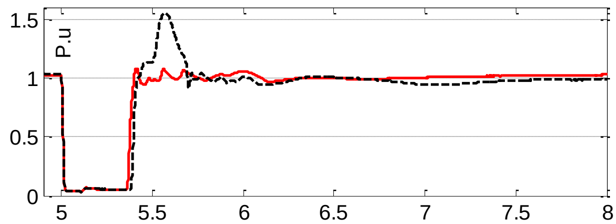


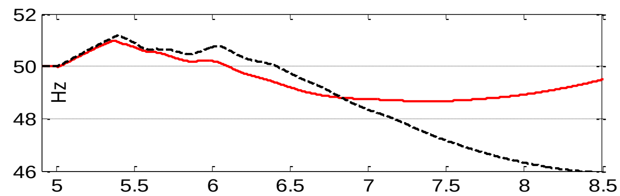
a) The DC-link voltage of the DFIG



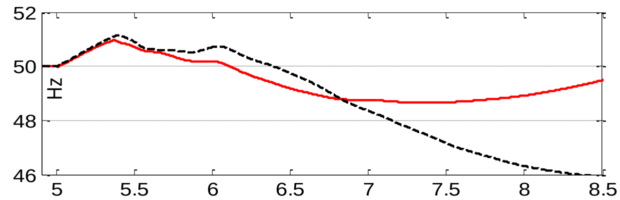
b) The DFIG output active power



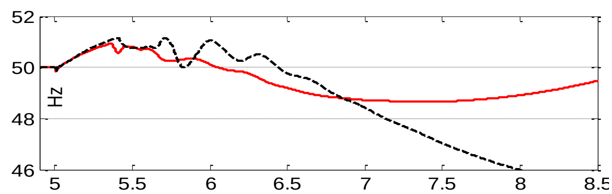
c) The DFIG terminal voltage



d) The frequency of the synchronous generator at bus 1



e) The frequency of the synchronous generator at bus 7

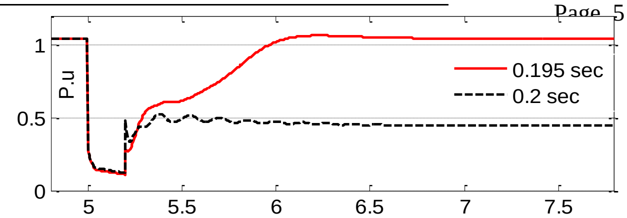


f) The frequency of the synchronous generator at bus 9

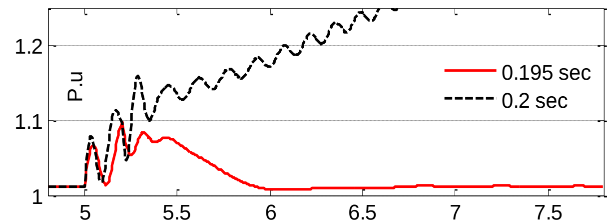
Fig. 7 Effect of short circuit duration on the power system stability considering the DFIG at bus 15

——— The short circuit duration is 0.36 sec

--------- The short circuit duration is 0.37 sec



a) The terminal voltage of the FSIG connected at bus 15



b) The rotor speed of the FSIG connected at bus 15

Fig. 8 Response of the FSIG connected at bus 15 when subjected to a three-phase short circuit at the PCC.

B. Occurrence of a 3-Phase Short Circuit Fault at the DFIG Transformer Terminals with Different Duration.

A short circuit at the Point of Common Coupling (PCC) of the wind farm represents one of the most significant disturbances the system may encounter. Therefore, it is crucial to assess the impact of the short circuit duration on both the performance of the DFIG and the overall stability of the power system. To conduct this analysis, it is assumed that the synchronous generator at bus 15 is replaced with a DFIG, maintaining the same installed capacity. A three-phase short circuit is introduced at the PCC at t = 5 seconds. To examine the effect of fault duration on system stability, the fault duration is gradually increased until the system loses stability. Figure 7 illustrates the system's performance for a fault duration of 0.36 seconds, which represents the critical clearing time, and 0.37 seconds, at which the system becomes unstable.

As shown in Fig. 7, when the short circuit duration reaches 0.37 sec the rotor protection circuits, crowbar and chopper circuits, failed in maintaining the DC voltage within the acceptable range, where at t=5.39 sec the DC voltage is increases to about 2 p.u of the nominal value, and as a result the terminal voltage of the DFIG is increased to about 1.5 p.u as shown in c.

The terminal voltage variation of the DFIG leads to voltage increase for all the power system buses. The voltage increase at the load buses increases the load demanded power, as the load is represented as a constant impedance load, which represents an overloading on the conventional synchronous generators, G_1-G_4. The synchronous generators over loading lead to frequency instability as shown in Figs. 7 d-f.

When comparing the DFIG to an FSIG under identical installed capacity and fault conditions, it was found that the critical clearing time for the system with the FSIG is

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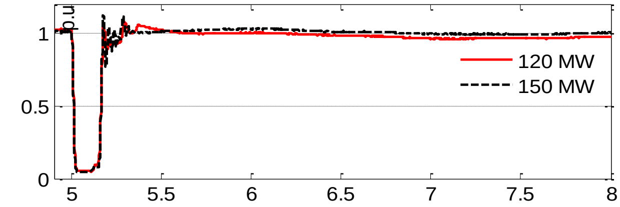
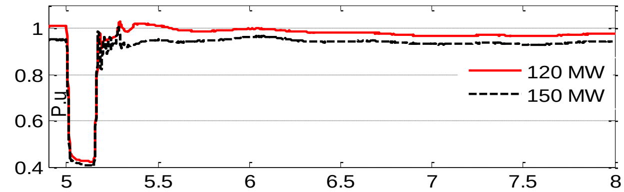
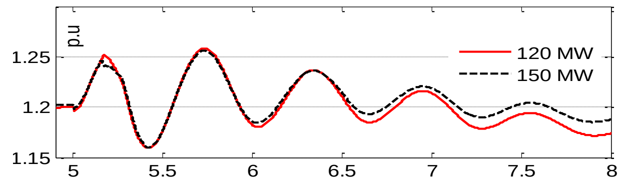
0.195 seconds. Beyond this time, the system loses voltage stability as the fault duration exceeds 0.2 seconds, as illustrated in Fig. 8.



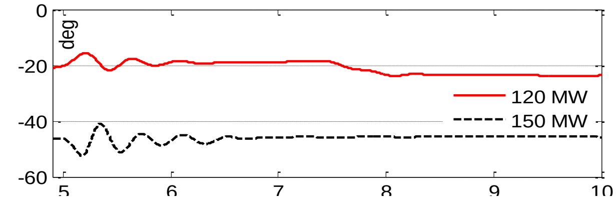
a) Terminal voltage of the DFIG



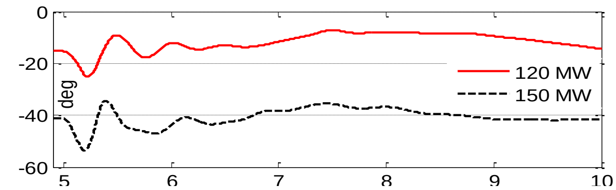
b) The voltage at bus 11



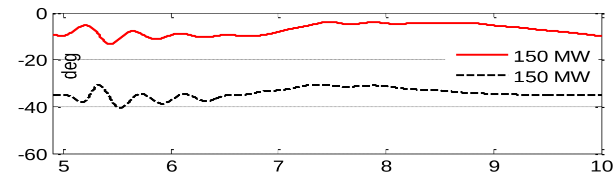
c) Rotor speed of the DFIG



d) Relative angle of G2 with respect to G1



e) Relative angle of G_3 with respect to G_1



f) Relative angle of G_4 with respect to G_1

Fig. 9 The power system response for a three-phase short circuit at the PCC of the DFIG wind farm with different penetration levels

C. Impact of the DFIG Penetration Power Ratio on the Power System Stability.

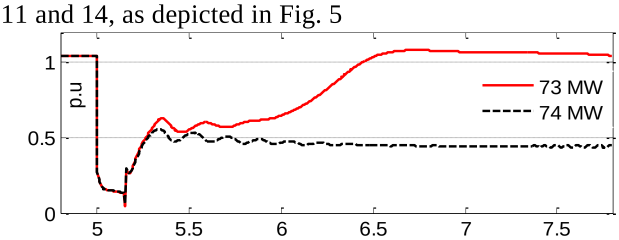
To assess the maximum wind power generated by the DFIGs that can be integrated into the system while maintaining stability, it is assumed that the synchronous generator at bus 15, as shown in Fig. 5, is substituted with a DFIG wind turbine. For this generator the output active power is assumed, at first, the same of the original synchronous generator, and increase continuously to the value at which the system lose its stability. For each of the DFIG output active power the load flow computation is carried out. Based on the load flow analysis, it was determined that the active power at bus 15 should not exceed 150 MW, as doing so would cause the voltage at bus 11 to drop to an unacceptable level of 0.948 P.U. As a result, stability calculations were performed for output values of 120 MW and 150 MW.

Subsequently, a three-phase short-circuit fault is assumed to occur near bus 13, with a fault duration of 0.15 seconds. The system's response to this disturbance, considering two different penetration levels, is depicted in Fig. 9.

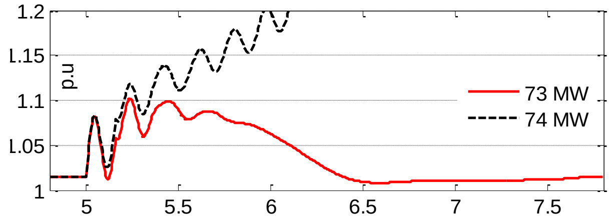
As illustrated in Fig. 9, the system retains both angle and voltage stability when the DFIG penetration level, under the given disturbance, reaches approximately 36% of the total generated power. For the same disturbance when the FSIG is used it is found that the maximum allowable penetration power cannot exceed 74MW, about 18% as shown in Fig. 10 [8]. It is to be noted that whenever the fault duration increased the penetration ratio is decreased.

D. Performance of the DFIG on the Isolated Area

In this case study, it is suggested that a new 80 MW wind farm be integrated into the existing power system. The suggested connection points for the wind farm are buses 11 and 14, as depicted in Fig. 5



a) The terminal voltage of the FSIG connected at bus 15



b) The rotor speed of the FSIG connected at bus 15

Fig. 10. FSIG performance for a short circuit fault at the PCC point for different penetration ratio

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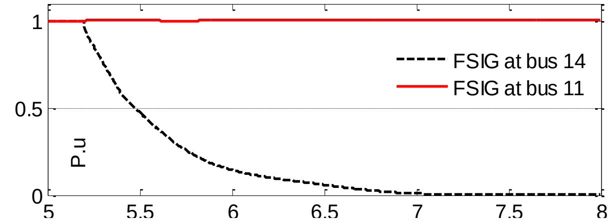
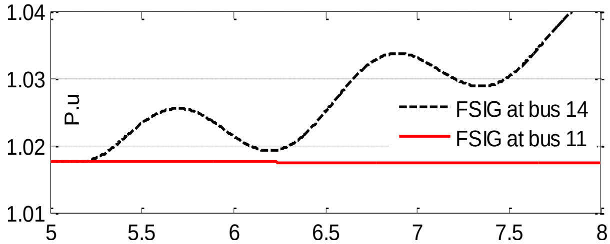
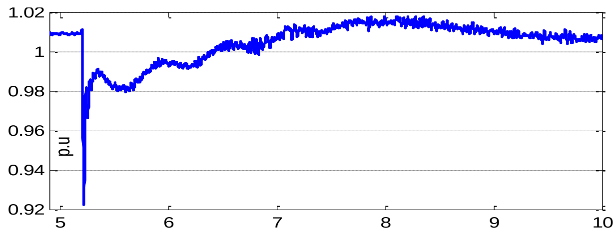


a) The terminal voltage of the FSIG

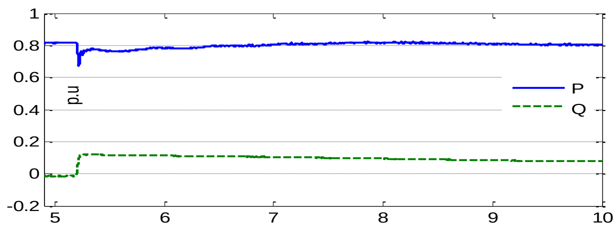


b) The rotor speed of the FSIG

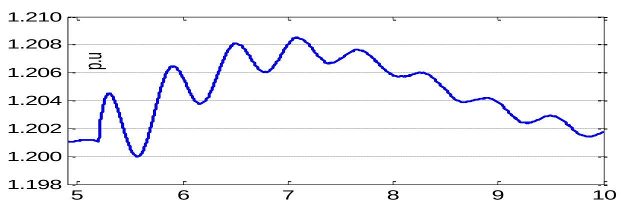
Fig. 11 The response of the FSIG when connected to bus 11 or 14 for the considered disturbance



a) The terminal voltage of the DFIG



b) The DFIG output active and reactive power



c) The rotor speed of the DFIG

Fig. 12 The response of the DFIG when connected to bus 14 for the considered disturbance

Now in order to determine which of the two considered bus is more suitable for the wind farm connection, it is assumed that the line connecting buses 4 and 12 of the system is suddenly opened, without a fault.

The stability analysis is performed for the given power system, initially with the FSIG wind farm connected to either bus 11 or bus 14, and the results are presented in Fig. 11.

As shown in Figs. 11 and 12 the considered fault leads to islanding the area containing bus 12 and 14 and the connected loads, and this mean that the connection of the FSIG at bus 14, for the considered fault, makes it the only power source in the isolated area and it can be concluded that the FSIG wind farm should not be the only power in case of the power system islanding as it leads to voltage collapsing.

It is now assumed that the DFIG wind farm is connected to bus 14, and the power system experiences the same fault as previously analyzed. As shown in Fig. 12 the DFIG can supplies the loads at bus 12 and 14 without losing the voltage stability in the isolated area.

V. CONCLUSION

Doubly-Fed Induction Generators (DFIGs) have become the most commonly used generators in modern wind power systems due to their efficiency and ability to support the grid during faults by injecting reactive power. This paper investigates the impact of high DFIG penetration on power system stability, particularly under fault conditions. The study compares DFIG-based and Fixed-Speed Induction Generator (FSIG)-based systems, revealing that the critical clearing time (CCT) for a three-phase short-circuit fault at the Point of Common Coupling (PCC) is longer for DFIGs, allowing for better fault tolerance. Despite their advantages, DFIGs negatively affect power system frequency stability, whereas FSIGs primarily cause voltage instability. This distinction highlights the need for advanced grid integration strategies. Additionally, DFIGs can operate in isolated systems, supplying both active and reactive power, similar to synchronous generators, making them suitable for remote and hybrid energy applications. While DFIGs enhance grid support and fault tolerance, their impact on system stability necessitates effective control mechanisms to ensure reliable operation.

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Appendix

The parameters of the utilized power system are listed below in the following tables.

TABLE I
TRANSMISSION LINE DATA (MVA_{BASE}=100).

Transmission line	Impedance (Z) P.u.	Susceptance (B/2) P.u
TL1	0.0275+j0.1512	J0.13965
TL2	0.0275+j0.1512	J0.13965
TL3	0.0413+j0.2268	J0.20940
TL4	0.0157+j0.0080	J0.06980
TL5	0.0157+j0.0080	J0.06980
TL6	0.0224+j0.1181	J0.01505
TL7	0.0224+j0.1181	J0.01505
TL8	0.0373+j0.1968	J0.02515

TABLE II
GENERATOR DATA

Generator	G1	G2	G3	G4	G5
Rated MVA	125	75	100	125	75
KV	15.5	13.8	13.8	15.5	13.8
Xd (p.u)	1.22	1.05	1.18	1.22	1.05
X\`d (p.u)	0.174	0.185	1.22	0.174	0.185
Xq (p.u)	1.16	0.98	1.05	1.16	0.98
X\`q (p.u)	0.25	0.36	0.38	0.25	0.36
X1 (p.u)	0.078	0.07	0.075	0.078	0.07
T\`do sec	8.97	6.1	5.9	8.97	6.1
T\`qo sec	0.5	0.3	0.3	0.5	0.3
H(MJ/MVA)	4.75	6.15	4.98	4.75	6.15

TABLE III
THE LOAD DATA.

Load	Power (P) MW.	Power (Q) MVAR.
L1	32.0	39.0
L2	40.0	30.0
L3	30.0	25.0
L4	60.0	40.0
L5	40.0	30.0
L6	60.0	15.0
L7	40.0	30.0
L8	40.0	-10.0
L9	40.0	-10.0