Transient stability analysis of IEEE 9-bus system integrated with DFIG and SCIG based wind turbines

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Abstract. Electricity is in high demand with a fast-growing population; hence it is advisable to turn towards green energy. In this research, Wind Turbine (WT) is modelled with two different types of induction generators (IGs), which are the Doubly-Fed Induction Generator (DFIG) and Squirrel-Cage Induction Generator (SCIG) and implemented to IEEE 9-Bus system to assess the transient stability. MATLAB/Simulink R2019a platform was considered to carry the whole examination. DC1A excitation system was applied to Synchronous Generators (SGs) as well as Power System Stabilizer (PSS). The transmission line7-5 was found to suffer from a high peak value of a relative power angle of approximately 130 degrees. As for the settling time, without PSS it was 20.69 s and with PSS it became 6.23 s. A wind farm with a rated capacity of 60 MW was used in the system. WT integrated with DFIG has the lowest peak value of 127 degrees at Bus locations 4 and 5 and for SCIG, Bus 5 with a peak value of 136 degrees. Thus, it can be propelled as the perfect location. Moreover, this is due to the three-phase fault was located at the transmission line7-5 which is far away from Buses 4 and 5. In the end, the WT integrated with DFIG provides a lower peak value of relative power angle compared to SCIG, whereas for settling time, it is the opposite.

1. Introduction
Climate change has become a major cause to the environment in the burning of fossil fuels to generate energy. Renewable energies have become a priority to fulfill the energy demand of the world’s growing populations. Wind Power Plants (WPPs) are amongst the one which is widely used in the world to generate the electricity [1–3]. However, the power system stability has been a major concerned towards the technology in which researchers are working on it. Voltage and transient instabilities are part of the issues faced in an electrical network [4]. It has to be highlighted that insufficient damping torque leads to voltage and transient instabilities [5]. A Wind Turbine (WT) consists of several components such as rotor aerodynamic, transmission system, generator, power electronic interface, transformer, and grid.

In this research, a study on the WT’s generator will be carried out to see if it impacts power system stability. Over the years, the generation part of WT was a major cause of stability issues in the electric grid [6]. The generator integrated into the WT can be either a Synchronous Generator (SG) or an Asynchronous (Induction) Generator (IG). However, IGs will be considered, and some of the available types are the Doubly-Fed Induction Generator (DFIG), Squirrel-Cage Induction Generator (SCIG), and
Wound Rotor Induction Generator (WRIG) [7]. Due to most related works made use of the DFIG, thus in this paper, DFIG and SCIG will be chosen to carry the investigation. SCIG has been considered since it is also a very well-known type of generator, but researchers haven’t used it as much. It is a robust and stable generator with mechanical simplicity, greater efficiency, and low maintenance [8]. As for DFIG, the rotor uses a back-to-back power converter; the converter’s rate is about 25% - 35% of the generator rating [8].

In transient stability studies, disturbances are a challenging task that engineers are required to tackle to bring a power system to stable conditions. Likewise, voltage instability is also present in the power system through the process of voltage breakdown. Voltage stability can be improved through the implementation of additional reactive power [9]. There are different types of controllers that were developed to address the stability issues, and in this research, Power System Stabilizer (PSS) controller will be discussed. PSS is described as a traditional damping device by researchers. The excitation system of the Synchronous Generator (SG) is controlled by using an auxiliary stabilizer signal by PSS to boost the dynamic performance of the power network. Power, shaft speed, and terminal frequency are better known as PSS input signals [10]. An unstable network led to the formation of oscillations which is highly recommended to control to avoid signal delay or even, blackouts. PSS is connected to an excitation system, where the alternator’s speed deviation field exciter experiences a control signal [11]. The functional aspect of PSS to improve system stability is simply by adding damping at the lowest formed natural resonant frequency. Thus, the damping torque supplied to the network help to remove the disturbances such as oscillations formed will be damped out [12]. Figure 1 shows a structure of a PSS where it consists of mainly three blocks which are: gain, washout filter, and phase-compensation.

![Figure 1. PSS structure [13].](image)

A power system can be described as a country's power distribution. It is unrealistic to use a real network to perform an investigation, neither build a real system due to its exorbitant cost. Also, one of the important aspects is that a real system parameter is not made available for the public, researchers, etc. However, it exists a typical Institute of Electrical and Electronics Engineers (IEEE) network. Over and above, based on most research papers, testing was carried out on the IEEE 9-Bus system. Hence, it is fair enough to use a similar system since comparisons can be easily drawn. In brief, an IEEE 9-Bus system consists of 3 loads, 3 transformers, 3 SGs, 6 transmission lines, and 9 buses where all connections are made at their respective phases. Researchers made use of prominent platforms such as MATLAB/ Simulink [4,14], DlgSILENT PowerFactory by DlgSILENT Simulation Language (DSL) [15], and ETAP [10] to construct the IEEE system and carry simulation. Again, based on familiarisation and simplicity, the MATLAB/ Simulink R2019a will be used as the simulation platform throughout the entire research.

In this research, a series of simulations will be carried out where the network will be investigated with three-phase fault implementation at different transmission line locations. An excitation system will be added to the SGs, and the relative power angle of the system will be evaluated. Likewise, the simulation will be repeated once PSS is added to the system. The WPP of 60 MW integrated with DFIG and SCIG will be applied to the IEEE 9-Bus system at different bus locations and tested separately. In the end, based on a comparative study, the best IG will be selected and use for further research work.
2. Literature Review

Research papers proposed their ideas on how the PSS was used, as follows: a PSS with a local and global signal where one input is for damping mainly local mode and the other input for inter-area modes damping [16]. Authors in [17] recommended that a power system’s entire average speed by the generator’s speed deviation has to be in phase with a PSS stabilization signal. A paper mentioned that PSS was applied to a similar network to this research, an IEEE 9-Bus system, and it has been found that it is much appropriate than classical controllers since improvements were achieved in terms of performance and SG parameters [13]. A simulation was carried out on a modified IEEE 39-Bus system to address the issue of electromechanical low-frequency oscillations, in which it was concluded that the performance was augmented with PSS is superior under heavy power flow, unpredictable network, various faults, and wind speeds [18].

The excitation system helps rotor winding of synchronous machine with field current and controls field voltage of a power system. The aim of the excitation system is to provide a direct current to the field winding of SG and keep the voltage within specific limits [10]. There are three main types of excitation systems as follows: Static, AC, and DC excitation systems. Static excitation system refers to system components that are stationary; AC ones make use of alternators to act as the generator, and lastly, DC exciter’s excitation power source is DC generators. Moreover, the findings in this study [19] state that the DC1A excitation system for a synchronous machine is better, stable, and reliable compared to the other types.

Researchers integrate WTs into the network with different types of generators such as DFIG, SCIG, and Variable Speed Synchronous Generator (VSSG) to perform testing on the IEEE network [20,21]. In this literature review, some of the research works have been analysed to view their findings on their respective testing.

A paper [22] used the MATLAB/Simulink platform and the IEEE 21-Bus system to study the effects of VSSG with a conventional power plant, Diesel-Powered Synchronous Generator (DPSG). DPSG Load changes, line breaks, and three-phase faults were the conditions used to carry the testing. A comparison was drawn after simulation where it mentioned that VSSG consists of similar behaviour as DPSG when it is faulted. Contrarily, it doesn’t reflect the same when a line outage is applied to VSSG. Moreover, the bus voltage of the generator experienced a rise when there is a dropped in the load. At lower wind speeds, power output can be produced by VSSG, but it is not stable and feasible compared to DPSG when it comes to voltage fluctuations [22]. Ref [15] analysed an IEEE 39-Bus system with DFIG based WT as an opportunity to provide support to synthetic inertia and primary frequency control which is known as active power functionalities. Compared to an original system, the frequency behaviour was not favourable with a penetrated system of 50% by standard WPP. However, the frequency behaviour can be improved by additional frequency. An improved system was obtained by the implementation of Frequency Supporting Functionalities (FSF) in WPP. On the other hand, when WPP is replaced by an SG, the worst behaviour was obtained. In the end, a 2.5% power as reserved is sufficient to keep the frequency behaviour next to a conventionally powered system.

Another work [23] investigated an IEEE 14-Bus system with small-signal effects on stability with load disturbances and the presence of a high amount penetration of wind through DFIG. Small-signal stability in an electrical power system is referred to as even though a system suffers from small perturbation, the ability to ensure the asymptotic stability such as steady voltages should be maintained for a given equilibrium point [24]. A researcher chose an IEEE 9-Bus system with a wind farm capacity of 20 MW with an applied three-phase fault for 100 ms at the Point of Common Coupling (PCC) to analyse the network behaviour [25]. Voltage dips were experienced by the SGs and the PCC bus during the three-phase fault. Due to a voltage dip of 80% for less than 1 minute, no tripping will occur on generators with frequency fluctuation is not guaranteed. Even though with the presence of a fault in the network, low voltages help WT to continue riding. After all, it was recommended by the author to always carry transient analysis on the network before applying wind farms to it. This was to observe the operation of the network to the stability limit. At the end of the analysis, with a three-phase fault applied
at PCC, both the frequency and voltage were at the limit of operation of 47 – 52 Hz and 0.95 – 1.05 pu [25].

Jia, Ying, and Wenfeng [26] used the IEEE 9-Bus system integrated with DFIG to study the effect. The dynamic stability was improved, and the power system damping ratio was increased by connecting the DFIG with a proper controller to the 9-Bus network. By adding a controller based on pitch angle control, the power output of the WT can be changed based on a change in system frequency [26]. Another research [27] analysed a modified IEEE 9-Bus system to carry an investigation on power system transient stability. WT integrated with DFIG was applied to the network, and the analysis was made through the observation of rotor angle performance of generator to lead to the calculation of critical clearing time (CCT). Some of the studies are based on the effects of integration of wind farms, transient stability due to high penetration of wind farms, and thermal generator loading. However, it was found that those effects affect the transient stability performance of the system. On the other hand, transient stability is better when the CCT value is higher. But, with low CCT value for integration of wind farm, high penetration of wind farm, and generator high load, the transient stability is worse [27].

Ref [28] carried a study on the South East Australian 14-Generator power system to investigate the effects on low-frequency oscillation through the influence of high wind penetration. Eigenvalue analysis was used to carry comparison between post- and pre-wind system damping performance. The system's small-signal stability was identified by considering wind penetration from different levels and for wind farms simulation, DFIG was used. Through findings, the system damping performance can be improved by voltage control at SG’s to stabilize them.

In this research, the generation part of WT will be assessed by analysing the transient stability through the observation of the relative power angle based on an IEEE 9-Bus system. The settling time and the peak value of the relative power angle are the only parameters that will typically be observed to conclude the power network transient stability throughout the entire study. Most research works and studies are frequently based on WT integrated with DFIG. SCIG is a famous and popular type of generator that is not frequently used in WT. However, DFIG and SCIG are two different types of IGs that will be considered and integrated into WT separately to carry an investigation. High penetration of wind energy will be part of the study to observe which type of IG is capable to resist and make the power network remains stable. In the end, a comparative study will be carried out to distinguish the best generator between the two. The suitable IG will be then recommended to continue business in WT fabrication.

3. Research Methodology

In this chapter, the research methodology is explained stepwise, and the up-to-date tasks are illustrated. The research used the MATLAB/ Simulink R2019a platform to carry the investigation. An IEEE 9-Bus system is selected to analyse the transient stability of the electrical power system. Such a network is chosen due to majority of related works were based on the IEEE 9-Bus network; hence it is appropriate to draw comparison simultaneously. In the basic, an IEEE 9-Bus system exists of three SGs, three transformers, three loads, six transmission lines, and nine buses. The parameters of the IEEE 9-bus system are found in different references [29–31]. Figure 2 shows the diagram of the studied network simulated by MATLAB.
At first, the network parameters such as loads, transformers, SGs, and transmission lines were chosen from the MathWorks example, article, and book [29–31]. SG 1 was considered as the reference generator in which was selected as ‘swing’ type, and due to SGs 2 and 3 voltages and active powers were known, hence were then set to as ‘power voltage’ (PV) types. Additionally, the power system is operating under a frequency of 60 Hz. Load flow analysis is required to check whether the system parameters remain within the designated limits during different load conditions [32,33]. The simulated IEEE 9-Bus system’s load flow was consulted and then compared to the book results [30]. Furthermore, the network was well constructed with proper connections due to obtaining simulated results that were precise as the book listed data. From Table 1, the recorded parameters are: $V_{LF}$ (pu) stands for ‘load flow reference voltage’, $P_{LF}$ is the ‘load flow active power’, and $Q_{LF}$ is the ‘load flow reactive power’.

In the second stage, simulation was carried out on Buses 4 to 9 to analyse the voltage, and the obtained findings were as expected with all buses having constant oscillations. The transient stability of the IEEE 9-Bus system was assessed by observing the relative power angle of the SG. Stage 3 proceeded by considering the excitation system type DC1A. The simulation was carried with the presence of a fault in the system at transmission line 7-5 due to the output result from previous simulations was high at this particular location. Hence, transmission line 7-5 remained the reference for testing.

Figure 2. Diagram of IEEE 9-Bus system.
Table 1. Simulated IEEE 9-Bus network results.

| BUS | V_LF (pu) | P_LF (MW) | Q_LF (Mvar) |
|-----|-----------|-----------|-------------|
| 1   | 1.0400    | 72.19     | 26.78       |
| 2   | 1.0250    | 163.00    | 6.69        |
| 3   | 1.0250    | 85.00     | -10.79      |
| 4   | 1.0261    | 0.00      | 0.00        |
| 5   | 0.9962    | 125.00    | 50.00       |
| 6   | 1.0132    | 90.00     | 30.00       |
| 7   | 1.0259    | 0.00      | 0.00        |
| 8   | 1.0160    | 100.00    | 35.00       |
| 9   | 1.0324    | 0.00      | 0.00        |

The DC1A excitation system has a good performance to improve the transient stability of the IEEE 9-Bus system, and the parameters of DC1A come from this source [29]. Stage 4 focuses on further improvement of the transient stability of the network. Hence, the PSS was introduced to the network where it was connected to the DC1A excitation system and the following simulations were carried out:

1. Simulation with DC1A excitation system with fault at different transmission line locations.
2. Simulation with DC1A excitation system with PSS, and with fault at different transmission line locations.

The parameters of PSS are found in IEEE Standard [34]. The relative power angle graphs showed a stable network after the implementation of the PSS. Stage 5 expands the research towards wind energy participation to assess its impact on transient stability based on the IEEE 9-Bus system. WT integrated with DFIG and with SCIG were used separately. A wind energy capacity of 60 MW was used and different levels of wind penetration will be observed in future works. In the end, a comparison will be drawn on which type of WT integrated with IG gives a suitable outcome that results in a stable network.

Figure 3 shows the IEEE 9-Bus network with PSS connected to the DC1A excitation system and then both linked to the SGs. A three-phase balanced fault is fixed at transmission line 7-5 due to it is the location with the highest effect based on the previous simulation. Thus, the dotted-encircled red in Figure 3 shows the WT integrated with DFIG at Bus 4 and is movable to other bus locations while performing the simulation. The placement of WT integrated with SCIG is done as in Figure 3 and simulated separately. The IEEE 9-Bus network has a 100 MVA apparent power and 230 kV as base voltage. The WT is rated at 60 MW with a total of 40 turbines each with a voltage of 575 V and frequency of 60 Hz, as applied in the literature [14]. Moreover, the power angle is obtained by the subtraction of generator 1 rotor angle from generator 2 rotor angle, thus multiplied by (180/\pi). Hence, a similar concept is applied for generator 3.
Some of the useful mathematical models that are associated with the IEEE power system model to configure equipment, controllers, etc. parameters are described as follows:

1. The swing equation or the 2nd order differential equation is well known for the representation of an SG rotor’s motion and is given by Eq. (1) [35]:

   \[ M \frac{d^2 \delta}{dt^2} = -D \frac{d\delta}{dt} + P_m - K \sin \sin \delta \]  

   Where,
   - \( P_m \) = Mechanical input active power measured in watt, W
   - \( M \) and \( D \) = Synchronous generator inertia and damping
   - \( K \) = Electromagnetic energy coefficient
   - \( \delta \) = Synchronous generator Rotor or Power angle measured in degree, \(^\circ\)

2. The transient power angle of SG relation is given by Eq. (2) [36]:

   \[ \delta_0 + \phi_0 + \theta_0 = 90^\circ \]  

   Where,
   - \( \theta_0 \) = Angle between rotor and stator measured in degree, \(^\circ\)
   - \( \phi_0 \) = Phase difference between current and voltage measured in degree, \(^\circ\)

   In the end, in the transient state the generator power angle is given by Eq. (3) [36]:

   \[ \delta = 90^\circ - \phi - \theta \]  

**Figure 3.** DFIG based wind energy implemented in the IEEE 9-Bus system.
3. The relative power angle of SG is used to assess the transient stability of electrical power systems [14,37]. The system is stable if the relative power angle decreases. On the other hand, the system is unstable if the relative power angle increases significantly [30]. The relative power angle of SG is given by Eq. (4) [30]:

\[ \delta_{2,\text{Ref}} = \delta_2 - \delta_{\text{Ref}} \] (4)

4. The wind power from the WT is calculated based on the Eq. (5) given below [38]:

\[ P = \frac{1}{2} \rho x A x V^3 \] (5)

Where,

- \( \rho \) = Density of air, kg.m\(^{-3}\)
- \( A \) = Area of swept, m\(^2\)
- \( V \) = Wind speed, m.s\(^{-2}\)

Moreover, the power output can be obtained from Eq. (6) [39]:

\[ P_{\text{out}} = \frac{1}{2} \rho x A x C_p x V^3 \] kg.s\(^{-2}\) or W (6)

Where,

- \( C_p \) = Power coefficient

4. Results and Discussion

This section covers the simulated results carried out on the IEEE 9-Bus system discussed in the methodology. The results have been presented step by step to easily understand every single stage of the project. The first subsection discusses the existing IEEE 9-bus system with and without PSS. However, the second part investigates the effect of DFIG and SCIG on the transient stability of the studied system.

4.1 IEEE 9-Bus system simulation with DC1A excitation system, without- and with-PSS

Table 2 shows the relative power angle of SG 2 (Delta 2-1) in two different scenarios. The analysis of results is carried out based on SG’s experiencing high peak value of relative power angle. Thus, SG 3 (Delta 3-1) results are ignored due to the focus is to mitigate high oscillations, which will automatically contribute to mitigating small ones. The first scenario is based on the existing system including the DC1A excitation system that was simulated at different transmission line locations. On the other hand, the simulation was repeated with PSS added to the system. This simulation will help to understand the purpose of the PSS integrated into the system as well as to be able to find the critical situations in the IEEE 9-bus system during the faults.

The simulation of the IEEE 9-Bus system without PSS had to be conducted for 30 seconds due to the system regain stability over more than 10 seconds and somehow, for some transmission lines like 6-4, 9-6, and 8-9 it has been seen to take a longer timing. As illustrated in Table 2, a system can be said to become stable at a shorter timing with PSS compared to a system without PSS. By taking the obtained parameters of transmission lines 7-5 as an example, the settling time, was 20.69 s without PSS compared to 6.23 s with PSS which is a reduction of 70 %. Through observation of the peak value of relative power angle, transmission line 7-5 suffers a lot with an approximate value of 130 degrees whereas transmission line 6-4 can be described as the location with the lowest effect with a value of roughly 70 degrees. This paper presents the graphs of transmission line 7-5 as shown in Figures 4 and 5 to enable the reader to view the difference between a system without PSS and after integrating the PSS controller.
Table 2. Relative power angle of SG 2 when faults occur at different transmission lines.

| Fault at Line | Settling Time [s] | Peak Value of Relative Power Angle [degree] |
|---------------|------------------|------------------------------------------|
|               | System with DC1A | System with DC1A and PSS | System with DC1A | System with DC1A and PSS |
| 7-5           | 20.69            | 6.23                      | 132.07          | 130.99                   |
| 5-4           | 14.80            | 4.98                      | 78.13           | 78.05                    |
| 6-4           | 29.89            | 4.61                      | 71.42           | 71.30                    |
| 9-6           | 29.76            | 5.01                      | 88.11           | 88.16                    |
| 8-9           | 29.68            | 4.18                      | 71.89           | 71.84                    |
| 7-8           | 19.73            | 5.14                      | 86.62           | 86.61                    |

Figure 4. Relative power angle of SG 2 and SG 3 when a fault occurred at transmission line 7-5, System integrated with DC1A excitation system.

As observed in Figures 4 and Figure 5, the peak values of both results are quite similar, but the settling time decreases from 20.69 to 6.23 s after adding PSS. Moreover, it has been decided to consider the fault in transmission lines 7-5 for upcoming simulation due to that this fault location has the highest impact on relative power angle compared to other locations.
Figure 5. Relative power angle of SG 2 and SG 3 when the fault occurred at transmission line 7-5, System integrated with DC1A excitation system and PSS.

4.2 IEEE 9-Bus system simulation with DC1A excitation system, without- and with-PSS, with DFIG and SCIG

The research topic was based on the participation of WPPs in the IEEE power system to analyze the transient stability of the network. From the beginning and up to now, several simulations have been brought forward to make the utmost possible to have a complete stable network before integrating WPPs into the network. As from the previous subsection, the DC1A excitation system and PSS were amongst new devices implemented to have a stable network. In this section, the SGs were equipped with DC1A and PSS, and the effects of DFIG and SCIG based WT integrated into the IEEE 9-bus system were discovered. The findings are depicted in Table 3, as shown below.

| Wind Energy is connected to Bus No. | System Integrated DFIG | System Integrated DFIG and PSS | System Integrated SCIG | System Integrated SCIG and PSS |
|-----------------------------------|------------------------|---------------------------------|------------------------|---------------------------------|
| Settling Time [s] | Relative Power Angle [degree] | Settling Time [s] | Relative Power Angle [degree] | Settling Time [s] | Relative Power Angle [degree] | Settling Time [s] | Relative Power Angle [degree] |
| 4 | 21.76 | 127.20 | 6.58 | 127.87 | 17.71 | 138.86 | 7.34 | 140.38 |
| 5 | 21.75 | 127.00 | 7.02 | 127.69 | 18.77 | 135.27 | 6.36 | 136.40 |
| 6 | 21.91 | 127.85 | 7.97 | 128.53 | 19.02 | 144.89 | 6.63 | 146.98 |
| 7 | 17.16 | 139.42 | 7.87 | 140.55 | 17.51 | 144.20 | 6.51 | 146.14 |
| 8 | 18.10 | 134.54 | 8.79 | 135.30 | 17.82 | 151.03 | 6.69 | 153.95 |
| 9 | 19.05 | 132.64 | 8.73 | 133.51 | 17.85 | 150.92 | 6.73 | 153.90 |
At this stage, a wind farm of a rated capacity of 60 MW was placed at different bus locations to identify the suitable location in the IEEE 9-Bus system. Two different types of WT, DFIG and SCIG, were considered to investigate their presence in the system and thus draw a concrete comparative study. Table 3 shows the four available scenarios with recorded parameters of settling time and peak value of relative power angle, and from these parameters, it will help to evaluate transient stability. A maximum relative peak value of approximately 153.95 degrees can be observed at Bus 8 with WT integrated with SCIG, compared to WT integrated with DFIG is roughly 140.38 degrees at Bus 7. Once again, PSS shows its significant contribution towards a stable network. Simulated results before PSS and after PSS with DFIG have a decreasing value for the settling time. In this context, it can be said that DFIG has better results in terms of the reduction of peak values of relative power angle. However, SCIG has better settling time values. All in all, Bus 5 seemed to be an ideal location to implement the SCIG due to that particular place made a good response to stability in a shorter time frame of 6.36 s. On the other hand, Bus 4 and Bus 5 are the proper locations to implement DFIG. At last, Figures 6 to 9 present a graphical overview of the system with both types of WT based on the highest peak value relative power angle results.

![Figure 6. Existing system integrated with DFIG at Bus7.](image)

The presence of DFIG without the implementation of PSS to the IEEE 9-Bus system hasn’t disrupted the system. The system can operate and return to a stable condition from 17.16 s as shown in Figure 6, but in terms of the peak value of relative power angle, Bus 7 suffered from a high peak value of 139.42 degrees. The reason behind this is due to the applied three-phase fault is at transmission lines 7-5, which is the closest to Bus 7.
Figure 7. System with PSS integrated with DFIG at Bus7.

Figure 7 shows the power angle graph of the system with PSS and WT integrated with DFIG at Bus 7. The peak value remained approximately constant whereas the observed change in settling time, which is 7.87 s.

Figure 8. Existing system integrated with SCIG at Bus8.

Figure 8 shows the output of power angle based on the IEEE 9-Bus system implemented with WT integrated with SCIG. As stated above, SCIG made an impact on the peak value where an augmentation can be observed and the settling time is more satisfactory in front of the DFIG. To highlight, such a system made bus 8 suffers the most when the WT integrated with SCIG has been applied across.
As shown in Figure 9, PSS helped the IEEE 9-Bus network with WT integrated with SCIG applied at Bus location 8 to become stable at an early timing of 6.69 s.

5. Conclusion

The research paper focused on the discussion of transient stability of an IEEE 9-Bus system simulated on the MATLAB/Simulink R2019a software. Through several simulations and improvements, the network has found itself compatible with the DC1A type of excitation system and PSS for the mitigation of oscillation and stabilizing the system more rapidly. The relative power angle was observed at transmission line 7-5 when a three-phase fault was applied. The rated capacity of the WPPs was 60 MW. Buses 4 and 5 are suitable locations to apply the DFIG and Bus 5 for SCIG ones. By considering fault in transmission lines 7-5, the settling time, $T_s$, without PSS was 20.69 s and with PSS was 6.23 s. After the system was integrated with DFIG, the settling time was 21.76 s, and it was 6.58 s for the system integrated with both DFIG and PSS. Besides, when the system was integrated with SCIG, $T_s$ was 17.71 s and 7.34 s for the system integrated with both SCIG and PSS. On the other hand, by comparing the peak value of relative power angle for Bus 5, for system integrated with DFIG was 127 degrees and remain unchanged when PSS was applied. Similar scenario for SCIG, peak value was approximately 136 degrees for both. To conclude, it is highly recommended to use some alternative methods to optimize the controller’s parameters so as both the peak value and settling time can be reduced. Hence, improve the overall transient stability of the IEEE 9-Bus system.

In future works, different levels of wind penetration will be considered to observe which WT integrated with IGs can resist and deliver suitable output. Thereby, it is expected to end up with a proper recommendation on if either DFIG or SCIG is the appropriate one.

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