Stability enhancement of power system with the implementation of power system stabilizer PSS and excitation system IEEE Type-1

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Abstract. Stability of power system is an ability of an electric power system that reaches its stable condition after fault happens in its network. The system is unstable when one generator loses its stable synchronism performance. This paper investigates the transient stability of an IEEE 9-bus system during faults that happen in different bus locations. Additionally, the analysis contributes to the integration of the exciter IEEE type-1 for synchronous generator and integration of power system stabilizer (PSS) to improve the power angle stability in the power system. The fault at bus 4 has the highest amplitude in which it increases to 77.58 degrees for the power angle of Synchronous Generators (SGs). The absence of PSS showed that the existing system oscillated and it is unstable. However, the integration of PSS enables the system to damp the oscillations of power angle and reduce the settling time to 5.69 seconds during the fault at bus 4. Moreover, the PSS is connected to SGs through the excitation system to improve the stability of the system in relative power angle of SGs, speed deviation, and electrical power of SGs. Hence, the integration of PSS and excitation system enhances the transient stability of the power system.

1. Introduction

In recent years the number of electricity consumers is increasing. Electrical energy is being used in many fields such as commercial areas, transportation, and healthcare sectors. All around the world, the countries are improving in terms of industry, manufacturing, and infrastructure to increase their economy. In addition, the development will also increase the need for electricity in the country [1]. On the other hand, it required the energy institutions to develop the field of energy to meet the need of energy for consumers. Furthermore, governments, energy-related institutions, and scientists are developing the energy field to meet the demand for electricity. Therefore, many types of renewable energy sources such as wind power [2,3], hydropower, bioenergy, and photo-voltaic system [4,5] are considered. From all the energy sources, many countries are moving toward renewable energies which are sustainable and far from causing air pollution [1].

The power system is of an engineering field in which it includes generation, transmission and distribution of electrical energy from source to destinations. For synchronous generators, it is required
to maintain stable condition at a steady state to deliver constant energy for the users. Power system stability is the ability to maintain enhanced synchronized output at generation during the fault condition [6]. A power system stabilizer (PSS) is a controller that is connected as feedback to the system of a synchronous generator and it is used to improve the stability of the system when the system experience instability caused by various disturbances in the electrical network [7].

An excitation system is an excitation of a synchronous generator in which it supplies field current into the rotor winding side of a synchronous generator. The parameters of the excitation system depend on the load currents and the power factor of the load. In large scale synchronous generators application, which generates high power, the amount of excitation also makes current to support the performance of the generator [8,9].

This paper analyzes the IEEE 9-bus in terms of power angle stability, enhancement of speed deviation and electrical power, and the effect of excitation system with exciter IEEE type-1 in the SGs. The exciter IEEE type-1 is a rotating rectifier with a static voltage regulator [8,9]. The paper provides the necessary information and carries some practical works in the software application to improve the performance of the system. MATLAB/Simulink is used to perform the analysis, the integration of PSS1A stabilizer type PSS studied in this paper to damp the oscillation of power angle and improve the settling time for relative power angle of the generators during fault conditions in different bus locations. Hence, the results are obtained for this paper and discussed in the results and discussion part of the study. This paper is organized as follows. Literature review and methodology are explained in Section 2 and Section 3, respectively. The results are discussed in Section 4. Section 5 presents the conclusion of this paper.

2. Literature Review
Reza Hemmati [10] argued that a modified design of Model Reference Adaptive System (MRAS) was used to design a power system stabilizer in an electrical network. The proposed design was investigated under different operating conditions and during the disturbances. Moreover, the proposed design was evaluated against the conventional PSS. The simulation was carried based on MATLAB Simulink, and the results showed that the proposed design showed enhanced performance in several operating conditions and during faults as compare to conventional type controllers. Another article [11] claimed that Robust-PSS is a type of power system stabilizer that can be used in the electrical control system to improve the performance of the network in different conditions. The control system was designed based on various types of control theories to improve the stability of the power system. In addition, the article conducted a study on Static Output Feedback Technique (SOFT) to improve the performance of the power system. The study showed better performance than other techniques which are conventional and fuzzy logic-based power system stabilizers. This article claimed that after conducting the simulation and obtaining results, the speed of response and peak overshoot have improvement for SOFT than the conventional and fuzzy logic-based. The article [12] conducted a study on robust modified PSS using Particle Swarm Optimization (PSO) technique to enhance the dynamic stability of PSS. The technique was integrated into PID controller using the proposed technique and then was connected to the system. In addition, the mathematical method of the proposed technique was used to develop the performance of the model, and it showed a better result as compare to other PSS-types. To validate the result of the model, it was investigated in different operating conditions to see the improved performance of the proposed design technique. Hence, the proposed technique enhanced the dynamic stability of the power system under fault disturbances and different operating conditions.

Authors in [13] evaluated the transient stability of the IEEE 9-bus system connected with Double Fed Induction Generator (DFIG). The analysis was carried based on the variation of wind penetration and it was considered to see the effect on the power angle of synchronous generators. The proposed technique evaluated that the increase in penetration of wind energy in some buses makes the system unstable. Moreover, the research showed that the locations for the wind farm are necessary for assessing the transient stability in the system. However, the research did not include the power system
stabilizer controller to damp the oscillation of the power angle more efficiently and to obtain stable transient conditions even with high penetration of wind energy. An interval type-2 fuzzy logic PI controller was proposed by the author [14]. The proposed design was implemented in the rotor side of DFIG and investigation was carried in several fault conditions. In addition, the fault on voltage was investigated due to variation in wind speed. The study was carried based on MATLAB/Simulink and for real-time simulation, the design was carried in a real-time lab using RTW to evaluate the results. Then the results were compared with other related controllers and the proposed design enabled stability of the system and voltage sag. Hence, the research does not cover the improvement in the oscillation of power angle to its steady-state condition, and the study is limited for settling time improvement. A summary of the above-mentioned literature review is shown in Table 1 by using different stabilizing techniques.

For the basis of the following research, the power angle stability of SGs, speed deviation and electrical power in the system were studied. The research was performed, and we present our acknowledgment to these authors. Refer to the above articles; some researchers argue that several methods can be used to improve the stability of the network. Some authors developed power system stability by adding different types of controllers. Moreover, an author assessed the transient stability of the system and integrated wind farm to stabilize the network [13]. The comparison of different stabilizing techniques of the literature reviews is presented in Table 1. However, some challenges noticed that need to be improved. In this paper, the research is going to achieve the following details.

1. Analyzing exciter IEEE type-1 exciter in IEEE 9-bus during fault conditions in different bus locations.
2. Analyzing PSS controller in IEEE 9-bus during fault conditions in different bus locations.
3. Identify the maximum power angle in the system, enhance power angle stability of SGs and settling time by integrating the PSS.
4. Enhance speed deviation and electrical power for the system.

**Table 1. Comparison of different stabilizing techniques.**

| Ref | Year | Controller         | Disturbance                               | Electrical Network | Remark                                                                 |
|-----|------|--------------------|-------------------------------------------|--------------------|----------------------------------------------------------------------|
| [10] | 2018 | Modified MRAS      | Different types of uncertainties, different types of faults in the system | 9-bus dynamic system | The system showed improved performance as compared to conventional PSS types |
| [11] | 2019 | SOFT               | Poor performance in stability when the load changes | Single machine connected to large system | The technique showed better performance as compared to other types of conventional PSS |
| [12] | 2019 | PSO-PID-MPSS model | Various types of disturbances in the system | Modified MPSS      | The proposed model showed better performance in terms of peak duration and settling time |
| [14] | 2020 | Interval type-2 fuzzy logic PI controller | Sever fault, voltage sag with reference to varying wind penetration | MATLAB/Simulink   | The proposed design improved the transient stability during faulty conditions, and it has the capability to show better performance than type-1 fuzzy logic controller |
3. Methodology

Based on Figure 1, the system was built in the IEEE 9-bus system. It includes generator 1, generator 2, and generator 3. In addition, it contributes transformer 1, transformer 2, and transformer 3, which are connected to each generator and load a, load b, and load c are located between transmission lines at bus 5, bus 6, and bus 8. The excitation system with exciter IEEE type-1 with fixed parameters was found in [8]. The excitation system was integrated into generators and was simulated in the IEEE 9-bus system. The parameters of IEEE 9-bus system are found in [15–17]. Parameters of PSS1A were found in [18]. It was integrated into the system to improve the power angle stability of the generators. The output of PSS is assigned to be the input of the excitation system with exciter IEEE type-1 and the output of the excitation system with exciter IEEE type-1 is the input of the synchronous generator as shown in Figure 2. Hence, generator 1 is considered to be a swing generator and bus 1 is a slack bus. The excitation system IEEE Type-1 and PSS were integrated into the system. The integration of IEEE Type1 and PSS1A was used in the literature [19]. The PSS model and swing formulas are represented in this section.

Load flow was conducted to calculate the voltage of buses, active and reactive power. The load flow results were used to check whether the system operates within specific limits during normal conditions and under disturbances [20,21]. Three-phase faults in different buses are considered, and the faults are cleared after 83 ms. The clearing time of this fault was discussed in the literature [13,15]. The simulation is used to investigate the transient stability of the power system with the integration of PSS and excitation system. The performance of the IEEE 9-bus system with excitation system and without PSS is analyzed.

Figure 1. IEEE 9-bus system Simulated by MATLAB/Simulink.

The paper analyzed the transient stability of IEEE 9-bus system and investigated the effect of PSS and excitation system integrated into the system to enhance the stability of the network.
3.1. **Power system stabilizer**

Figure 3 shows the diagram of power system stabilizer [22]. The input signal for PSS is the machine speed deviation, $dw$, and it receives the information from the output signal of generators. Each generator contributes PSS with similar parameters. The parameters for the following PSS are represented as follows.

- $dw$ - machine speed deviation.
- Overall Gain - The total gain $K_s$ of the PSS.
- Wash-out - Time constant in seconds (s), first-order high-pass filter.
- Lead-lag #1 - $T_1, T_2$ time constant in seconds (s), of Lead-lag #1 transfer function.
- Lead-lag #2 - $T_3, T_4$ time constant in seconds (s), of Lead-lag #2 transfer function.
- Limiter - The limit of minimum voltage and maximum voltage in pu of Vstab.
- Vstab - output of Vstab is connected to the input of excitation system with exciter IEEE type-1, and it is used to control the terminal voltage of the synchronous generator.

\[ P_a = P_m - P_e \quad (1) \]

The swing equation for the rotor of synchronous generator is given by equation (2) [23], which is formulated based on Newton’s equation of rotation.
\[ M \frac{d^2 \delta}{dt^2} = -D \frac{d\delta}{dt} + P_m - k \sin \delta \]  

(2)

The damping of synchronous generator \( D \) is neglected, and \( \delta \) is the power angle of synchronous generator. \( k \) is coefficient of electromagnetic energy, and \( M \) is the inertia constant in J.s. The inertia constant in s is given by equation (3)

\[ H = \frac{1}{2} \frac{M \omega_{sm}}{S_{rated}} MJ/MVA \]  

Then

\[ \frac{2H}{\omega_{sm}} \frac{d^2 \delta_m}{dt^2} = \frac{P_a}{S_{rated}} = \frac{P_m}{S_{rated}} - \frac{P_e}{S_{rated}} \]  

(4)

\( \delta_m \), and \( \omega_m \) represent the mechanical radians/s. In a synchronous generator, the generator has poles, the angle and frequencies are relevant to the mechanical variables as shown below [15]:

\[ \delta(t) = \frac{p}{2} \delta_m(t) \]  

(5)

\[ \omega(t) = \frac{p}{2} \omega_m(t) \]

The synchronous electrical radian is relevant to angular velocity as shown below:

\[ \omega_s(t) = \frac{p}{2} \omega_{sm}(t) \]  

(6)

The swing equation can be write in the form of per-unit equation as follow:

\[ \frac{2H}{\omega_s} \frac{d^2 \delta}{dt^2} = P_a = P_m - P_e \]  

(7)

From the unit of the \( \delta \) angle, we can write the swing per-unit equation where \( \delta \) is in electrical degree as shown below

\[ \frac{H}{180^2} \frac{d^2 \delta}{dt^2} = P_a = P_m - P_e \]  

(8)

In this research, the relative power angle of SG is used to evaluate the transient stability of IEEE 9-bus system. The relative power angle is defined as a power angle of SG with respect to the generator reference, the swing generator, as represented in equation 8 [15]. A system is stable if the relative power angle decreases. However, the system is unstable when the relative power angle increases significantly.

\[ \delta_{2,1} = \delta_2 - \delta_1 \]  

(9)

4. Results and Discussion

The IEEE 9-bus was built as shown in Figure 1. The generator type for generator 1 was selected swing and for the other two generators, the generator type was selected as PV. The power base for the power system network is considered to be 100 MVA and for the voltage base, it is considered to be 230 kV. The system was constructed in MATLAB/Simulink R2020a version and it is shown in figure 1. The study for excitation system with exciter IEEE type-1, PSS to enhance the relative power angle, speed deviation, and electrical power is discussed in this section.

4.1. Results with excitation system with exciter IEEE type-1 and with PSS
The excitation system with exciter IEEE type-1 was used to improve the transient stability by damping certain power angles in a synchronous generator. In addition, PSS, with parameters from IEEE standard [18], was integrated into the system to improve the power angle, reduce the settling time and the proposed PSS was able to produce constant stability to the system to keep the generation enhanced during fault. The fault measurement was taken in different bus locations and the bus locations with excitation system with exciter IEEE type-1 and PSS with the highest relative power angle were taken into account for the analysis, then the system was enhanced with PSS. When the fault improved during the highest power angle amplitude, it provides stable output during fault at other bus locations. The fault time was set for 0.083 seconds in Figure 4 [13,15]. When the switching of the fault time is released the system still oscillates. Hence, the integration of PSS1A enables the stability of power angle in the IEEE 9-bus system.

The following table shows the results for relative power angle of SGs and settling time in the network with excitation system with exciter IEEE type-1. Moreover, it contributes the power angle stability after the PSS with a suitable parameter is added in the network. Table 2 compares the peak value and settling time of the relative power angle of generator 2 for different scenarios. The first scenario is the excitation system with IEEE Type 1, but the second scenario is considered after adding PSS1A.

![Figure 4. Three-phase fault block](image)

| Items                      | Measurement   | 9-BUS System, Fault at bus 4 | 9-BUS System, Fault at bus 5 | 9-BUS System, Fault at bus 6 | 9-BUS System, Fault at bus 7 | 9-BUS System, Fault at bus 8 | 9-BUS System, Fault at bus 9 |
|----------------------------|---------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Excitation System with Exciter Type1 | Settling Time (s) | 8.06                          | 9.54                          | 9.53                          | 9.54                          | 9.56                          | 9.58                          |
|                            | Peak Amplitude (deg) | 77.58                         | 91.03                         | 69.17                         | 74.52                         | 71.66                         | 70.33                         |
| Generic PSS                | Settling Time (s) | 5.69                          | 6.12                          | 6.14                          | 4.80                          | 5.07                          | 5.13                          |
The measurements were taken from bus 4 to bus 9. For the excitation system with exciter IEEE type-1, the relative power angle of SGs was damped to a certain level. However, the system was still oscillating, making the system unstable. The integration of PSS enabled the power angle to achieve its stability. The highest amplitude for relative power angle generator 2 is 77.75 degrees was achieved at fault in bus 4 and the least power angle 69.11 degrees, was achieved at fault in bus 6. When the amplitude increases to highest amplitude then following the swing it reduces to lower amplitude. The following figure contributes the result for relative power angle of generator 2 and generator 3 with the excitation system with exciter IEEE type-1 at bus 4.

Based on Figure 5, the power angle amplitude of SGs reaches 77.58 degrees and settling time remains unstable. From the graph, it can be seen that the system still oscillated, it did not achieve its stable condition. The integration of PSS into the system enabled the power angle of SGs to achieve its stable condition at 5.69 seconds settling time. The following figure shows the enhancement of power angle stability by integrating the PSS.

As observed in figure 5, the power angle increases to a maximum power angle of 77.58 degrees and following the swing the system improved in power angle but still oscillates, and the system remains unstable. Following the analysis, Figure 6 contributes the PSS during fault at bus 4. The proposed design enhanced the power angle of SGs to reach its stable condition at power angle 77.75 degrees at 5.69 seconds settling time.
Figure 6. Relative power angle of generator 2 and generator 3 when fault occurs at bus 4, (system with PSS).

4.2. Results of speed deviation and electrical power
The speed deviation and electrical power analysis was taken based on IEEE 9-bus. The study first was analyzed with excitation system IEEE type-1, and then it was analyzed with PSS during a fault condition. The following figure shows the speed deviation of SGs during the fault condition at bus 4.

Figure 7. Speed deviation of SGs at fault condition, (system with Excitation System IEEE Type-1).

Based on Figure 7, the amplitude of speed deviation for generator 2 increases to 0.0084 pu and following the swing it reaches negative speed deviation. In addition, it can be seen that the system still oscillates, and the system remains unstable. The integration of PSS enables the speed of deviation for SGs to improve the stability of system and the result is shown in Figure 8.
Figure 8. Speed of deviation of SGs during fault condition, (system with PSS).

The electrical power analysis was carried based on IEEE 9-bus and the study was taken based on the effect of excitation system IEEE Type-1 and then the effect of PSS in the system. The following figure contributes the electrical power of SGs in the system.

Figure 9. Electrical power of SGs at fault condition, (system with Excitation System IEEE Type-1).

Based on Figure 9 the amplitude of electrical power for SGs increases to maximum 3.3 pu, and following the swing it reduces. However, the electrical power results remain unstable. To improve the electrical power, the PSS is integrated into the system and the result is shown in Figure 10.
5. Conclusion
The paper analyzed the transient stability of IEEE 9-bus system and investigated the effect of PSS and exciter IEEE type-1 in the enhancement of the power system. The system was studied based on PSS to improve the system by analyzing the relative power angle of SGs, speed deviation and electrical power during fault conditions. The excitation system was used for a synchronous generator, and it reduced the relative power angle by 75%, but the system still was unstable. When the fault happened, the amplitude of power angle increased to 77.58 degree and following the swing the amplitude of power angle decreased. However, the system still oscillates. A similar unstable condition was observed in speed deviation and electrical power. Furthermore, the integration of PSS1A enabled the relative power angle to produce constant output for SGs at 5.69 seconds settling time at fault condition at bus 4. The improvement in settling time for relative power angle stability shows that the system has become stable. In addition, the improvement in speed deviation and electrical power was achieved during faults. The results show that the research was conducted based on the highest amplitude of relative power angle of SGs at bus 4 in the system, any fault at different bus locations which has lower amplitude than bus4, the PSS is able to stabilize the performance of generators. For future work the research study, integration of DFIG with the suitable control system to improve the transient stability of power system connected with wind energy. Hence, the DFIG with control system enables the system to achieve its stability during short circuits and drop voltage in the IEEE 9-bus system.

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