Performance Improvement of Synchronous Generator in Power System During Line Disturbance Using an Adaptive Control Scheme

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Abstract
This research work presents the improvement of the performance of synchronous generator in power system during line disturbances using an adaptive control scheme. This is necessary in order to ensure stability of power system during transient and other disturbances. The adaptive control scheme due to its robustness was incorporated into the excitation and steam valve controller to improve the stability of the system during fault or disturbances. This proposed scheme will also ensure proper frequency and voltage regulation during small perturbation to the mechanical power. The backstepping controller was first designed after which a sliding mode controller was introduced for evaluating the control variables (gains) of the backstepping controller. The performance of the developed scheme was compared with the results obtained when coordinated immersion and variance control method was used, using settling time of power angle, relative speed of recovery, transient potential and input mechanical power as performance metrics. The obtained results of the adaptive control scheme for the settling time of the power angle of the system is 0.25 seconds, while that of the relative speed of recovery, transient potential stability and input mechanical power are 0.2 seconds, 0.2 seconds and 0.21 seconds respectively. The immersion and variance control recorded a settling time of 0.26 seconds for the power angle of the system, 0.25 seconds for the relative speed of recovery, 0.95 seconds for the transient potential stability and 0.92 for the input mechanical power.

Keywords: Synchronous generator, Power system, line disturbance, Backstepping control

Introduction
The power system stability is a serious problem that needs to be handled effectively to ensure a reliable and secure supply of electricity (Abubakar *et al.*, 2019; Xu & Hou 2012). The excitation control of synchronous generators has attracted lots research efforts, as an economic and effective way to improve power system stability (Li *et al.*, 2015). As power system stability and voltage regulation are two major issues, they are desired to be considered in the stage of designing the excitation controllers (Kundur *et al.*, 1994; Olarinoye & Abdulwahab 2022). When a large disturbance occurs in the power systems, the transient stability should be assured. In recent years, several works have been done in designing generator excitation and steam-valve coordinated controller to improve transient stability of power systems (Li *et al.*, 2018). Distributed excitation and steam-valve control has been distinctly proposed to improve system transient stability, when power systems with uncertain parameters are subjected to faults and disturbance (Afsari *et al.*, 2002). When the fault occurs, the kinetic energy of system is increased, and if the system kinetic energy exceeds a certain amount, system instability will occur. Generator tripping is one of the most effective methods for improving stability in case of serious faults (Baydokhty *et al.*, 2011).

The electric utility industry is undergoing unprecedented changes in its structure worldwide (Abdulwahab *et al.*, 2021). The emergence of separate entities for generation, transmission and distribution have given rise to new issues in power system operation and planning (Guo *et al.,* 2000). There are currently a lot of efforts to find high performance stabilizing controllers which are able to mitigate the results from many severe contingencies such as voltage collapse, islanding faults, and loss of synchronism (Abdulwahab *et al.,* 2020; Ibrahim *et al.,* 2017). The excitation control of synchronous generator is an effective way for transient stability enhancement of power systems (Adirak & Ekkachai, 2018). However, in most cases, the turbine and excitation controls are considered as independent and decoupled processes characterized by different time scales, which is unsuitable for modern power systems since the appearance of advanced governors, such as digital governors, results in tight mutual interaction between excitation and governor loop (Fombu *et al.,* 2016).

Researchers have worked on excitation control of large synchronous generators improving the dynamic performance and transient stability of power system (Kenne *et al.,* 2016). Halder *et al.,* (2018), worked on a novel non-linear control scheme for Thyristor Controlled Series Capacitors (TCSCs) for the analysis of a transient stability of a multimachine power system. A non-linear control strategy of the TCSC controller was formulated by Zero dynamic design approach. However, the efficiency of the method is restricted due to chattering effect caused by the control switching. Li *et al.,* (2018), worked on the coordinated immersion and invariance control of power systems with excitation and steam-valve in order to ensure a reliable and secure planning under a deregulated electric market condition. However, the adoption of state feedback for non-linear system without a device that can assess first swing stability of the network will lead to increase in rotor angle which will result in loss of synchronism. The adaptive back stepping control has ability to maintain it steady state when there is a fault or unforeseen disturbance in order to maintain the desirable performance while the sliding mode is to stabilize the state of the system.

Continuous upgrade is being done on the power system in order to load demand. The complexity in the power system has been accompanied by various types of problems; among them is power system instability which is the major concern. A power system may undergo transient instability when it is being subjected to a various disturbance such as variations in load, inadequate generation and faults on transmission lines. This problem not only deteriorates the stability of the power system but also may cause mechanical failure if not well damped or removed. This research proposes a nonlinear adaptive controller to overcome the problem of conventional controllers' inability to tackle the network uncertainties and deal with various operating conditions and disturbances.

Methodology

Model of the Single Machine Infinite Bus System

The proposed design methodology is applied to a single-machine infinite bus power system with control equipment such as a speed governor and voltage regulator in this work. The system parameters used in this work is shown in the Table 1 from the work of *Li et al 2018.*

Table 1 System Parameters

X_L	1.0p.u	M	7s	V_s	0.995p.u
ω_s	1.0p.u	T'_{d0}	7.4s	E_{fds}	1.123p.u
D	0.1p.u	$T_{H\Sigma}$	0.2s	X_T	0.15p.u
P_{m0}	0.9p.u	C_H	0.3	X'_d	0.3p.u
X_d	1.8p.u	C_{ML}	0.7		

Where;
X_L : is the reactance of the transmission line, M = $\frac{2H}{\omega_S}$: which represents the inertial. V_s : the voltage of the infinite bus. ω_s = 2πf: is the synchronous speed of the generator, T'_{d0} : d-axis transient open circuit time constant, E_{fds} : Excitation voltage when power system operation in a equilibrium. D: ≥ 0 is a damping constant. $T_{H\Sigma}$: Is the equivalent time constant of steam valve control system. X_T : Is the reactance of the transformer, P_m : The initial value of mechanical input power, C_H : Is the partition co- efficient for the high-pressure cylinder, X'_d : Is the d- axis reactance of the transformer.X_d : Is the d- axis reactance of the synchronous generator, C_{ML} : is the equivalent power partition co- efficient.

The model of the generator containing both power control and excitation loop were adopted. To solve the transient stability control problem of the single machine infinite bus power system, several controllers have been adopted by various researchers. For the purposed of this study, dynamic backstepping controller is adopted. The implementation procedures for dynamic backstepping controller are discussed in the following subsection.

Adaptive Backstepping Controller Design for Power Systems Stability

The technique of designing a nonlinear adaptive backstepping controller for power systems with excitation and steam-valve is described in this section. Proof of boundedness of the closed-loop system state trajectories is also presented. When there is a disturbance, the suggested adaptive backstepping controller ensures that the resulting closed-loop system is asymptotically stable and improves the transient stability of power systems. The adaptive back stepping controller's principal function or premise is to decouple a complicated nonlinear system into subdivisions or subsystems that do not exceed the system order. The goal is to create an adaptive control law for the generator power angle and steady-state frequency. In order to achieve the aforementioned goal, the following governing equations were defined:

The vertical stabilization function for speed can be formulated as follows

$$x_2^* = x_1^* + k_1 e_1 \quad (1)$$

Where;

$$x_1 = (d_1 e_1' + d_2 e_2' + x_3^* - b_2 c_s x_1 + b_3 x_3 - C^- + k_3 s_1)$$

$$V_2 = -K_3 S_1 - K_4 S_2$$

The Lyapunov function for speed is given as:

$$\frac{1}{2} e_2^2 \quad (2)$$

Where;

$$e_1 = x_2^* - x_1,\ e_2 = x_2^* - x_2$$

The virtual stabilization for transient potential is defined as:

$$x_3^* = -\frac{x_2^{;*} - \theta^{\Delta} + m_1 x_4 + d_1 p - k_2 e_2}{b_1 \sin x_1} \quad (3)$$

Where;

$$e_3 = x_3^* - x_3$$

Development of a sliding mode surface for stabilizing the states

In the development of a sliding mode surface for stabilizing the state, the dynamic model of a large-scale power system is described in phases, including all mathematical intricacies and physical assumptions. Therefore, in this research work, the following dynamics and electrical equations are used.

Step1: Choose an error compensation and virtual stabilization function

$$X_2 = -C_1 e_1 - P_1 e_2 \quad (4)$$

Where;

C_1 is a positive constant, $P_1 e_2$ is an error to compensate for the impact of the unknown error in the stabilization process? The value of e_1 can be expressed as $e_1 = -C_1 e_1 = +(1 - P_1)e_2$
$V_1 = e_1 e_1 = -C_1 e_1^2 + (1 - P_1)e_1 e_2$. It there for means that when $e_1 = 0\, V_1(< 0)$

Step 2: Define a Lyapunov function as follows.

$$V_2 = V_1 + \frac{1}{2} e_2 \quad (5)$$

Where;

$V_1 = \frac{1}{2}\, e_1^2$. Therefore, the V_1 Derivative along the trajectory is:

$$e_2 = X_2 - X_2 = \theta X_2 + \alpha_0 X_3 + b_0 \quad (6)$$

$$\mathrm{e}_2 = \frac{1}{1 - \mathrm{P}_1}[\theta X_2 + \alpha_0 X_3 + b_0 - k\sin(X_1 + \delta) + C_1 X_2] \quad (7)$$

and the derivative of V_2along the trajectory is:

$$V_2 = V_1 + e_2 e_2 \quad (8)$$

$$V_2 = C_1 e_1^2 + \frac{e_2}{1 - P_1}\{(1 - P_1)^2 e_1 + \theta X_2 + [\alpha_0 X_3 + b_0 - k\sin(X_1 + \delta_0) + C_1 X_2]\} \quad (9)$$

The vertical stabilization function can therefore be chosen as:

$$X_3 = -\frac{1}{\alpha_0}[(1 - P_1)^2 e_1 + \theta X_2 + b_0 - k\sin(X_1 + \delta_0) + C_1 X_2 + C_2 e_2 + P_2 e_3] \quad (10)$$

$$V_2 = -\mathrm{C}_1 e_1^2 + \frac{e_2}{1 - P_1}[\theta X_2 + C_2 e_2 + P_2 e_3 + \alpha_0 e_3] \quad (11)$$

Step 3: For the entire system, select the global Lyapunov function as:

$$V = V_2 + \frac{1}{2}\, e_3^2 + \frac{1}{2_\rho}\theta^2 \quad (12)$$

Where ρ > 0is a given adaptive gain parameter while

$$e_3 = X_3 - X_3'$$

$$= -\frac{1}{T_{H\Sigma}}X_3 + \frac{C_H}{T_{H\Sigma}}u + \frac{1}{\alpha_0}\Big\{(1-P_1)^2X_2 + \theta X_2 + \Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)[\alpha_0 X_3 + b_0 - ksin(X_1+\delta_0)] + \frac{C_2C_1X_2}{1-P_1} - kcos(X_1+\delta_0)X_2 + P_2e_3\Big\} \quad (13)$$

Where P_2e_2 refers to error compensation term, which compensate the dynamic impact of the unknown error in the stabilization process. The derivative of V is

$$V = V-2 + e_3\dot{e}_3 + \frac{1}{\rho}\theta\theta = -C_1e_1^2 + \frac{e_2}{1-P_1}[\theta X_2 + C_2e_2 + P_2e_3 + \alpha_0 e_3] - \frac{1}{\rho}\theta\theta + e_3\dot{e}_3 \quad (14)$$

$$V = -C_1e_1^2 - \frac{C_2}{1-P_1}e_2^2 + \frac{e_2\theta X_2}{1-P_1} - \frac{1}{\rho}\theta\theta + \frac{e_3}{\alpha_0-P_2}\Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)\theta X_2 + \frac{e_3}{\alpha_0-P_2}\Big\{\frac{\alpha_0e_2(\alpha_0-P_2)}{1-P_1} - \frac{P_2e_2(\alpha_0-P_2)}{1-P_1} - \frac{\alpha_0}{T_{H\Sigma}}X_3 + \frac{C_H}{T_{H\Sigma}}\alpha_0u + (1-P_1)^2X_2 + \theta X_2 + \Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)[\theta X_2 + \alpha_0X_3 + b_0 - ksin(X-1+\delta_0)] + \frac{C_2C_1X_2}{1-P_1} - kcos(x_1+\delta_0)X_2 + (\alpha_0-P_2)C_3e_3\Big\} \quad (15)$$

If the value of θ is:

$$\theta = \rho\Big[\frac{e_3X_2}{1-P_1} + \frac{e_3}{\alpha_0-P_2}\Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)\Big]X_2 \quad (16)$$

Then

$$V = -C-1\,e_1^2 - \frac{C_2}{1-P_1}e_2^2 - C_3e_3^2 \quad (17)$$

Finally, according to the defined problem statement and the controller objective which is to stabilize the states in the power system the backstepping adaptive controller was obtained, as described in the following theorem.

Consider model for the valve control system, if there exist new control parameter ρ_i and constant $C_I.0 < \rho_i, C_i < 1$

i. The control law u which based in backstepping adaptive controller for the nonlinear system is as follows.

$$u = -\frac{T_{H\Sigma}}{C_H\alpha_0}\Big\{\frac{\alpha_0e_2(\alpha_0-P_2)}{1-P_1} - \frac{P_2e_2(\alpha_0-P_2)}{1-P_2} - \frac{\alpha_0}{T_{H\Sigma}}X_3 + (1-P_1)^2X_2 + \theta X_2 + \Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)[\theta X_2 + \alpha_0X_3 + b_0 - ksin(X_1+\delta_0)] + \frac{C_2C_1X_2}{1-P_1} - kcos(X_1+\delta_0)X_2\Big\} \quad (18)$$

ii. The control law u, the closed loop under new coordinate (e_1, e_2, e_3) is as follows:

$$e_1 = -C_1e_1 + (1-P_1)e_2, \quad (19)$$

$$e_2 = \frac{1}{1-P_1}[\theta X_2 + \alpha_0e_3 - e_1(1-P_1)^2 + C_2e_2 + P_2e_3], \quad (20)$$

$$e_3 = -\frac{\alpha_0e_2}{1-P_1} + \frac{P_2e_3}{1-P_1} + \frac{1}{\alpha_0-P_2}\Big(\theta + C_1 + \frac{C_2}{1-P_1}\Big)\theta. -C_3e_3 + kcos(X_1+\delta_0)X_2 \quad (21)$$

iii. Under the influences of the control input, the closes loop error system is asymptotically stable. This implies that V(t) ≤ V (0), namely e_1, e_2, s, X_1, X_2 are bounded and V (0) is bounded V(t) is also decreasing and bounded.

The Lyapunov function is made up of one error variable and one virtual control design for each step in traditional backstepping. However, error compensation outperforms typical backstepping because we enhance the Lyapunov function for each step by mixing an error variable, virtual, and error compensation to increase the dynamic impact of the unknown error.

Comparison of the performance of the developed controller

The performance of the developed model in this research is assessed using a set of metrics. Settling time of the power angle, relative speed of recovery, transient potential stability and input mechanical power are the measures used. The comparison is made by comparing the results of the developed scheme with that of the Immersion & Invariance controller which is implemented in the work of (Li et al., 2018).

Results

The outcomes of the designed adaptive structure control scheme in a power system with excitation and steam valve are presented and explored. The controller's performance was examined for transmission line faults. Because this is one of the most serious problems that can occur during synchronous machine operation. The developed system was simulated in MATLAB/Simulink using the parameters listed in table 1, as explained in section 3. The power system's power angle response is shown in Figure 1.

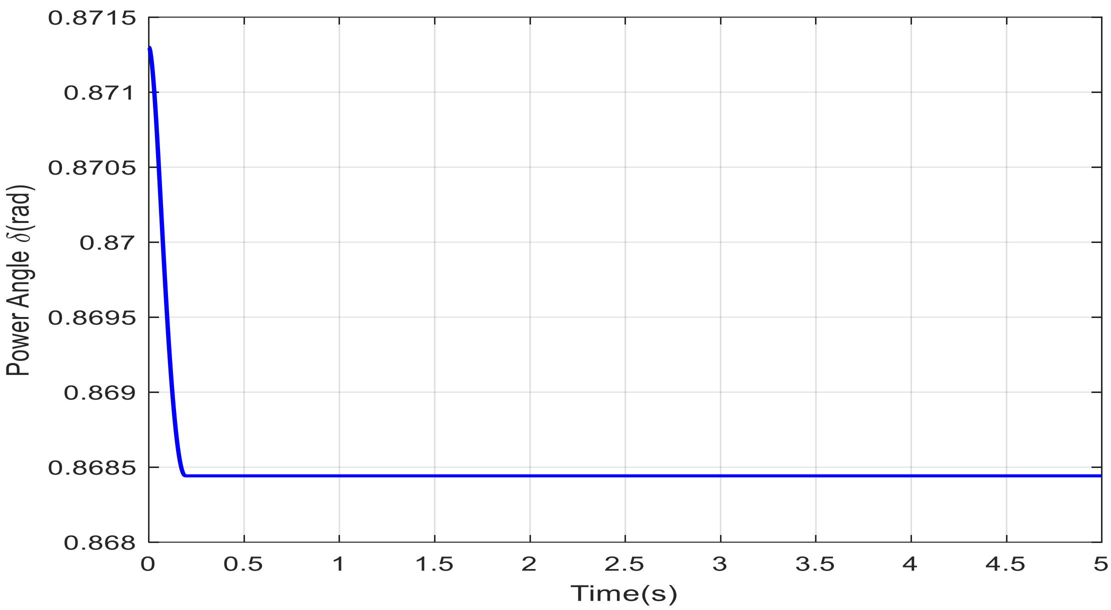

Figure 1: Power Angle Response of the System

The system achieves stability at 0.25 seconds after the problem occurs, as seen in the plot. This is well within the system's tolerable range before it loses synchronization. Figure 2(a) shows the system’s relative speed. It is seen from the figure that the system converges at time 0.2 seconds after the introduction of fault. This shows that the controller implemented in this work was able to damp out the oscillations quickly.

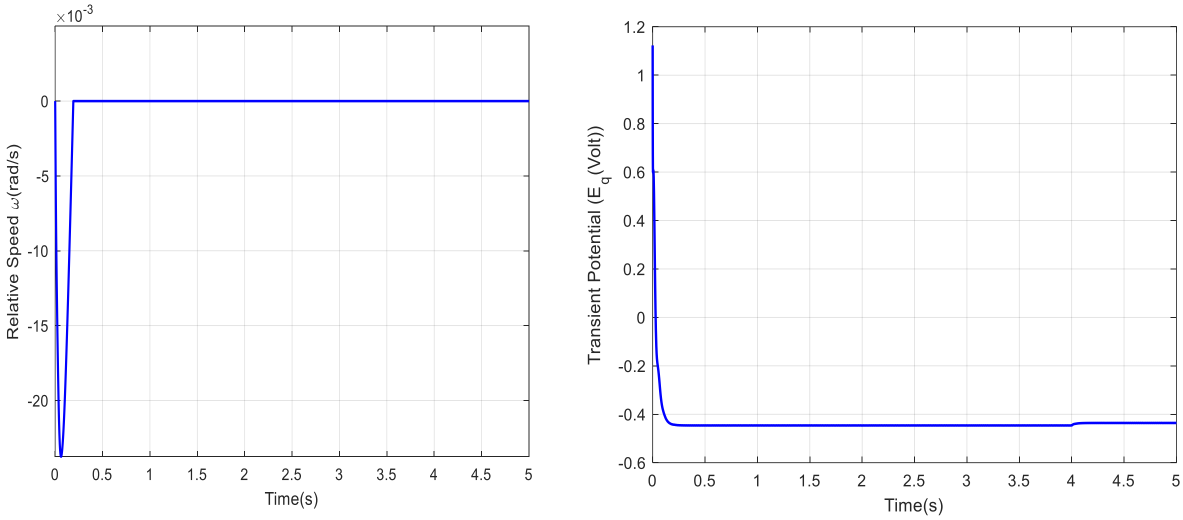

Figure 2(a): Relative Speed of System Recovery. (b) Figure b: The Transient Potential Stability

Figure 2(b) shows the transient potential stability obtained from the proposed controller. As seen in the plot, the introduction of fault in the system causes oscillations in the system. The system settling time obtained was 0.2 seconds. This is well within the limit set by IEEE standard.

Figure 3(a) shows the plot obtained for change in input mechanical power of the system. As seen from the plot the system settling time is 0.21 seconds. After which the system maintains its stability all through. Figure 3(b) shows the excitation control of the power system. The developed system was incorporated into the excitation and steam valve controller to ensure stability of the system during the occurrence of fault. Based on this, the result presented in Figure 3(b) show the obtained result.

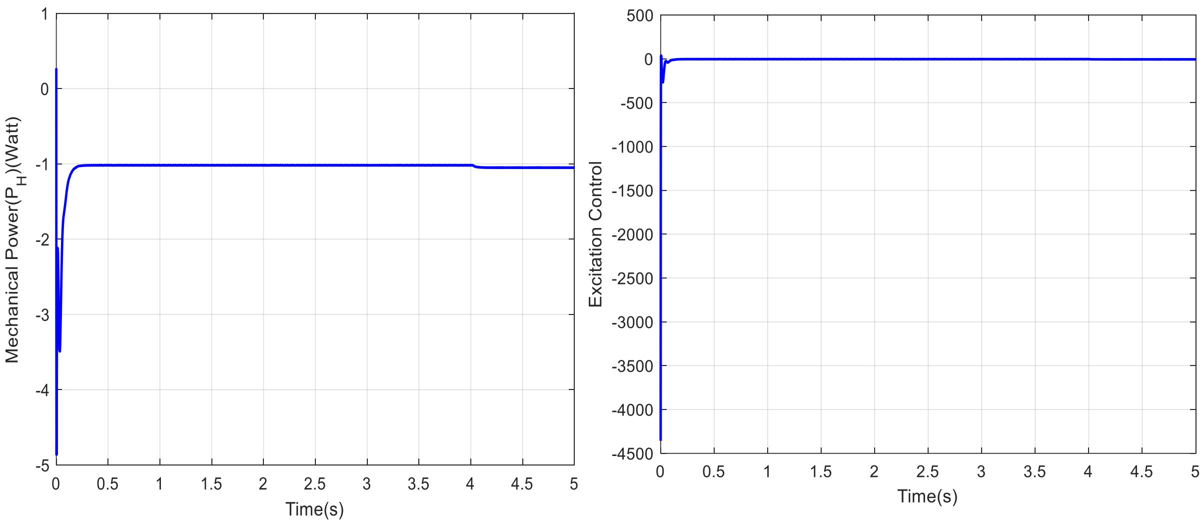

Figure 3(a): The Change Input Mechanical Power (b): Excitation Control of Proposed Controller

As seen in the Figure, immediately after the introduction of fault, the excitation plot was able to settle at time 0.15 seconds. This shows that the adaptive controller was able to minimize the disturbances.

Figure 4(a) shows the steam valve control of the synchronous generator in power system from the proposed controller. As seen in the Figure, the introduction of fault causes oscillation. However, it was observed that the system settles at time 0.15 seconds.

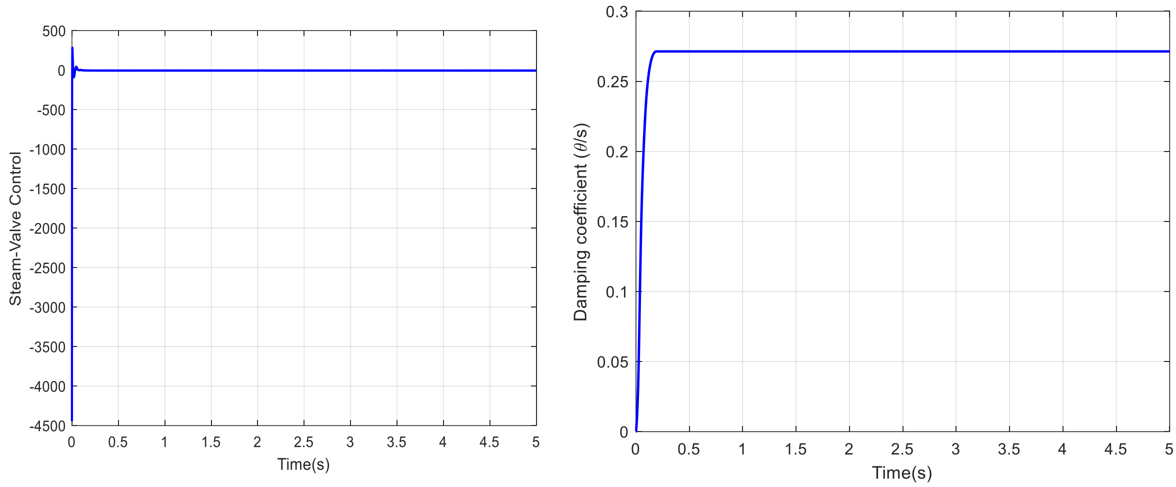

Figure 4(a): Steam-valve Control from Proposed Controller (b): Damping Coefficient of the Proposed Controller

Figure 4(b) shows the damping coefficient of the synchronous generator in power system from the proposed controller. As seen in the Figure, since the introduction of fault causes oscillations, the damping coefficient of the proposed controller was observed to be 0.2 seconds.

Figure 5 shows the surface sliding of the synchronous generator in power system from the proposed controller. As seen in the figure, immediately after the introduction of fault, the excitation plot was able to settle at time 0.25 seconds. This shows that the adaptive controller was able to minimize the disturbances.

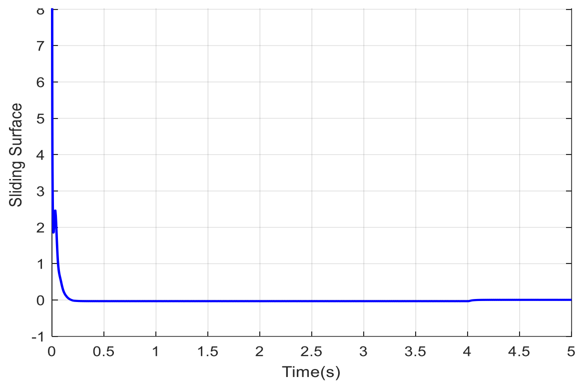

Figure 5: Sliding Surface of the Proposed Controller

Comparison of the Results Obtained

The power system results achieved when the adaptive control scheme was utilized were compared to those obtained when immersion and variance control were applied. The power angle, relative speed, transient potential, and input mechanical power graphs obtained when a disturbance was applied to the system were used to compare the two methods' performance. Figure 6 shows the comparison of the power angle plots of the system.

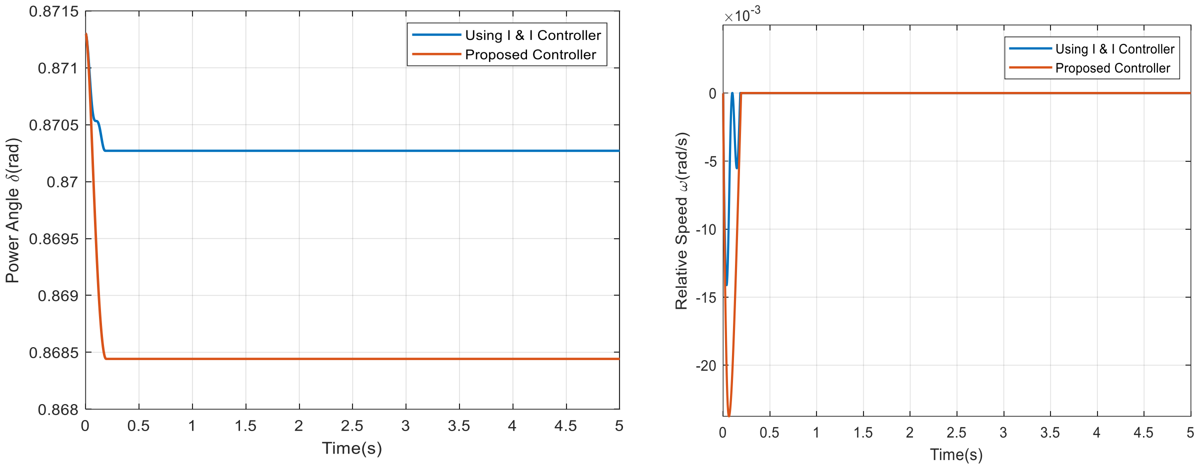

Figure 6(a): plot of Comparison of Power Angle (b): Plot of Comparison for Relative Speed of System Recovery

It is seen from the plots that the power angle of the developed system attains stability at time 0.250 seconds, while that of the immersion and variance control method attains stability at time 0.263 seconds. The result obtained from the developed scheme showed 5.2% improvement over that of the immersion and invariance technique (I & I controller). It is seen from the figures 6(b), that the relative speed of recovery of the proposed scheme is 0.2 seconds, while that for the immersion and invariance control is 0.25 seconds. However, it was observed that the improvement of the developed scheme over that of I & I control scheme, in terms of settling time is 20 %. Figure 7(a) shows the transient potential stability obtained from the developed scheme and the I & I scheme respectively.

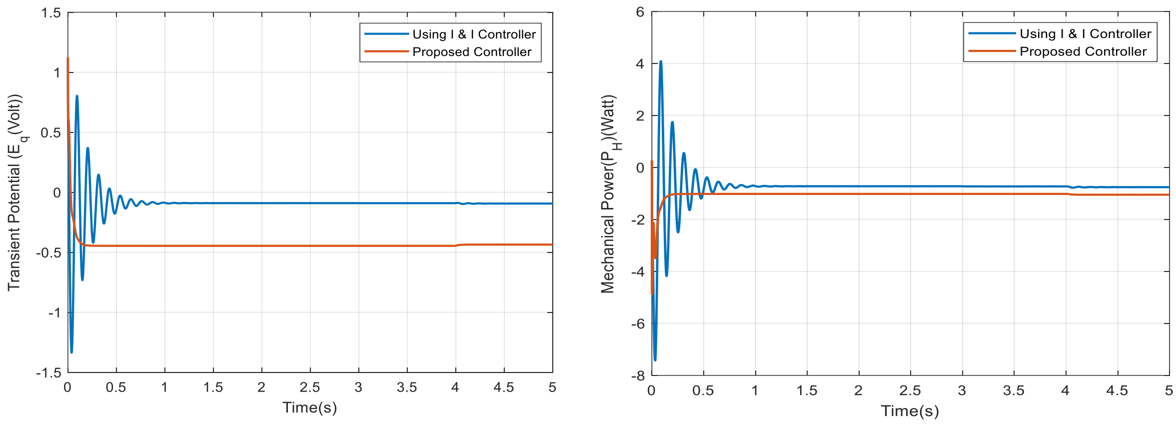

Figure 7(a): Comparison of the Transient Potential Stability (b) Change in Input Mechanical Power

From the results obtained, it was observed that for the developed scheme, the transient potential stability settling time is 0.2 seconds. While that of the I & I control technique only settles at 0.95 seconds. These show that the developed system achieves a performance improvement of 78.9% over that of the I & I technique. Figure 7(b) shows the plot for the change in input mechanical power for the developed system and that of the immersion and variance control. The Figure showed the plots obtained for the change in input mechanical power for the developed system and the I & I technique. From the plots it is observe that for the developed scheme, the system settles at 0.210 seconds, while a settling time of 0.920 seconds was obtained for the I & I control scheme. This shows that 78.9% percentage improvement was obtained for the developed scheme over the I & I method.

Figure 8(a) shows the plot for the excitation control for the developed system and that of the immersion and variance control. The Figure showed the plots obtained for the excitation control for the developed system and the I&I technique. From the plots it is observe that for the developed scheme, the system settles at 0.15 seconds, while a settling time of 0.6 seconds was obtained for the I&I control scheme. This shows that 75% percentage improvement was obtained for the developed scheme over the I&I method. Figure 8(b) shows the plot for the excitation control for the developed system and that of the immersion and variance control. The Figure showed the plots obtained for the steam value control for the developed system and the I&I technique. From the plots it is observe that for the developed scheme, the system settles at 0.15 seconds, while a settling time of 0.6 seconds was obtained for the I&I control scheme. This shows that 75% percentage improvement was obtained for the developed scheme over the I & I method.

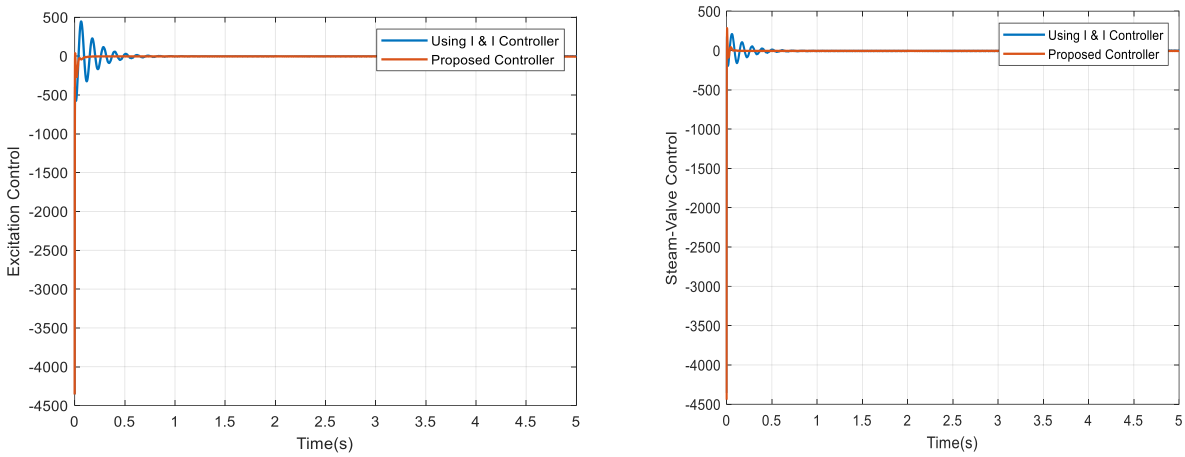

Figure 8(a): Plot of Comparison of the Excitation Control (b): Steam-Value Control

Conclusion

An improved performance of synchronous generator in power system has been developed in order to improve the system stability during line disturbance. The developed scheme was implemented using MATLAB. From the analysis, it was observed that the settling time for the stability criteria: power angle, relative speed of system recovery, transient stability, mechanical input power, excitation control, steam-value control, damping coefficient and sliding surface of the developed scheme is 0.25, 0.20, 0.20, 0.21. 0.15, 0.15, 0.2 and 0.25 respectively. b) The adaptive voltage control scheme produced a percentage improvement of 5.2%. 20%, 78.9%, 78.9%, 75%, 4.76% and 64% over the immersion and invariance control scheme (I&I method.) in terms of power angle, relative speed of system recovery, transient stability, mechanical input power, excitation control and steam-value control. This showed that the developed scheme was able to damp out disturbances in the system quickly due to the dynamic back stepping controller introduced.

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