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Power system stability and control: a comprehensive review focusing on the rotor angle case

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ABSTRACT

This paper provides a review of power system stability, focusing on the rotor angle case. To gain a preliminary understanding of the stability studies, the discussion begins with an overview of generators in power system generation. The distinguishing parameters of synchronous generators as compared to their counterparts such as induction generators, inductor alternators, and direct current generators are also emphasized. The discussion that is not bounded within their stability issues and control strategies is briefly assessed. The shortcomings and advantages of various modeling approaches are also discussed therein. To extend the thoughts, this review includes a thorough discussion and classification of power system stability, which includes rotor angle stability, frequency stability, and voltage stability. The stability of the rotor angle is important as it ensures frequency stability and voltage stability. This paper also presents the power system modeling approach that is able to facilitate the rotor angle stability studies. This paper also aims to review the established rotor angle stabilizers and algorithms developed by previous researchers.

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1. INTRODUCTION

The power system has become very crucial in the generation of electrical power for worldwide use. This electrical power system provides electrical power to homes and industries within an extended area. Basically, the electrical power system is a grid of generation, transmission, and distribution systems. In the generation system, the kinetic energy from turbines, either steam, hydro, or gas, is converted into electrical power. Then, the transmission system carries the power produced by the generation system to the distribution system, where it will be distributed to nearby homes and industries. According to Shu and Tang [1], the generation system is the most important component in the power system because the generator will assure the stability of power system operation even with the occurrence of failures by providing voltage and frequency support and also grid control measure coordination. There are several types of generators used in power systems: a synchronous generator, an induction generator, an inductor alternator, and a direct current generator. All of these generators have different characteristics.

A synchronous generator is designed to control the amplitude and frequency of the generated voltage [2]. According to Kim and Park [3], synchronous generators are mainly used in medium and large power plants. Kim and Park [4] stated that a synchronous generator has advantages in terms of rotational inertia, reactive power supply, voltage support, and durability. A synchronous generator has its own magnetic field; thus, it is capable of delivering active and reactive power, which means it is able to generate and control output voltage [5], [6].

The induction generator is the simplest form of alternating current (AC) generator and is designed to produce a power frequency supply. Induction generators, which are simple in shape and easy to maintain, produce small output power, which makes them preferable for small power plants of less than 1000 kW [3], [6]. The most commonly used induction generator is in wind power plants [7]. The induction generator also has a relatively low price, good reliability, and a self-defence feature against short circuits [6], [8]–[10]. However, the voltage and frequency of the induction generator are very difficult to control in a stand-alone state [11]. It has no magnetic field and needs an electric supply. Thus, this type of generator is capable of delivering only active power and consuming reactive power to generate a magnetic field [6], [8], [9]. Commonly, for small power plants, synchronous generators are parallel to induction generators in order to provide the reactive power required by induction generators [6]. On the other hand, according to Lee and Sim [10], reactive power can be supplied by connecting a capacitor bank with a suitable rating of a pre-charged capacitor across the stator terminal. The reactive power can also be supplied by battery start-up on the DC-side of the voltage source inverter, or by the grid connection of the induction generator, which then becomes a self-excited induction generator [12]. Furthermore, the inrush current generated by the induction generator corresponds to the starting current of the induction motor. As such, resulting in a voltage drop on the grid, which may lead to damage to equipment on the same branch line and consumer load equipment and deteriorate the stability of the system [3], [13], [14]. According to Rafa *et al*. [15], the induction generator that is connected to the wind turbine will absorb and consume reactive power during steady state and fault occurrence, which reduces the system voltage and affects the voltage stability. Another limitation of an induction generator is that it can only be operated in a saturated region [16].

An inductor alternator is a special type of synchronous generator. It is designed for high-frequency supplies, such as high-frequency heating loads [16], [17]. The armature winding and field winding are fixed, and both windings are located in the stator slots. The rotor of an inductor alternator consists of a solid core forged with alloy [18]. It is slotted, which results in induced voltage due to the reluctance of the flux path of the phase and field coil to pulsate between maximum and minimum values [19]. According to Serebrjakovs *et al*. [20], inductor alternators are mostly used as small and medium power machines such as diesel alternators, rail vehicle and welding alternators, and gearless wind alternators, while [18] stated that inductor alternators are widely used for medium to high frequency generation such as flywheel energy storage system (ESS) and pulse power systems. This inductor alternator has the same advantages as a self-excited induction generator in terms of ruggedness, ease of maintenance, and the absence of slip rings and brushes. Moreover, inductor alternators are able to operate in the complete range of magnetization characteristics. On the contrary, the inductor alternator is a heavier unit compared to other generators because it contains less than 50% iron. This generator increases the total air gap in the magnetic circuit, which requires moving excitation.

A direct current generator is frequently used to generate electricity in stationary and portable autonomous power sets for vehicles such as aeroplanes, trains, and automobiles, as well as unconventional power plants [21]. This type of generator has high reliability [22], [23]. According to Carlin *et al*. [24], the principle of a direct current generator is based on load current induction in the armature winding by moving the armature winding in a stationary magnetic field. This type of generator provides its own field current. However, the inclusion of commutators and brushes increases the design's cost and decreases its reliability. Due to their low efficiency, copper losses, eddy current losses, hysteresis losses [25], and mechanical losses, direct current generators cannot be used with transformers. This generator also reports a voltage drop over long distances. The rest of the sections in this manuscript aim to focus more thoroughly and deeper on a synchronous generator.

2. SYNCHRONOUS GENERATOR

A synchronous generator plays an important role in a power system. The synchronous generator consists of a stator, an armature winding, a rotor, a field winding, and a damper winding. The stator is the synchronous generator's stationary component. The armature winding is housed in slots on the stator. It generates balanced three-phase voltages. The generator's revolving component, the rotor, is propelled at a constant speed by a prime mover. It consists of a field winding that generates the main field flux. A field exciter is required, and it is powered by direct current through two slip rings. The rotor and exciter are both positioned on the same shaft. The generator voltage must be maintained, and reactive power flow must be controlled. The damper winding is a short-circuit winding that is located on the rotor.

2.1. Rotor construction of a synchronous generator

The synchronous generator can be categorized into a salient pole and a non-salient pole, also known as a cylindrical pole, according to the rotor construction. The salient pole rotor has concentrated winding on the poles, which produces non-uniform air gaps. This results in a non-uniform flux. This type of rotor is designed for low- and medium-speed operation, which is preferable for hydroelectric power stations. The characteristics of a salient pole rotor are a large number of poles, a large diameter, and a small axial length. On the other hand, a non-salient pole rotor has one distributed winding and a uniform air gap, which result in uniform flux distribution. This type of rotor is designed for high-speed operation (1800 rpm or 3600 rpm), preferably driven by a steam turbine. This non-salient pole rotor has either two or four poles, a small diameter, and a large axial length. According to Saadat [26], most large synchronous generators employ non-salient pole rotor types ranging from 150 to 1500 MVA. The structure of both salient pole and non-salient pole rotors is shown in Figures 1(a) and (b).

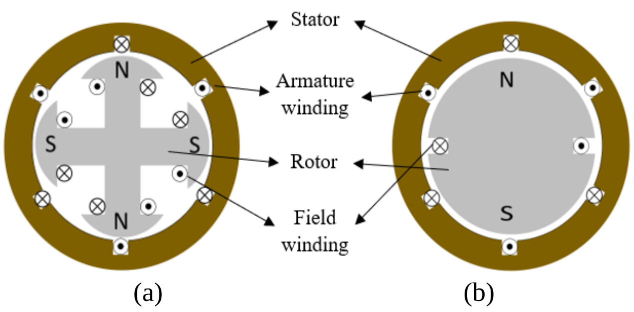

Figure 1. Pole rotor: (a) salient and (b) non-salient

2.2. Method to model a synchronous generator

The most crucial component in modeling the power system is the formulation of the dynamics of the synchronous generator. This is because its synchronism and operational stability are vital to the stability of the power system [27], [28]. The dynamic performance of the synchronous generator predominantly determines the dynamic behavior of the power system [29]. However, the accuracy of power analysis depends on the assumptions and simplifications made to the synchronous generator model [28].

The basic modeling of synchronous generators is via a direct-phase modeling approach. The model developed from this approach is known to be able to be simulated under various load conditions. The load conditions may include the sudden application and removal of balanced and unbalanced loads, symmetrical and asymmetrical faults, and rectifier loads [30]. Even though the model is complicated and incures high level mathematical burden, it features an excellent level of accuracy. As such, the validation of the model is non-disputable.

Park’s transformation is another type of mathematical modelling for synchronous generators. Under steady-state conditions, Park's transformation principle converts the voltages, currents, and flux linkages that make up three-phase time-varying stator quantities into time-invariant direct-axis and quadrature-axis quantities. This type of modelling is also known as abc to $dq0$ transformation, where the three-phase instantaneous voltages (or currents) are transformed into the synchronously rotating reference $dq0$ at time $t = 0$ second. Yurika *et al.* [28] stated two advantages of Park’s transformation model: due to its independence from the rotor position, the corresponding equation becomes time-invariant, and state variables are constant in steady-state conditions. However, this model is incapable of easily simulating unbalanced and rectifier loading conditions [30]. This model limits symmetrical systems in terms of reducing computation, while asymmetric systems lead to inaccuracies [31]. Moreover, simplifications made in this model degrade the accuracy towards disturbances, such as assuming constant inductance values along direct and quadrature axes and neglecting the effect of space harmonics in the air gap flux distribution [32].

3. POWER SYSTEM STABILITY

Maintaining synchronization between various components of the power system has become more challenging over time. If synchronism between the generator and the power systems is disrupted at any point, voltage and current fluctuations may occur, potentially causing catastrophic impacts on end users and power systems. As such, the need for power system stabilizers (PSS) is a must and crucial to the design engineers. Power system stability is the ability of an electrical power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to physical disturbances. It is noted that most of the power system variables are bound, so practically the entire system remains intact [33]. The classification of power system stability proposed here is founded on the following factors, which were taken into account by the authors in [34]: first, the physical nature of the ensuing mode of instability, as indicated by the main system variable in which instability can be observed. Second, the method of computation and stability prediction is affected by the magnitude of the disturbances that are taken into account. Lastly, the devices, the method, and the duration must all be taken into account in order to reach stability. Figure 2 depicts the categories and subcategories of the power system stability problem generally. Power system stability can be categorized into rotor angle stability, frequency stability, and voltage stability.

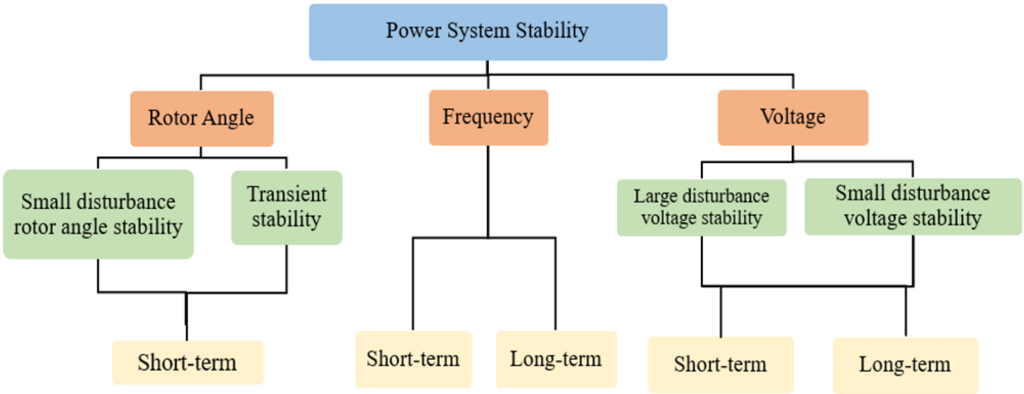

Figure 2. Classification of power system stability

The power system is a highly nonlinear system that functions in a dynamic environment that includes loads, generator outputs, and important operational factors. The stability of a system under disturbance is dependent on both the initial state and the type of disturbance. Power systems are vulnerable to a wide range of small and large disturbances. Small disturbance refers to disturbances that occur randomly and slowly, while large disturbance refers to the sudden occurrence of disturbances that must be eliminated rapidly [28]. Continuously, there are small disturbances in the form of load variations, and the system must be able to adapt to the changing environment and function well. Additionally, it must be able to withstand several severe disturbances, like a transmission line short or the loss of a sizable generator. Due to the isolation of the faulted parts, a large disturbance may result in structural alterations.

According to Kundur *et al*. [35], at equilibrium, a power system may be stable for one physical disturbance and unstable for another. Designing power systems to be stable for all potential disturbances is therefore impractical and uneconomical. A stable equilibrium set has a finite region of attraction, and the wider the region, the more robust the system is with respect to large disturbances. The region of attraction fluctuates depending on the state of the power system.

Rotor angle stability refers to the ability of the synchronous generator of an interconnected power system to remain in synchronism both under normal operating conditions and after being subjected to a disturbance [36]. This type of stability depends on the ability to preserve or restore equilibrium between the electromagnetic torque and mechanical torque of each synchronous machine in the system. The rotor angle stability can be categorized into two categories: small disturbances and transient disturbances [37]. The stability of a small disturbance is determined by the operational point rather than the disturbance. The instability may cause a non-oscillatory or aperiodic increase in rotor angle and an increase in the magnitude of rotor oscillation due to insufficient damping. The time frame for response to a small disturbance is within 10 to 20 seconds. Transient stability, on the other hand, is influenced by the disturbance's location, type, size, and initial operating point. The system response includes a substantial excursion of the generator rotor angles. In most cases, the instability takes the form of periodic angular separation, and the response time frame is within 3 to 5 seconds. However, for a very large system, it may be extended for a longer period, from 10 to 20 seconds. The instability caused by large disturbances may originate from a short circuit on the transmission line, a system fault, the opening of fault line outages, or generation or load losses. Both small disturbances and transient disturbance instability are short-term phenomena that arise in the first few seconds after the occurrence of disturbances [38].

Frequency stability refers to the ability of a power system to maintain a steady state of frequency following severe disturbances. Stability is dependent on the ability to restore equilibrium between system generation and load demand with the least amount of load loss. Unbalanced generation and load, poorly coordinated control and protection equipment, a lack of sufficient generation reserves, inadequate equipment responses, a lack of system inertia and damping as a result of increased penetration of renewable energy sources, and unexpected load disturbances are all factors that contribute to instability [39]. Frequency stability can be categorized as short-term or long-term. The short-term phenomenon is the formation of islands with insufficient generation and frequency load shredding, which causes system frequency degradation and island blackouts within a few seconds [40]. In contrast, for long-term phenomena like boiler protection and control or steam turbine overspeed control, the response time will vary from 10 seconds to several minutes.

Voltage stability is the ability of a power system to maintain a constant tolerable voltage at every single bus of the network, both during regular operation and in the event of a disturbance [41]. Stability is determined by the system's ability to maintain an equilibrium between load demand and load supply. Reactive power restrictions, severely loaded, faulty, or insufficient reactive power sources, as well as the system's failure to satisfy its unexpectedly increasing demands for reactive power, are all contributing factors to the instability. Voltage stability can also be divided into short-term and long-term phenomena. The short-term phenomena involve the dynamic response of fast-acting load components over several seconds. Conversely, slower-acting devices, such as tap-changing transformers and generator current limiters, involve long-term phenomena [35]. The voltage stability is classified into small and large disturbances. Small disturbance stability refers to the ability to maintain a stable voltage in the presence of small disturbances, such as gradual changes in load. This is mostly influenced by the load characteristics and controls in place at any given time. On the other side, large disturbance voltage stability refers to the ability to keep a constant voltage after a large disturbance. It necessitates computation of the power system's nonlinear response, which takes into account interactions between a variety of components, including motors, transformer tap changers, and field current limiters.

4. ROTOR ANGLE STABILITY AND CONTROL

A power system dynamic can be obtained via the modeling of a single-machine infinite bus system (SIMB). In this configuration, one generator is connected to a significant substation of a very large system through a transmission line, as depicted in Figure 3 where E' is the voltage, X'_d is the direct axis transient reactance, V_g is the generator terminal voltage, V is the voltage at load terminal, Z_L is the load impedance, and Z_S is the source impedance. Power system disturbance simulation frequently employs this model since it is highly representative of the actual power system [27].

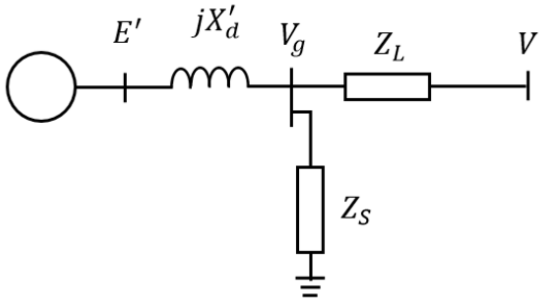

Figure 3. Single machine infinite bus system

The swing equation is the most beneficial mathematical representation of a SIMB system that facilitates the stability analysis of the rotor angle. In other words, it is a nonlinear second-order differential equation [42] that defines the dynamic of the SIMB system. It describes the temporal relationship between the relative motion of the rotor axis and the synchronously rotating stator field. The relative position remains constant under normal operating conditions. However, during the disturbance, the rotor experiences relative motion as it either accelerates or decelerates with regard to the synchronously rotating air gap magneto motive force (MMF). The relative motion causes an angle to form between the rotor axis and the resulting magnetic field, which is known as the power angle, as shown in Figure 4. The power angle is required to remain in the optimum range to ensure the rotor angle is in equilibrium. In a stable system, the power angle lies between 20° and 30°. However, the power angle can reach a maximum of 90° in stable operation before the generator loses synchronism.

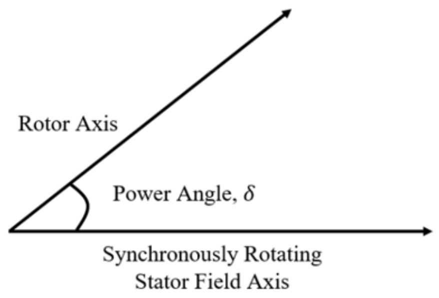

Figure 4. Power angle

In synchronous generators, the power angle curve is very important as it represents the graphical electrical output of the generator with respect to the power angle, as shown in Figure 5. Note that the nomenclature P_m represents mechanical power, P_e represents electrical power, P_{max} denotes maximum power, and δ_o is the initial power angle. At the intersection of P_m and δ_o of the curve, the rotor angle stability is said to be in a steady state condition in which $P_m = P_e$, load angle δ=δ_o, and rotor speed ω_m is in synchronism with synchronous speed, ω_{sm}. When P_e is in the range of the curve 1, $P_m > P_e$ and $\omega_m > \omega_{sm}$. Thus, the rotor will accelerate, which increases the load angle. The rotor will oscillate a few times around δ_o until it returns to a steady state condition again. When P_e is in the range of the curve 2, $P_m < P_e$ and $\omega_m < \omega_{sm}$. As a result, the rotor will decelerate to regain steady-state conditions. However, if P_e is beyond P_{max} point as indicated by the curve 3, the rotor is in an instability region in which the load angle δ is increasing and never come back to its initial power angle δ_o.

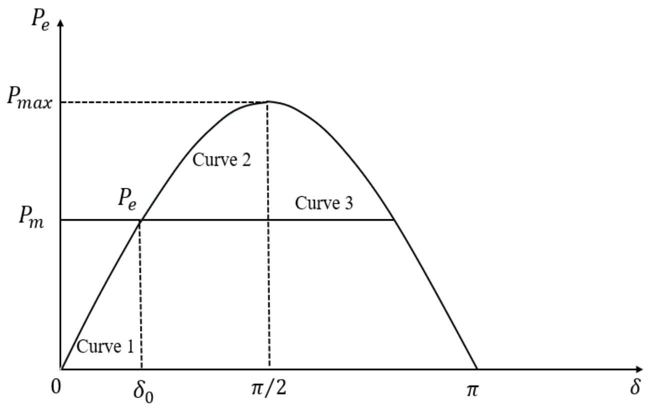

Figure 5. Power angle curve

The stability of the synchronous generator is maintained if the rotor locks back into synchronous speed. The rotor returns to its normal operating condition if the disturbances do not involve any net change in power. Otherwise, the rotor operates at a new power angle corresponding to the synchronously rotating field. The performance of the synchronous generator will be degraded if the rotor angle changes due to disturbances.

Ensuring the stability of the rotor angle also ensures frequency stability as well as voltage stability of the power system. This is due to the fact that power system frequency is directly proportional to the rotational speed of the generator, which refers to rotor speed [40]. The system's synchronous generator can become unstable by either having an increasing rotor angle due to insufficient synchronizing torque or an increasing amplitude due to insufficient damping torque [35], [37], [43], [44]. The damping power is an important function that minimizes the difference between the two angular velocities, so neglecting it is an impractical assumption [45], [46]. In recent years, numerous articles have studied rotor angle stability via various methods, emphasizing only the assessment of the stability without proposing a controller for stabilization enhancement: Lyapunov exponent method [47], voltage source converter-based (VSC-based) high-voltage direct current method [48], energy index based on normal form method [49], stability index vector [50], Lyapunov direct method [42], maximum Lyapunov exponent [51], and fault-on trajectory [38]. These assessment studies are focusing on how fast and accurately the analysis can be conducted, which is expected to help in planning the power system by providing a protection system and corrective action that result in a safe power system [38].

On the other hand, in the past five years, numerous researchers have conducted studies on rotor angle stability enhancement via numerous methods. For instance, Charafeddine *et al.* [52] employed Euler's numerical solution of the swing equation to regain the stability of the synchronous generator of a power system. However, the damping power is neglected, which is an impractical assumption for the system. Moreover, Euler's method is only accurate for the occurrence of small disturbances. The analysis conducted on a SIMB system in this article defines the critical clearing time of the system, which was found to be 0.4 seconds. The authors also consider transient stability for multi-machine systems via the Newton-Raphson method, but this is limited to analysis purposes only. The voltages behind the transient reactance are obtained by neglecting generator armature resistances. The stability of the system is determined by the fault clearing time. The well-defined fault clearing time helps in setting the operation of the power system.

Other common numerical techniques for estimating the solution of the swing equation, as stated by Zaidi and Cheng [53], are the Euler-modified method, the Runga Kutta method, and the point-by-point method. However, the limitations of these techniques confine their functional domain. The researchers [54], [55] use PSS to regulate the rotor angle stability, which helps add damping to the generator's rotor. The advantages of PSS are clear physical concepts, a simple circuit, and convenience for on-site adjustment [54]. However, a shortcoming of using PSS is that it is time-consuming to tune the stabilizer.

Baadji *et al.* [55] studied rotor angle stability via PSS. The synchronous model employed in this paper is model 2-2, which has one d-axis damper winding and two q-axis damper windings. The simulation is done with a SIMB system in the time domain. The IEEE Type ST1A is used to present the excitation system, while the IEEE type PSS1A is used to present PSS in the simulation. According to the authors, PSS extends stability limits by modulating generator excitation. The disturbance considered in this paper is a symmetrical three-phase short circuit fault that occurred at 2 seconds. The fault clearing time is set to 0.05 seconds and 0.08 seconds, respectively. The finding is the comparison of the system output voltage between three scenarios: manual excitation control, automatic voltage regulator without PSS, and automatic voltage regulator with PSS. The model proved that PSS helps ensure a satisfactory response for transient stability studies.

A rotor angle stability study via PSS was also conducted by the authors in [54]. The study regulates the synchronous generator's rotor angle to solve the inter-area mode of oscillation. The synchronous model used in this study is the t-model. The excitation control system is required for the synchronous generator. The PSS supplied an accurate DC voltage in the exciter input, which then properly excited the generator for rotor stabilization. The result, which compared the system with and without PSS, proved that PSS helps enhance power system stability. However, according to the authors, the PSS effect on inter-area oscillation is very limited. Moreover, the synchronous generator model in this study is linearized with small stator winding resistance, which is neglected. Thus, this study is limited to small disturbance stability.

Kumar *et al*. [56] use PSS and a thyristor-controlled series compensator (TCSC) in order to enhance the rotor angle stability of a SIMB system. The model of the synchronous generator used by the authors is a linearized swing equation; thus, the research is limited to small signal stability enhancement only. On the other hand, online tuning of PSS using genetic programming is conducted by authors in [57] in order to enhance power system stability. However, the fourth-order model is linearized, thus the research is limited to small signal stability.

The researchers [58], [59] enhanced the rotor angle stability by solving the swing equation via sliding mode control (SMC). However, the chattering problem of SMC is inevitable. Jiang and Wang [58] conducted a study on the enhancement of transient stability via SMC and VSC control. The power system considered in the study is composed of 3 generators, 3 loads, and 9 buses. The swing equation is used to model the synchronous generator. The advantages of SMC stated by the authors are its robustness, fast convergence, and wide application in nonlinear systems. The proposed control method in this study is the regulation of frequency. The Lyapunov function technique is also applied in the proposed method to ensure convergence and asymptotic stability. The simulation result of the study proves that the proposed method is able to enhance power system transient stability by reducing rotor oscillation and improving critical fault clearing time. However, damping power is neglected in the system model.

Rotor angle stability can also be achieved by reshaping the accelerating power of synchronous generators and decoupling them after grid disturbances, as conducted by the authors in [59]. The proposed method used an ESS-based SMC. The swing equation of a synchronous generator is applied to a 2-area, 4-generator system. In this study, a switching term is required for SMC to compensate for the disturbance term. The switching term must be very large in conjunction with a very large disturbance term. However, the ESS-SMC will lose its functionality if the ESS power rating is unable to meet the switching term's large requirement and fails to achieve the aim of this study. Moreover, the active current regulation of the ESS of the proposed method diminished the effect of improving the power system rotor angle stability during low-voltage periods.

Particle swamp optimization (PSO) is also one of the numerical methods used by the authors in [53] to sustain the transient stability of a synchronous generator's rotor. The power systems considered in this study are single machines with infinite buses and two machines with five buses modelled by the swing equation. However, the damping power is neglected. The swing equation is transformed into an optimization problem that has yet to be solved via PSO. The result gives a satisfactory approximation of the solution. The result shows that a well-predetermined fault clearing time helps in ensuring system stability and reliability at all times, but the regulation of the speed might not be accurate due to partial optimism.

Conversely, Papageorgiou and Alexandridis [60] employed observer-based output-feedback control to enhance rotor angle stability. The model used is a nonlinear swing equation in a SIMB system. The result of the closed-loop system and the estimation error dynamic guarantee the asymptotic stability and state convergence of the complete observed-based controlled system. However, the dominance of the observer's linear part over the nonlinear part diminished the impact of nonlinear terms. Sunny *et al*. [61] employed dynamic mode decomposition to predict rotor angle deviation of multi-machine systems during faults and model predictive control (MPC) to tune thyristor control series compensation (TCSC) for enhanced rotor angle stability for SIMB systems. The result proves the enhancement of the rotor angle stability, but the system is linearized, which limits it to small disturbances only.

A resistive-type superconducting fault current limiter combined with the damper winding method is employed by the authors in [62] to enhance the rotor angle stability. This method helps in damping the rotor angle oscillation and reducing fault current in a short time by increasing impedance during fault occurrences. The results obtained prove the effectiveness of this method. However, the disadvantages of this method are undesirable power, a higher cost, and a power quality problem [63].

5. ANALYSIS AND SYNTHESIS OF REVIEW

Analysis of rotor angle stability can be performed via the nonlinear swing equation, which presents the dynamic behavior of a SIMB system as in (1):

$$\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_{max}\sin\delta \tag{1}$$

where H is the inertia constant defined as the ratio of kinetic energy stored at rated speed to the generator rating, δ is the power angle, P_m is the mechanical power, P_{max} is the steady-state stability limit defined as maximum power, and $P_{max}\sin\delta$ is the electrical power in terms of P_{max}. The power angle, δ is the sum of the initial power angle, δ_0 and the power angle deviation, $\Delta\delta$.

Linearization of the swing equation allows for determining the root locations as well as the parameters that affect the stability of the rotor. The linearization is made on the assumption that the power angle deviation is very small. The linearized swing equation is as in (2):

$$\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt^2} = -P_{max}\cos\delta_0\Delta\delta \tag{2}$$

where $P_{max}\cos\delta_0$ is the slope of the curve in the power angle graph as shown in Figure 5, which is known as the synchronizing coefficient, P_s which (2) can then be rewritten as (3):

$$\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt^2} + P_s\Delta\delta = 0 \tag{3}$$

Laplace transforming (3) will renders $\mathcal{L}\left\{\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt^2}\right\} + \mathcal{L}\{P_s\Delta\delta\} = 0$, which then results in obtaining the root location of the linearized swing as (4):

$$s^2 = -\frac{\pi f_0}{H} P_s \tag{4}$$

The root location obtained in (4) shows that synchronizing coefficient, P_s has give significant impact on the pole's location. Simulation via MATLAB/Simulink verified that when value of P_s is negative, the transient response of rotor angle deviation and frequency is exponentially increased and losing stability as shown in Figures 6(a) and (b), respectively. This is due to the fact that only one pole exists on the right half of the s-plane. Whereas when the value of P_s is positive, the transient response of rotor angle deviation and frequency is marginally stable with oscillatory and undamped motion, as shown in Figures 7(a) and (b), respectively, due to two poles existing on the $j\omega$-axis.

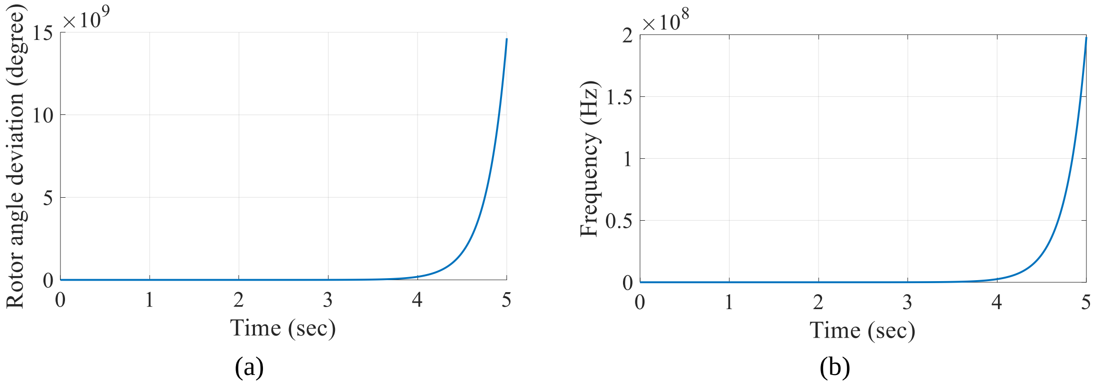

Figure 6. Transient response when $P_s = -1$: (a) deviation and (b) frequency

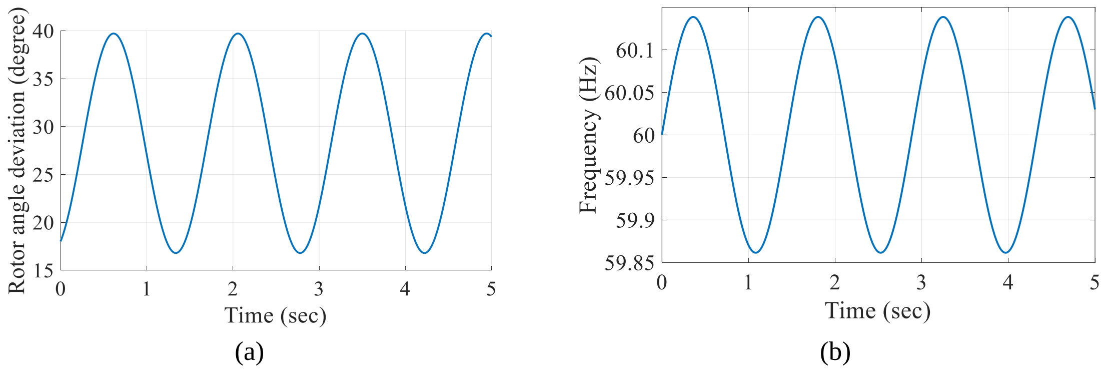

Figure 7. Transient response when $P_s = 1$: (a) deviation and (b) frequency

Further analysis of the swing equation is performed by taking into account the incremental change of fault, also called power input, ΔP and damping power, $D\frac{d\delta}{dt}$. The swing equation from (3) then becomes:

$$\frac{H}{\pi f_0}\frac{d^2\Delta\delta}{dt^2} + D\frac{d\delta}{dt} + P_s\Delta\delta = \Delta P \tag{5}$$

Rearranging (5) into a standard characteristic equation result in obtaining the natural frequency, $\omega_n = \sqrt{\frac{\pi f_0}{H} P_s}$, and damping ratio, $\zeta = \frac{D}{2}\sqrt{\frac{\pi f_0}{H P_s}} < 1$. The natural frequency and the damping ratio of the linearized swing equation show that the inertia constant, H and the synchronizing coefficient, P_s have give significant impact on the transient response. Simulation via MATLAB/Simulink verified that variation of the inertia constant, H results in varying transient responses of rotor angle deviation and frequency, as shown in Figures 8(a) and (b), respectively.

Thus, the inertia constant, H and the synchronizing coefficient, P_s can be exploited to design a robust controller for the rotor angle deviation, ensuring the stability of the power system.

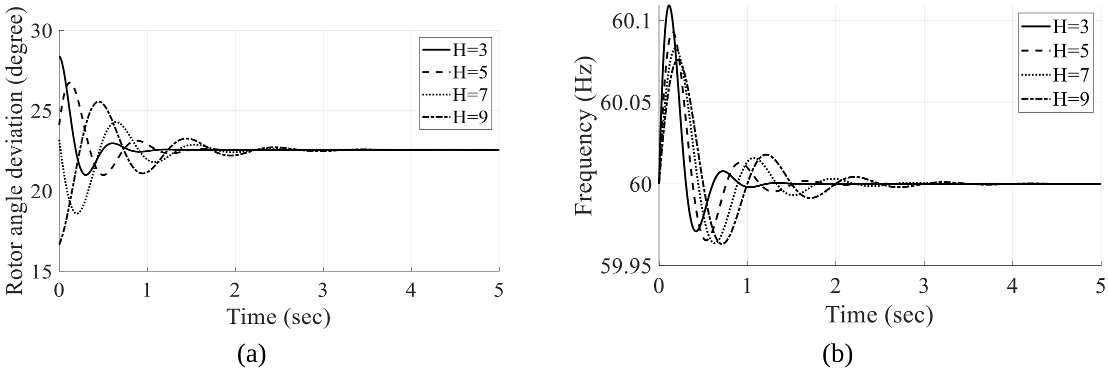

Figure 8. Transient responses when H varied; (a) rotor angle deviation and (b) frequency

6. CONCLUSION

Among other stability problems such as frequency and voltage stability, rotor angle stability is crucial. Thus, formulating a rotor angle stability control is vital to ensuring the stability of the synchronous generator as well as the power system. The swing equation is an important mathematical expression that represents the dynamical behavior of the power system. Through the analysis of the swing equation, stabilization of the power system due to rotor angle perturbation can be realized. In the modeling phase, the review concludes that the swing equation is a nonlinear function where linearization can be made to facilitate the formulation of the stabilizer. Thus, this review leaves the researcher to explore the shortcomings of the linearization in terms of the accuracy of the model. The review also presents numerous stabilizing techniques with advantages and shortcomings that open up new research avenues for enhancing the stabilization techniques.

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