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Introductory Chapter: Power System Stability

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1. Technical Background

Among the various available energy systems, electrical energy is the most popular form, because it can be transported easily at high efficiency and reasonable cost from one place to the other. Electrical machine is a device that converts mechanical energy to electrical energy or vice versa. In the earlier case, the machine is known as a generator, while in the latter case, it is called a motor. The action of magnetic field is used in both machines for the conversion of energy from one form to the other. A power system is a network of components that is well designed and structured to efficiently transmit and distribute electrical energy produced by generators to locations where they are utilized. Generators, motors and other utility loads are connected by a power system.

1.1 Overview of power system structure

Earlier electric network stations supplied DC (direct current) power for lightning. The power was generated by DC generators and distributed by underground cables. Due to excessive power loss (I^2R), at low voltage, the energy delivered from such system could only travel short distances from their stations. When electrical transformers were invented, it created room for the prevalence of the AC (alternating current) system over the DC system. This is because the electrical transformers were able to raise the level of AC voltage for transmission and distribution. The AC system was further boosted with the invention of induction motors to replace DC motors. In addition, the merits of the AC system became apparent due to the fact that more power can be produced at higher voltages at convenience because of the lack of commutators in the AC generators [1].

As a result of the apparent advantages of the AC system, the single-phase and three-phase AC systems emerged. Many electric companies and independent power producers were operating at different frequencies. However, as the need for interconnection and parallel operation became imperative, a standard frequency of either 50 or 60Hz was adopted. Consequently, transmission voltages rose steadily and gave birth to extra high voltages (EHVs) mostly used for commercial purposes.

It may be more economical to convert EHV based on AC to EHV based on DC, when considering power transmission over long distances. This would involve transmission of the power via a two-line system and its inversion from DC back to AC at the other terminal. From the literature, it was reported that it is of more benefit to consider DC lines when the transmission distance is 500 km or more. It should be noted that DC lines possesses no reactance and they have the ability of transferring more power considering the same conductor size than AC lines. The

main advantage of DC transmission is in the scenario where two remotely located large power systems are to be connected via a tie line. In this case, the DC tie line transmission system acts as a synchronous link between the two rigid power systems eliminating the instability problem that is common with the AC links. However, the production of harmonics that requires filtering in addition to the large amount of reactive power compensation required at both ends of the line is a major setback of the DC link system [1, 2].

The interconnection of the entire or overall network system is known as the power grid. When the system is divided into several geographical regions, they are called power pools. In an interconnected system or grid network, there exist fewer generators that are required as reserve for peak load and spinning reserve. The power grid allows energy penetration and transmission in a more reliable and economical way due to the fact that power can readily be transferred from one area to another. Most times, it may be cheaper for a power-producing company to purchase bulk power from the interconnected system instead of generating its own power.

1.2 Power system components

The major components of modern power systems are as follows.

1.2.1 Generators

Generators are one of the essential components of a power system. They produce electrical energy distributed by a power system. Most generators produce electrical energy by converting mechanical energy to electrical energy through the action of a magnetic field. The converted mechanical energy comes from a prime mover, which is a device that spins the generator. Steam and water turbines are some usual forms of prime movers, but in remote locations diesel engines have been used. Prime movers can operate based on many energy sources like water, coal, natural gas, oil, and nuclear energy. The prime mover based on water appears to be one of the best because it is non-polluting and requires no fuel cost. Nuclear power plants are expensive to construct and elaborate safety measures are required. Although, the cost of fuel is low and they are non-polluting energy sources in nature. Therefore, a combination of hydroelectric and nuclear power generators to power a given system would result in low fuel cost and the system can effectively run for long at full power rating. Coal plants are the most common source of electrical power generation because coal is a relatively cheap fuel. But it is unfortunate that coal is one of the most polluting fuel sources. Antipollution features are required in coal-fired plants in order to control pollution. Natural gas is a much cleaner and better energy source compared to coal. Its burning process emits little pollution and it is relatively cheaper. The main drawback of natural gas is that it is difficult to transport over long distances due to the fact that it is flammable in nature. Oil is much easier to transport; however, it is more polluting and more expensive than natural gas. Generally, coal, oil, and natural gas are the traditional non-renewable energy sources and this is a demerit of these energy sources. Wind, solar, biomass, and geothermal resources are other sources of energy that are renewable in nature; however, they are not yet economical when compared to the traditional sources of energy [1–3]. It should be noted that no source of electrical energy has all it takes to be perfect in producing electricity. All the available sources have their pros and cons and sometimes, a combination of two or more energy mix used in hybrid energy system is encouraged.

1.2.2 Transformers

Transformers are another major component of a power system that allows power to be transmitted with minimal loss over a long distance. Power is transferred with very high efficiency from one level of voltage to another level by the use of the transformers. In a transformer, the power transferred to the secondary side is almost the same as the primary side except for losses in the transformer. The product *VI* on the secondary side of the transformer is approximately same as that of the primary side. Hence, a step-up transformer of turns ratio *a* will reduce the secondary current by a ratio of $1/a$. Consequently, this will reduce losses in the line, which makes the transmission of power over long distance possible. Due to the insulation requirements and practical design problems, the generated voltage is limited to low values. Therefore, the step-up transformers are used for transmission of power, while at the receiving end of the transmission line, the step-down transformers are used to reduce the voltage to the required values for distribution and utilization. The transmitted power might undergo several transformations between generator and end users. Recent generators usually generate electrical power at voltages of 13.8–24 kV and transmission lines operate at very high voltages in order to reduce transmission losses. Electrical loads consume power at various voltage levels of 110 and 220 V, for residential and up to 4160 V for industrial applications [1, 2, 4].

1.2.3 Transmission and distribution (power lines)

The transmission and distribution lines are also known as power lines. They connect generators to loads, and transmit electrical power from one place to the other at minimal loss. Transmission lines also interconnect neighboring utilities, which permits not only economic dispatch of power within regions during steady-state or normal working conditions but also transfer of power between regions during emergencies. Thus, transmission lines are designed to efficiently transfer electrical power over long distances. In order to reduce resistive losses (I^2R) in the lines, they run at very high voltages [1, 2]. Upon receiving the power at the area of the end user, the transmission voltage is stepped down and the power is supplied through distribution lines to the final customer. Much less power is carried by the distribution lines and they operate for shorter distances at lower voltages without prohibitive losses compared to the transmission lines. The distribution system could be either overhead or underground. In recent times, the growth of the underground distribution has been rapid in modern residential constructions.

1.2.4 Loads

The loads on a power system are of different types. These loads could be electric motors, electric lighting, and others. However, a broad division of loads in a power system could be: industrial, commercial, and residential. The transmission system could serve very large industrial loads directly, while small industrial loads are served by the primary distribution network. The industrial loads are mainly composite loads and induction motors. The composite loads depend on voltage and frequency and they form bulk of the system load. Commercial and residential loads are made of lighting, heating, and cooling loads and they are independent of frequency with small or negligible reactive power consumption. Kilowatts or megawatts are used to define and express the real power of loads. The real power should be available to the end users and the magnitude of the load varies throughout the day. A composite of the demands made by various classes of utility end users gives

the daily load curve, and the greatest value of load during a period of 24 h is known as maximum or peak demand. Some key factors like the load factor (ratio of average load over a designated period of time to the peak load occurring in that period), utilization factor (ratio of maximum demand to the installed capacity), and plant factor (product of 8760 h and the ratio of annual energy generation to the plant capacity) help judge the performance of the system. In order for the a power system plant to operate economically, the load factor must be high, while the utilization and plant factors indicate how well the system capacity is usually operated and utilized [1, 5, 6].

1.2.5 Protection system

The protection system for a power system involves a variety of protective devices like current, voltage, power sensors, relays, fuses, and circuit breakers. The protective devices that are connected directly to the circuits are known as switchgears (e.g., instrument transformers, circuit breakers, disconnect switches, fuses, and lighting arresters). The presence of these devices is required in order to de-energize the power system either in scenarios of normal operation or in the occurrence of faults [1, 2]. The control house contains the associated control equipment and protective relays. There are basically two types of failures in a power system: overloads and faults. Overload conditions occur when the components in the power system are supplying more power than they were designed to carry safely. This scenario usually occurs when the total demand on the power system surpasses the capability of the system to supply power. Overloads often occur in new residential or industrial construction areas of the power system due to expansion. There are measures in place for the power system operator to immediately correct and control overload conditions due to the robustness of the system in order to avoid damage to the power network. On the other hand, fault conditions occur when one or more of the phases in a power system are shorted to ground or to each other (i.e., single phase to ground, three phases to ground, line to line, etc.). When a phase is open circuited, faults also occur in such situation. During periods of short circuit, very large currents flow and damage the entire power system if no measures are in place to quickly stop it. Faults must be cleared as quickly as possible in a power system when they occur, unlike overloads. For this reason, relays are employed to automatically open circuit breakers and isolate faulty areas; then, they are sensed in a power system [7, 8].

1.3 Power system stability

The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as stability. Power system stability problems are usually divided into two parts: steady state and transient. Steady-state stability refers to the ability of the power system to regain synchronism after small or slow disturbances like gradual power change. An extension of steady-state stability is dynamic stability [1]. Dynamic stability is concerned with small disturbances lasting for a long time with inclusion of automatic control devices. Transient stability deals with effects of large, sudden disturbances like fault occurrence, sudden outage of a line, and sudden application or removal of loads.

1.4 The swing equation

The position of the rotor axis and the resultant magnetic field axis is fixed under normal working conditions based on their relations. The angle between the two is

called the power angle or torque angle. During disturbances, the rotor accelerates/decelerates with respect to the synchronously rotating air gap, thus a relative motion begins. The equation describing this relative motion is known as the swing equation given below [1, 2].

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

where δ is the electrical radian; H is the per unit inertia constant; $P_m \wedge P_e$ are the per unit mechanical and electrical power, respectively; and f_0 is the frequency of the system. With δ in degrees, then

$$\frac{H}{180f_0} \frac{d^2\delta}{dt^2} = P_m - P_e \tag{2}$$

1.5 Stability studies for synchronous generator models

Consider a generator connected to a major substation of a very large system via a transmission line as shown below (**Figures 1** and **2**).

The substation bus voltage and frequency are assumed to remain constant (infinite bus). This is because its characteristics do no change regardless of power supplied or consumed by it. The generator is represented by a constant voltage behind the direct axis transient reactance X_d'. The node representing the generator terminal voltage V_g can be eliminated by converting the Y connected impedances to Δ with admittances as [1]
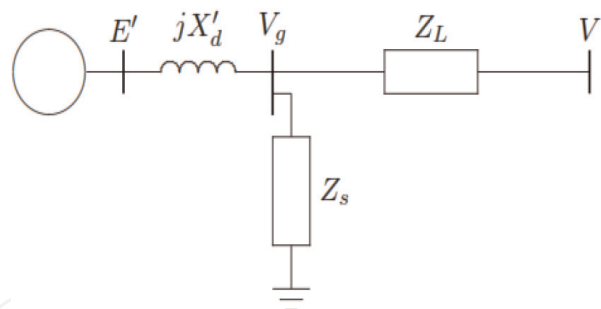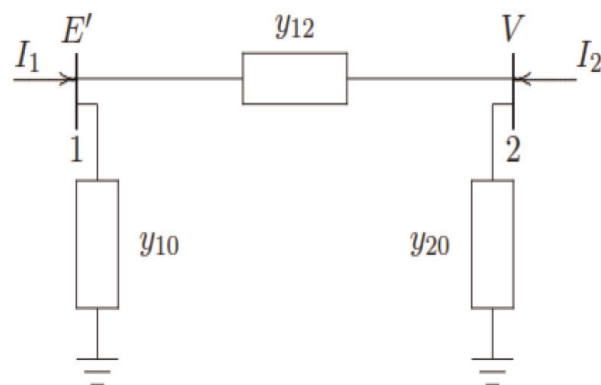

Figure 1.
One machine connected to an infinite bus.

Figure 2.
Equivalent circuit of one machine connected to an infinite bus.

$$y_{10} = \frac{Z_L}{jX'_d Z_s + jX'_d Z_L + Z_L Z_s}$$

$$y_{20} = \frac{jX'_d}{jX'_d Z_s + jX'_d Z_L + Z_L Z_s} \qquad (3)$$

$$y_{12} = \frac{Z_s}{jX'_d Z_s + jX'_d Z_L + Z_L Z_s}$$

Writing the node equations for the above diagram gives

$$I_1 = (y_{10} + y_{12})E' - y_{12}V$$
$$I_2 = -y_{12}E' + (y_{20} + y_{12})V \qquad (4)$$

The above equations can be written in terms of the bus admittance matrix

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} E' \\ V \end{bmatrix} \qquad (5)$$

The diagonal elements of the bus admittance are $Y_{11} = y_{10} + y_{12}$ and $Y_{22} = y_{20} + y_{12}$. The off-diagonal elements are $Y_{12} = Y_{21} = -y_{12}$. Expressing the voltages and admittances in polar form, the real power at node 1 is given by the following expression [1, 6].

$$P_e = \Re[E' I_1^*]$$
$$= \Re[|E'|\angle\delta(|Y_{11}|\angle-\theta_{11}|E'|\angle-\delta + |Y_{12}|\angle-\theta_{12}|V|\angle 0)] \qquad (6)$$

In most systems, $Z_L \wedge Z_S$ are predominantly inductive. If all resistances are neglected, $\theta_{11} = \theta_{12} = 90^\circ$, then $Y_{12} = B_{12} = 1/X_{12}$. The simplified expression for power is

$$P_e = |E'||V||B_{12}|\cos(\delta - 90^\circ)$$

or $\qquad (7)$

$$P_e = \frac{|E'||V|}{X_{12}}\sin\delta$$

The above equation is the simplified form of the power equation and basic to the understanding of all stability problems. The equation shows that the power transmitted depends upon the transfer reactance and the angle between the two voltages. The curve P_e versus δ is known as the *power angle curve* shown below (**Figure 3**).

Maximum power is transferred at a displacement of 90°. The maximum power is called the steady-state stability limit and is given by:

$$P_{max} = \frac{|E'||V|}{X_{12}} \qquad (8)$$

A further increase of the electrical power causes loss of synchronism, thus,

$$P_e = P_{max}\sin\delta \qquad (9)$$

Figure 3.
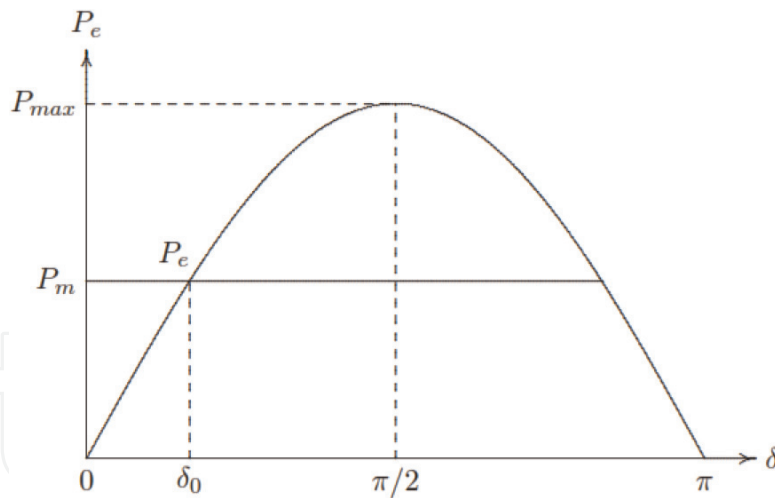*Power angle curve.*

1.6 Small disturbances' steady-state stability

The steady-state stability refers to the ability of the power system to remain in synchronism when subjected to small disturbances. Substituting the electrical power in Eq. (9) into Eq. (1) gives [1]

$$\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_{max}\sin\delta \tag{10}$$

Solving the above differential equation results in synchronizing coefficient denoted by P_S. This coefficient plays an important part in determining the system stability and is given by:

$$P_s = \left.\frac{dP}{d\delta}\right|_{\delta_0} = P_{max}\cos\delta_0 \tag{11}$$

The natural frequency of the marginally stable oscillation is

$$\omega_n = \sqrt{\frac{\pi f_0}{H}P_s} \tag{12}$$

The damping power and dimensionless damping ratio are respectively defined as

$$P_d = D\frac{d\delta}{dt} \tag{13}$$

$$\zeta = \frac{D}{2}\sqrt{\frac{\pi f_0}{HP_s}} \tag{14}$$

where δ is the damping coefficient. The response time constant and settling time for the system are given respectively by

$$\tau = \frac{1}{\zeta \omega_n} = \frac{2H}{\pi f_0 D} \tag{15}$$

$$t_s \cong 4\tau \tag{16}$$

1.7 Transient stability

Transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbances. A method known as the equal area criterion can be used for a quick prediction of stability. Consider a synchronous machine connected to an infinite bus bar. The swing equation with damping neglected is given by

$$\frac{H}{\pi f_0} \frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{17}$$

where P_a is the accelerating power. Scenarios for the equal area criterion are described below (**Figure 4**).

For a sudden step increase in input power, this is represented by the horizontal line P_{m1}. Since $P_{m1} > P_{e0}$, the accelerating power on the rotor is positive and the power angle δ increases. The excess energy stored in the rotor during the initial acceleration is [1]

$$\int_{\delta_0}^{\delta_1} (P_{m1} - P_e)d\delta = \text{area } abc = \text{area } A_1 \tag{18}$$

With increase in δ, the electrical power increases, and when $\delta = \delta_1$, the electrical power matches the new input power P_{m1}. For a situation where $P_m < P_e$, the rotor decelerates toward synchronous speed until $\delta = \delta_{max}$. The energy given up by the rotor as it decelerates back to synchronous speed is

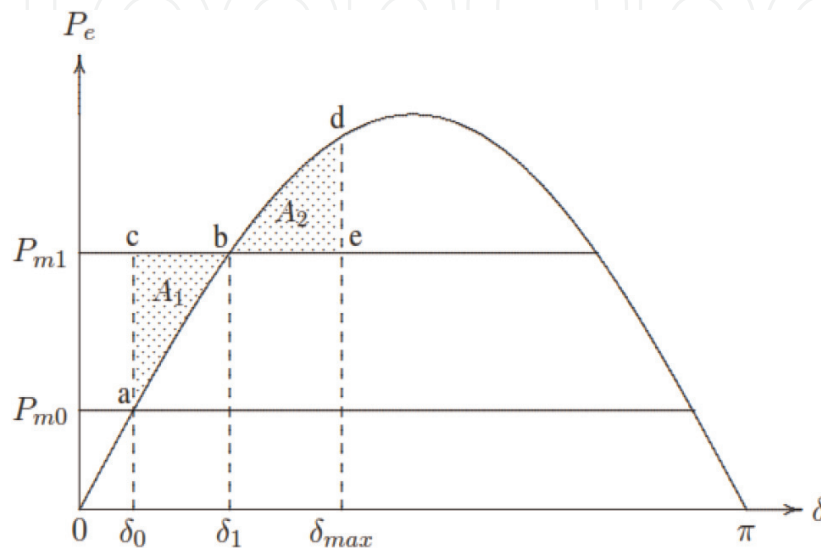$$\int_{\delta_0}^{\delta_1} (P_{m1} - P_e)d\delta = \text{area } abc = \text{area } A_1 \tag{19}$$

Figure 4.
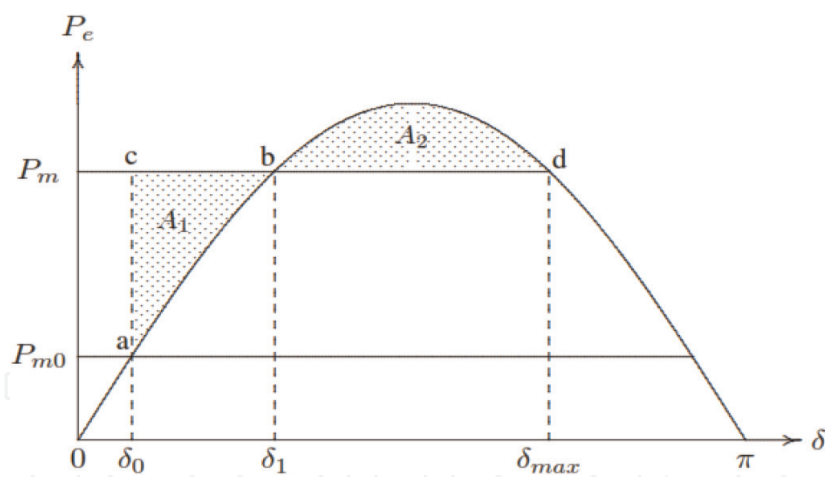*Equal area criterion—sudden change of load.*

Figure 5.
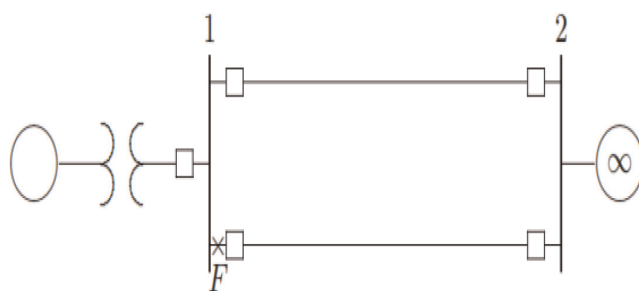*Equal area criterion—maximum power limit.*

Figure 6.
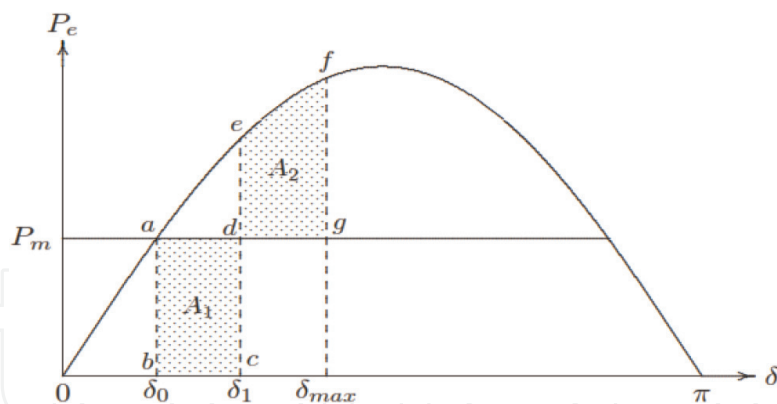*One machine system connected to infinite bus, three-phase fault at F, at the sending end.*

Figure 7.
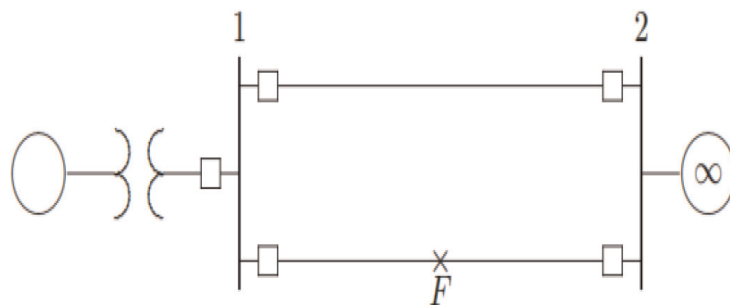*Equal area criterion for a three-phase fault at the sending end.*

Figure 8.
One machine system connected to infinite bus, three-phase fault at F, away from the sending end.
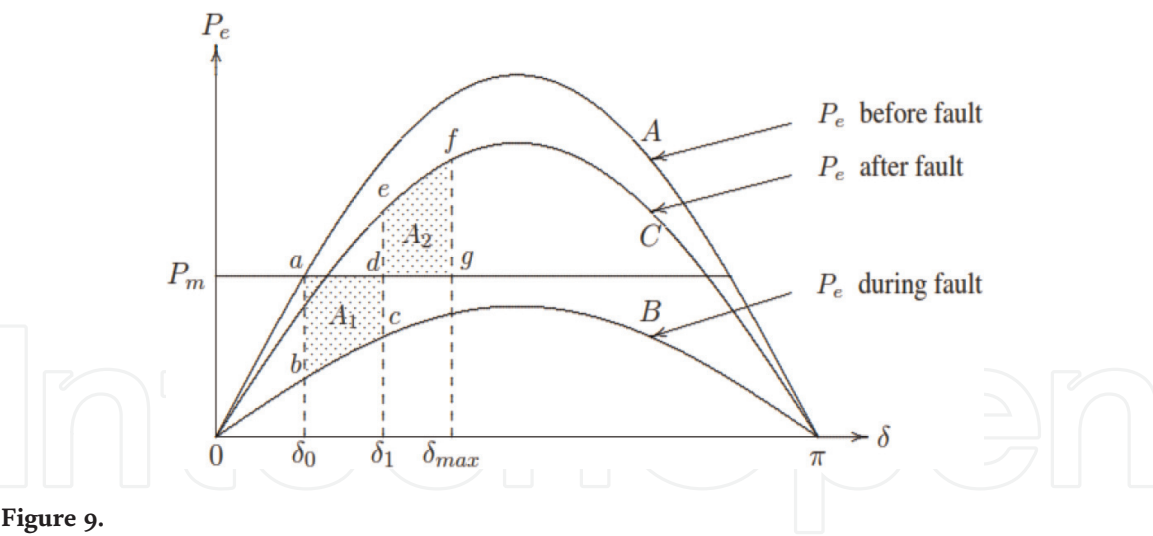
Figure 9.
Equal area criterion for a three-phase fault away from the sending end.

The equal area criterion is used to determine the maximum additional power P_m which can be applied for stability to be maintained. This could be termed as application to sudden increase in power input as shown in **Figure 5**. **Figures 6–9** show the application to three-phase fault considering the equal area criterion [1].

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