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Stability Improvement of AC System by Controllability of the HVDC

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Abstract**—**High Voltage Direct Current (HVDC) power transmission is employed to move large amounts of electric power. There are several possibilities to enhance the transient stability in a power system. One adequate option is by using the high controllability of the HVDC if HVDC is available in the system. This paper presents a control technique for HVDC to enhance the transient stability. The strategy controls the power through the HVDC to help make the system more transient stable during disturbances. Loss of synchronism is prevented by quickly producing sufficient decelerating energy to counteract accelerating energy gained during. In this study, the power flow in the HVDC link is modulated with the addition of an auxiliary signal to the current reference of the rectifier firing angle controller. This modulation control signal is derived from speed deviation signal of the generator utilizing a PD controller; the utilization of a PD controller is suitable because it has the property of fast response. The effectiveness of the proposed controller is demonstrated with a SMIB test system.

Keywords**—**HVDC, SMIB, Stability, Power System.

I. Introduction

THE power transfer capability of long AC transmission lines is generally limited by large signal stability. The development of effective ways to utilize transmission system close to its thermal limit has attracted much attention recently [1].

The central purpose of conventional HVDC transmission is to transfer a specific amount of electric power in one node to another and to offer the fast controllability of real power transfer. If the HVDC link is operated in parallel with a crucial AC line the load-flow of the AC line could be controlled directly. The HVDC link can therefore be employed for improving transient stability [2], [3].

HVDC links, under traditional controls, don't provide synchronizing or damping effects in a reaction to disturbance on AC side. However, the capacity of an HVDC connect to rapidly modulate the power flow, in response to manage signals, has been utilized for some time to enhance the dynamic stability of AC-DC systems [4].

For an AC–DC system, [5] have discussed the effect of DC modulation on the dynamic stability of (i) one machine, infinite bus and (ii) two machine, infinite bus configurations.

Lucas and Peiris [4] have utilized a parallel-small power DC link to improve the AC system small-signal stability. However, the power system stabilizers (PSS) have been widely utilized to improve damping of these oscillations, through modulation of the generator excitation.

Eriksson et al. [2] have studied the impact of a conventional HVDC link on the transient stability in a nine-bus benchmark power system.

Rahman and Khan [1] have studied a single machine infinite bus connected by a double circuit AC line, converted for simultaneous AC–DC power transmission; it is a bi-polar DC power transmission through a double circuit AC transmission line.

This paper presents a concept of improving the transient stability of power system by modulating the power transfer in HVDC. A SMIB system connected via a parallel AC and DC power transmission has been studied. In this study, the power flow in the HVDC link is modulated by the addition of an auxiliary signal to the current reference of the rectifier firing angle controller to enhance the transient stability. The strategy is dependant on fast balancing of the accelerating energy. The driving mechanical power should be balanced by the electric power to keep the system in synchronism. This is completed by controlling the power through the HVDC.

II. Model Explanation

A. HVDC Link

The HVDC considered in this paper (Fig. 1) is of conventional type based on the CIGRE benchmark system [6]–[8]. The rectifier and the inverter are 12-pulse converters using two 6-pulse thyristor bridges connected in series. The transformer tap changers are not simulated and fixed taps are assumed. Reactive power required by the converters is provided by a set of capacitor banks plus 11th, 13th and high pass filters on each side. A series reactor is also included between the two HVDC stations to make the DC current smooth. The controls used are primarily those of the CIGRE Benchmark model [8]–[10] modified to suit the necessary power.

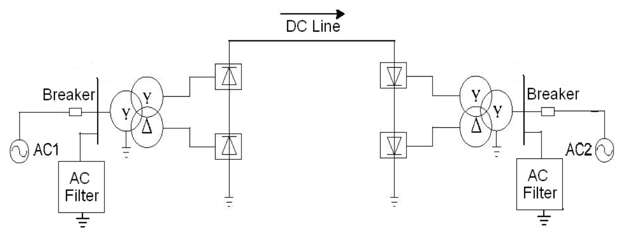

Fig. 1 The HVDC system diagram

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Preliminary qualitative analysis suggests that commonly used techniques in HVDC/AC system may be adopted for the purpose of the design of protective scheme, filter and instrumentation network. In case of symmetrical faults in the transmission system, gate signals to all the SCRs are blocked and the bypass valves are activated or force retardation method is applied (i.e. forcing the rectifier into inversion) to protect rectifier and inverter bridges [11], [12].

At the inverter the commutation failure prevention control will detect AC faults and reduce the maximum delay angle limit in order to decrease the risk of commutation failure. By controlling the firing angle for the rectifier α_{AOr}, the power through the HVDC is controlled.

The current controller is shown in Fig. 2. The limited current $I_{ref\text{-}lim}$ reference is generated using the Voltage Dependent Current Limit (VDCL) unit. These units provide current reference values during steady and transient state conditions respectively. In order to maintain the operation of the AC system, VDCL limits the current in the DC line, if the DC voltage decreases, e.g. due to an AC system disturbance. When normal operation has returned and the DC voltage recovered, current returns to its steady-state level I_{ref} (1 p.u.).

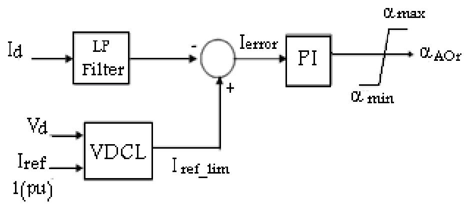

Fig. 2 The current controller

B. Test Power System

A single machine system connected to infinite bus through parallel AC and DC links is considered and is shown in Fig. 3. The generator is equipped with an excitation system (IEEE-Type I). Power system stabilizers (PSS) have been utilized to improve damping of oscillations, through modulation of the generator excitation. The mechanical power supplied by turbine is considered invariant for the duration of transient simulation runs. HVDC link is used to demonstrate the enhancement of stability by utilizing the controllability of the HVDC line.

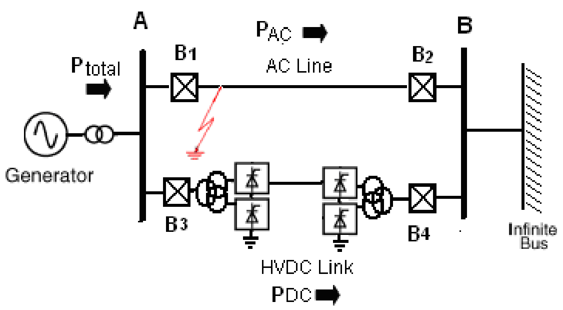

Fig. 3 Parallel AC-DC system

The power can go either through the AC lines or through the HVDC. The total power transfer P_{total} is 950 MW; the nominal values of the AC system are 500 kV and 50 Hz. The AC transmission line is 350 km long and nominal rating is 200 MW (P_{ac}). The HVDC is operating at 500 kV DC (V_{dc}) and is transferring 750 MW (P_{dc}) of total power in steady-state. Fig. 4 shows the power through the HVDC (P_{dc}), the AC line (P_{ac}) and total power transfer (P_{total}) in steady state conditions.

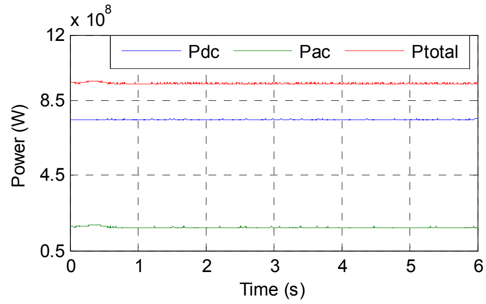

Fig. 4 P_{total}, P_{ac} and P_{dc} power transfer in steady state conditions.

III. Transient Stability of Power Systems

The first electric power system was a dc system built by Edison in 1882. The subsequent power systems that were constructed in the late 19th century were all dc systems. However despite the initial popularity of dc systems by the turn of the 20th century ac systems started to outnumber them. The ac systems were thought to be superior as ac machines were cheaper than their dc counterparts and more importantly ac voltages are easily transformable from one level to other using transformers. The early stability problems of ac systems were experienced in 1920 when insufficient damping caused spontaneous oscillations or hunting. These problems were solved using generator damper winding and the use of turbine-type prime movers [12]–[14].

The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. As mentioned before, power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence. We can thus define the power system stability as the ability of the power system to return to steady state without losing synchronism. Usually power system stability is categorized into steady state, transient and dynamic stability. *Steady state stability* studies are restricted to small and gradual changes in the system operating conditions. In this we basically concentrate on restricting the bus voltages close to their nominal values. We also ensure that phase angles between two buses are not too large and check for the overloading of the power equipment and transmission lines. These checks are usually done using power flow studies [13]–[16].

Transient stability involves the study of the power system following a major disturbance. Following a large disturbance the synchronous alternator the machine power (load) angle changes due to sudden acceleration of the rotor shaft. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance. The ability of a power system to maintain stability under continuous small disturbances is investigated under the name of *dynamic stability* (also known as small-signal stability). These small disturbances occur due random fluctuations in loads and generation levels. In an interconnected power system, these random variations can lead catastrophic failure as this may force the rotor angle to increase steadily. In this chapter we shall discuss the transient stability aspect of a power system [17]–[18].

A. Power-Angle Relationship

In this section we shall consider this relation for a lumped parameter lossless transmission line. Consider the single-machine-infinite-bus (SMIB) system shown in Fig. 5.

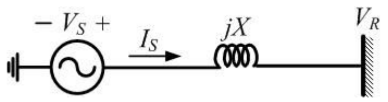

Fig. 5 An SMIB system

In this figure, the reactance X includes the reactance of the transmission line and the synchronous reactance or the transient reactance of the generator. The sending end voltage is then the internal emf of the generator. Let the sending and receiving end voltages be given by

$$V_S = V_1\angle\delta, \quad V_R = V_2\angle 0° \tag{1}$$

We then have

$$I_S = \frac{V_1\angle\delta - V_2}{jX} = \frac{V_1\cos\delta - V_2 + jV_1\sin\delta}{jX} \tag{2}$$

The sending end real power and reactive power are then given by

$$P_S + jQ_S = V_S I_S^* = V_1(\cos\delta + j\sin\delta)\frac{V_1\cos\delta - V_2 - jV_1\sin\delta}{-jX} \tag{3}$$

This is simplified to

$$P_S + jQ_S = \frac{V_1V_2\sin\delta + j\left(V_1^2 - V_1V_2\cos\delta\right)}{X} \tag{4}$$

Since the line is loss less, the real power dispatched from the sending end is equal to the real power received at the receiving end. We can therefore write

$$P_e = P_S = P_R = \frac{V_1V_2}{X}\sin\delta = P_{\max}\sin\delta \tag{5}$$

where $P_{max} = V_1V_2/X$ is the maximum power that can be transmitted over the transmission line. The power-angle curve is shown in Fig. 6. From this figure we can see that for a given power P_0. There are two possible values of the angle $\delta - \delta_0$ and δ_{max}. The angles are given by

$$\delta_0 = \sin^{-1}\left(\frac{P_0}{P_{\max}}\right)$$
$$\delta_{\max} = 180° - \delta_0 \tag{6}$$

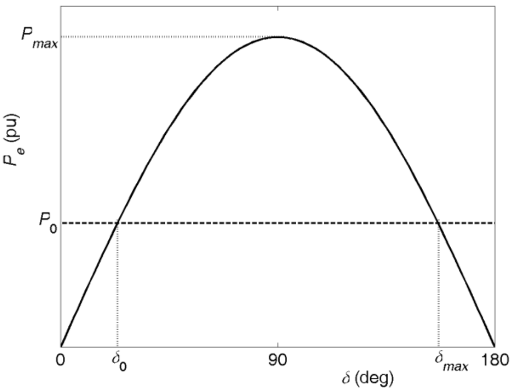

Fig. 6 A typical power-angle curve

B. Swing Equation

Let us consider a three-phase synchronous alternator that is driven by a prime mover. The equation of motion of the machine rotor is given by [10]–[12]

$$J\frac{d^2\theta}{dt^2} = T_m - T_e = T_a \tag{7}$$

where J is the total moment of inertia of the rotor mass in kgm^2; T_m is the mechanical torque supplied by the prime mover in N-m; T_e is the electrical torque output of the alternator in N-m; θ is the angular position of the rotor in rad.

Neglecting the losses, the difference between the mechanical and electrical torque gives the net accelerating torque T_a. In the steady state, the electrical torque is equal to the mechanical torque, and hence the accelerating power will be zero. During this period the rotor will move at *synchronous speed* ω_s in rad/s.

The angular position θ is measured with a stationary reference frame. To represent it with respect to the synchronously rotating frame, we define

$$\theta = \omega_s t + \delta \tag{8}$$

where δ is the angular position in rad with respect to the synchronously rotating reference frame. Taking the time derivative of the above equation we get

$$\frac{d\theta}{dt} = \omega_s + \frac{d\delta}{dt} \tag{9}$$

Defining the angular speed of the rotor as

$$\omega_r = \frac{d\theta}{dt} \tag{10}$$

We can write (9) as

$$\omega_r - \omega_s = \frac{d\delta}{dt} \tag{11}$$

We can therefore conclude that the rotor angular speed is equal to the synchronous speed only when $d\delta/dt$ is equal to zero. We can therefore term $d\delta/dt$ as the error in speed. Taking derivative of (9), we can then rewrite (7) as

$$J\frac{d^2\delta}{dt^2} = T_m - T_e = T_a \tag{12}$$

Multiplying both side of (13) by ω_m we get

$$J\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{13}$$

where P_m, P_e and P_a respectively are the mechanical, electrical and accelerating power in MW.

We now define a normalized inertia constant as

$$H = \frac{\text{Stored kinetic energy at synchronous speed in mega-joules}}{\text{Generator MVA rating}} = \frac{J\omega_s^2}{2S_{rated}} \tag{14}$$

Substituting (14) in (12) we get

$$2H\frac{S_{rated}}{\omega_s^2}\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{15}$$

In steady state, the machine angular speed is equal to the synchronous speed and hence we can replace ω_r in the above equation by ω_s. Note that in (15) P_m, P_e and P_a are given in MW. Therefore dividing them by the generator MVA rating S_{rated} we can get these quantities in per unit. Hence dividing both sides of (15) by S_{rated} we get

$$\text{per unit } \frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{16}$$

Equation (16) describes the behaviour of the rotor dynamics and hence is known as the swing equation. The angle δ is the angle of the internal emf of the generator and it dictates the amount of power that can be transferred. This angle is therefore called the *load angle*.

C. Equal Area Criterion

The real power transmitted over a lossless line is given by (5). Now consider the situation in which the synchronous machine is operating in steady state delivering a power P_e equal to P_m when there is a fault occurs in the system. Opening up of the circuit breakers in the faulted section subsequently clears the fault. The circuit breakers take about 5/6 cycles to open and the subsequent post-fault transient last for another few cycles. The input power, on the other hand, is supplied by a prime mover that is usually driven by a steam turbine. The time constant of the turbine mass system is of the order of few seconds, while the electrical system time constant is in milliseconds. Therefore, for all practical purpose, the mechanical power is remains constant during this period when the electrical transients occur. The transient stability study therefore concentrates on the ability of the power system to recover from the fault and deliver the constant power P_m with a possible new load angle δ [10]–[12].

Consider the power angle curve shown in Fig. 7. Suppose the system of Fig. 5 is operating in the steady state delivering a power of P_m at an angle of δ_0 when due to malfunction of the line, circuit breakers open reducing the real power transferred to zero. Since P_m remains constant, the accelerating power P_a becomes equal to P_m. The difference in the power gives rise to the rate of change of stored kinetic energy in the rotor masses. Thus the rotor will accelerate under the constant influence of non-zero accelerating power and hence the load angle will increase. Now suppose the circuit breaker re-closes at an angle δ_c. The power will then revert back to the normal operating curve. At that point, the electrical power will be more than the mechanical power and the accelerating power will be negative. This will cause the machine decelerate. However, due to the inertia of the rotor masses, the load angle will still keep on increasing. The increase in this angle may eventually stop and the rotor may start decelerating, otherwise the system will lose synchronism [18]–[19].

Note that

$$\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = 2\left(\frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right) \tag{17}$$

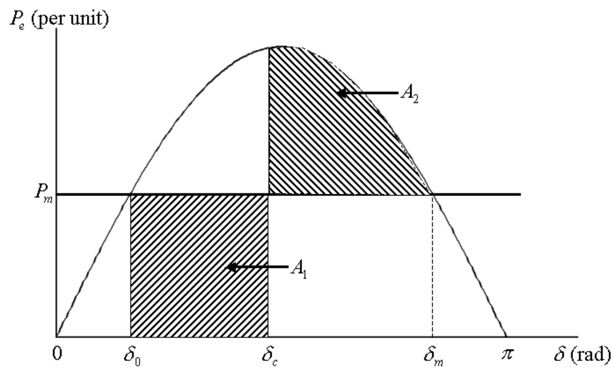

Fig. 7 Power-angle curve for equal area criterion.

Hence multiplying both sides of (16) by $d\delta/dt$ and rearranging we get

$$\frac{H}{\omega_s}\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = (P_m - P_e)\frac{d\delta}{dt} \tag{18}$$

Multiplying both sides of the above equation by dt and then integrating between two arbitrary angles δ_0 and δ_c we get

$$\frac{H}{\omega_s}\left(\frac{d\delta}{dt}\right)^2\Bigg|_{\delta_0}^{\delta_c} = \int_{\delta_0}^{\delta_c}(P_m - P_e)d\delta \tag{19}$$

Now suppose the generator is at rest at δ_0. We then have $d\delta/dt$ = 0. Once a fault occurs, the machine starts accelerating. Once the fault is cleared, the machine keeps on accelerating before it reaches its peak at δ_c, at which point we again have $d\delta/dt = 0$. Thus the area of accelerating is given from (19) as

$$A_1 = \int_{\delta_0}^{\delta_c}(P_m - P_e)d\delta = 0 \tag{20}$$

In a similar way, we can define the area of deceleration. In Fig. 7, the area of acceleration is given by A_1 while the area of deceleration is given by A_2. This is given by [10]

$$A_2 = \int_{\delta_c}^{\delta_m}(P_e - P_m)d\delta = 0 \tag{21}$$

Now consider the case when the line is reclosed at δ_c such that the area of acceleration is larger than the area of deceleration, i.e., $A_1 > A_2$. The generator load angle will then cross the point δ_m, beyond which the electrical power will be less than the mechanical power forcing the accelerating power to be positive. The generator will therefore start accelerating before is slows down completely and will eventually become unstable. If, on the other hand, $A_1 < A_2$, i.e., the decelerating area is larger than the accelerating area, the machine will decelerate completely before accelerating again. The rotor inertia will force the subsequent acceleration and deceleration areas to be smaller than the first ones and the machine will eventually attain the steady state. If the two areas are equal, i.e., $A_1 = A_2$, then the accelerating area is equal to decelerating area and this is defines the boundary of the stability limit. The clearing angle δ_c for this mode is called the *critical clearing angle* and is denoted by δ_{cr}. We then get from Fig. 7 by substituting $\delta_c = \delta_{cr}$

$$\int_{\delta_0}^{\delta_{cr}}(P_m - P_e)d\delta = \int_{\delta_{cr}}^{\delta_m}(P_e - P_m)d\delta \tag{22}$$

We can calculate the critical clearing angle from the above equation. Since the critical clearing angle depends on the equality of the areas, this is called the *equal area criterion*.

Now a frequently asked question is what does the critical clearing angle mean? Since we are interested in finding out the maximum time that the circuit breakers may take for opening, we should be more concerned about the critical clearing time rather than clearing angle. Furthermore, notice that the clearing angle is independent of the generalized inertia constant H. Hence we can comment that the critical clearing angle in this case is true for any generator that has a d-axis transient reactance of 0.20 per unit. The critical clearing time, however, is dependent on H and will vary as this parameter varies.

To obtain a description for the critical clearing time, let us consider the period during which the fault occurs. We then have $P_e = 0$. We can therefore write from

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}P_m \tag{23}$$

Integrating the above equation with the initial acceleration being zero we get

$$\frac{d\delta}{dt} = \int_0^t \frac{\omega_s}{2H}P_m dt = \frac{\omega_s}{2H}P_m t \tag{24}$$

Further integration will lead to

$$\delta = \int_0^t \frac{\omega_s}{2H}P_m t\,dt = \frac{\omega_s}{4H}P_m t^2 + \delta_0 \tag{25}$$

Replacing δ by δ_{cr} and t by t_{cr} in the above equation, we get the critical clearing time as

$$t_{cr} = \sqrt{\frac{4H}{\omega_s P_m}(\delta_{cr} - \delta_0)} \tag{26}$$

To illustrate the response of the load angle δ, the swing equation is simulated in MATLAB. The swing equation of (16) is then expressed as

$$\begin{aligned}\frac{d\Delta\omega_r}{dt} &= \frac{1}{2H}(P_m - P_e)\\ \frac{d\delta}{dt} &= \omega_s \times \Delta\omega_r\end{aligned} \tag{27}$$

where $\Delta\omega_r$ is the deviation for the rotor speed from the synchronous speed ω_s. It is to be noted that the swing equation of (27) does not contain any damping. Usually a damping term, that is proportional to the machine speed $\Delta\omega_r$, is added with the accelerating power. Without the damping the load angle will exhibit a sustained oscillation even when the system remains stable when the fault cleared within the critical clearing time.

Fig. 8 depicts the response of the load angle δ for two different values of load angle. It is assumed that the fault occurs at 0.5 s when the system is operating in the steady state delivering 0.9 per unit power. The load angle during this time is constant at 23.96°. The load angle remains stable, albeit the sustained oscillation when the clearing time t_{cl} is 0.253 s. The clearing angle during this time is 88.72°. The system however becomes unstable when the clearing time 0.2531 s and the load angle increases asymptotically. The clearing time in this case is 88.77°. This is called the loss of synchronism. It is to be noted that such increase in the load angle is not permissible and the protection device will isolate the generator from the system.

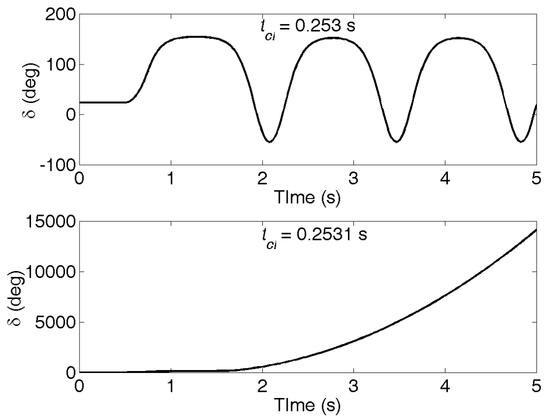

Fig. 8 Stable and unstable system response as a function of clearing time

IV. CONTROL TECHNIQUE

Transient stability in a power system refers to the ability of a power system to maintain a connected generator in synchronism after the system has been subjected to a major disturbance such as transmission system faults. The transient stability control strategy developed in the paper is based on fast balancing of the accelerating energy [9],[11]. The driving mechanical power must be balanced by the electrical power to keep the system in synchronism. This is performed by controlling the power through the HVDC.

The equal area criteria for stability study may be adopted to assess the transient stability limit of the system. Fig. 9 shows that the system becomes unstable for high value of pre-fault power P_{total} (= P_m), which is equal to the mechanical power input. If the fault clearing time t_1 is not very fast then the corresponding angle δ_1 becomes larger than the critical clearing angle and the system becomes unstable.

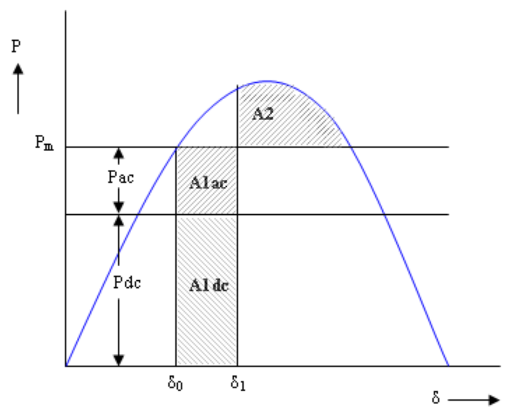

Fig. 9 Equal area criteria: P_{ac} steady state AC power by AC system, P_{dc} steady state DC power by the DC system; P_{total} total power transfer; δ_0 steady state power angle; δ_1 power angle at the time of clearing the fault by opening CBs (B1 and B2); $A1_{ac}$ accelerating energy gained due to decrement of AC power (P_{ac}) caused by the fault; $A1_{dc}$ accelerating energy gained due to decrement of DC power (P_{dc}) caused by the fault; A2 retarding energy of the generator.

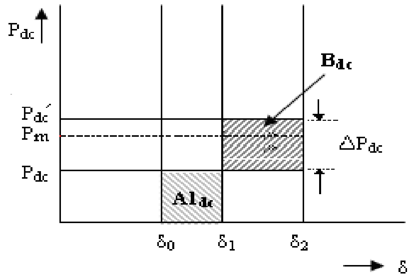

Fig. 10 Equal area criteria for DC control

HVDC links, under traditional controls, do not provide synchronizing or damping effects in response to disturbance on AC side. However, the controllability of an HVDC link is inherently fast and this can be used to modulate the power flow after the fault clearance for producing sufficient decelerating energy to improve the transient stability.

When 3-phase fault occurs in the AC transmission line, both P_{ac} and P_{dc} become zero. The fault is cleared after t1 second by tripping B1 and B2, so Pac remains to be zero even when the fault is cleared. But P_{dc} is allowed to flow through the line. Referring Fig. 10, at the instant of clearing fault t_1 rapid control of the converter system increases the DC power flow to $P_{dc}^{/}$:

$$P_{dc}^{/} = P_m + \Delta P_{dc} \tag{28}$$

where B_{dc} is increment of DC power required to give sufficient retarding energy to generator ($A1_{ac}$ + $A1_{dc}$ = kinetic energy gained by the rotor during acceleration)

When rapid control to increase DC power is not adopted, B_{dc}=0. The acceleration area ($A1_{ac}$ + $A1_{dc}$) becomes larger than deceleration (A2) and the generator may step-out. As a counter measure to improve the transient stability and solve the first swing stability, the DC power is increased by an amount:

$$B_{dc} = (A1_{ac} + A1_{dc}) - A_2 \tag{29}$$

$$\Delta P_{dc} = P_{dc}^{/} - P_{dc} \tag{30}$$

The criterion given in (2) is implemented by adding a ΔI_{dc} control signal to the limited current reference ($I_{ref\text{-}lim}$) of the rectifier current regulator.

The control signal (ΔI_{dc}) is derived from speed deviation signal (Δω) of the generator using a PD controller as shown in Fig. 11.

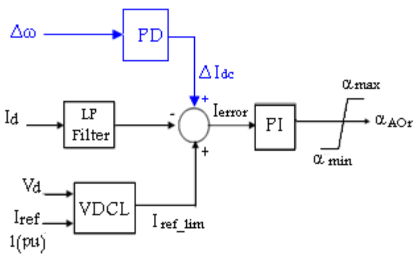

Fig. 11 Current controller and auxiliary signal

V. SIMULATION RESULTS

The simulation study is carried out for the following case. At time *t* = 1 s a three-phase to ground fault occurs at the AC transmission line close to bus A as shown in Fig. 3. After a period of 100 ms, trip signals are given simultaneously to circuit breakers B_1 and B_2 at both ends of faulty line to clear the fault. Thereafter, circuit breakers are reclosed after a delay of 400 ms from the instant of clearing fault. So the total fault clearing time becomes 500 ms in that case.

Time, t = 1 s Three phase to ground fault occurs near bus A
Time, t = 1.1 s Disconnection of AC line
Time, t = 1.5 s Reconnection of AC line

Fig. 12 shows the transient responses for this fault condition.

Comparison of results between both cases with DC power modulation (curves WPM) and without DC power modulation (curves NPM) for the similar nature and duration of faults indicate:

It can be observed through simulation studies that, AC–DC system without DC power modulation becomes unstable in the first swing. However, with DC power modulation the system remains stable after first swing.

Fig. 12 (a) gives the variation of generator speed. As can be seen in the figure, the system falls out of synchronism when the HVDC is transferring a constant amount of power, i.e. no auxiliary power control. When the control strategy is applied, the first swing is controlled in such a way that the system remains stable.

Fig. 12 (c) shows the generator terminal voltage. The voltage drops during the fault but recovers quickly after the disconnection of the faulted line. The real power oscillations subside much faster when the control strategy is applied. It can be observed that, there are no operational problems due to the modulation of the DC power (through the modulation of the rectifier firing angle) to improve the stability of the system.

VI. CONCLUSION

This paper presents a control technique for HVDC to enhance the transient stability in power systems. The strategy controls the power through the HVDC to help make the system more transient stable during disturbances. The proposed control strategy includes the PD controller; the utilization of a PD controller is suitable because it has the property of fast response. During the transient period after the fault clearance, AC power flow is temporarily switched off and the DC power flow is modulated to produce a retarding torque to bring back the generator to its normal speed.

It's has been demonstrated that the power flow in the HVDC link is modulated by the addition of an auxiliary signal to the current reference of the rectifier firing angle controller to enhance the transient stability in power system. The PD controller works well and damps the first swing oscillation transient so the system remains stable. Therefore, the control of HVDC has the potential for future application to power systems.

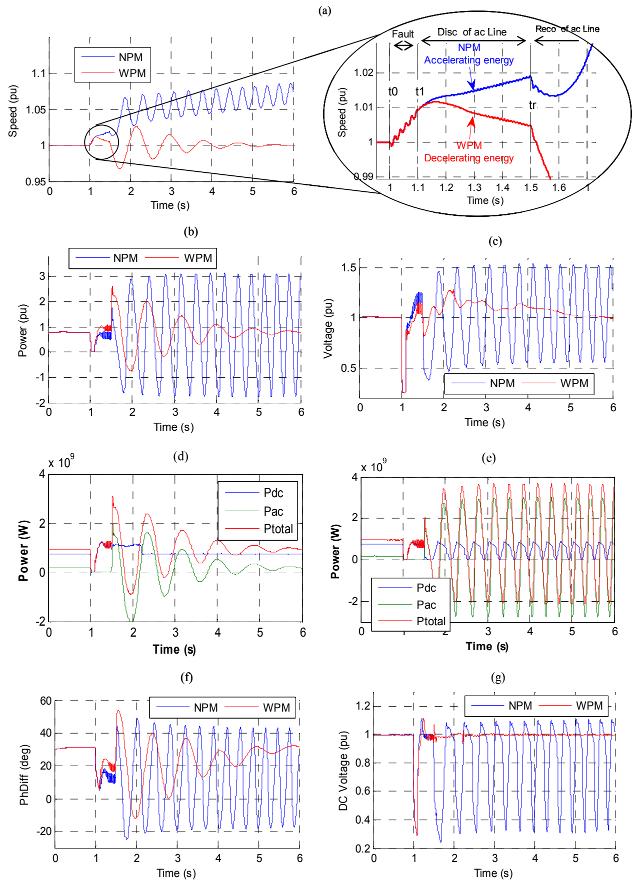

Fig. 12 (a) Generator speed (b) Generator active power output (c) Generator terminal voltage (d) AC (P_{ac}), DC (P_{dc}) and total (P_{total}) power transfer WPM (e) AC (P_{ac}), DC (P_{dc}) and total (P_{total}) power transfer NPM (f) Transmission angle (P_{hDiff}) between two ends (g) DC Voltage

APPENDIX

Generator:

Sn = 1200 MVA, Vn = 13.8 kV, f = 50 Hz, Xd =1.305 pu, Xd' = 0.296 pu, Xd'' = 0.252 pu, Xq = 0.474 pu, Xl = 0.18 pu, Tdo' = 1.01 s, Tdo'' = 0.053 s, Tqo'' = 0.1 s, Ra = 0.0028544 pu, H = 3.7 s, Xq'' = 0.243 pu,

Excitation System:

Ka = 200, Ta = 0.001 s, Ke = 1, Te = 0, K_f = 0.001, T_f = 0.1 s.

Power System Stabilizer:

T_w = 1 s, T1 = 0.06 s, T_2 = 1 s, T3 = 0 s, T_4 = 0 s,
$Vs_{\_max}$ = 0.15 pu, $Vs_{\_min}$ = .0.15 pu, K_{PSS} = 2.5.

Generator Transformer:

1200 MVA, 13.8 kV/500 kV

Converter Transformers:

Rectifier Transformer, 500/211.42*2 kV, 1200 MVA;
Inverter Transformer, 211.42*2/500 kV, 1200 MVA.

Converters:

$V_{d\ nom}$ = 500 kV, $I_{d\ nom}$ = 1500 A, $P_{dc\ nom}$ = 750 MW.
Rectifier: $\alpha_{min} = 5°$, $\alpha_{max} = 145°$.
Inverter: $\alpha_{min} = 110°$, $\alpha_{max} = 150°$

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