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Stability enhancement of power system by simultaneous ac-dc power transmission

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Abstract: Generators may supply power to infinite bus through a single circuit long ac transmission line. The system becomes unstable after the clearance of a fault if the pre fault power transfer or the fault clearance time is high. Conversion of the line for simultaneous ac-dc power flow may keep the system stable with high values of pre fault power and fault clearance time. During the transient period after the clearance of the fault, ac power flow is switched off and the dc power flow is augmented to produce a retarding torque to bring back the generator to its normal speed. Fast control of dc current regulator may be used for this purpose. The circuit breakers are then reclosed and the ac power flow is resumed at its pre fault value without any oscillation. The power swing is low and the system is optimally damped at the end of first swing.

Keywords: transient stability, ac-dc power flow, dc power modulation, fault clearing time, zigzag transformer

Classification: Science and engineering for electronics

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1 Introduction

HVDC transmission lines in parallel with EHV ac lines may be used to improve transient stability as well as to damp out oscillations in power system [1]. Long EHV ac lines cannot be loaded to its thermal limit to keep sufficient margin against transient instability.

EHV ac line may be loaded to a very high value if the conductors are allowed to carry superimposed dc current along with ac current. The added dc power flow does not create any transient stability problem.

The novel idea of simultaneous ac-dc power transmission through a single circuit ac transmission line is first proposed in reference [2]. The idea is extended to bi-polar dc power transmission through a double circuit ac transmission line [3] with power up-gradation and steady state stability improvement. Utilization of built-in short term overload capacity of converters in HVDC may improve the transient stability limit in an ac line operating in parallel with the dc line [4].

In this paper a single-machine connected to infinite bus through a single circuit ac transmission line, which is converted for ac-dc transmission, has been examined. A novel concept of modulating the dc power only and temporarily stopping the ac power flow just after the fault clearance is proposed to improve the transient stability limit and to restrict the power swing with optimal damping.

2 Basic simultaneous AC-DC power flow

The circuit diagram shown in Fig. 1 shows the basic scheme for simultaneous ac-dc power flow through a single circuit ac transmission line. The dc power is obtained through the rectifier bridge and injected to the neutral point of the zigzag connected secondary of sending end transformer TR2, and is reconverted to ac again by the inverter bridge at the receiving end. The inverter bridge is again connected to the neutral of zigzag winding of the receiving end transformer. The transmission line caries both 3-phase ac and dc power. Each conductor of each line carries one third of the total dc current I_d along with ac current I_a. The return path of the dc current is through the ground. Zigzag connected winding is used at both ends to avoid saturation

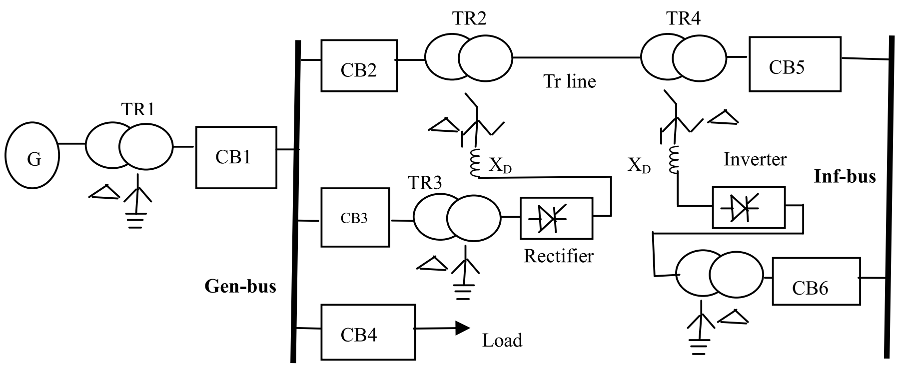

Fig. 1. Single machine connected to infinite bus through ac-dc transmission

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of transformer due to dc current flow and is used as an interfacing device of dc and ac supply. A high value of reactor X_D is used to reduce harmonics in dc current.

Assuming equal voltages at the two ends the total power transfer through the unconverted line with only ac power flow is;

$$P'_{total} = P'_{max} \sin \delta'_0 \tag{1}$$

To keep sufficient stability margin, the angular difference at the two ends of a long transmission line seldom exceeds 30° keeping the power angle δ'_0 low. P'_{total} becomes a fraction of the maximum power transfer capability P'_{max} of the line.

The total power transfer through the converted line with both ac-dc power flow is;

$$P_{total} = P_{ac} + P_{dc} = P_{max} \sin \delta_0 + V_d I_d \tag{2}$$

V_d is the dc voltage of the converted line. The power angle δ_0 between the ac voltages at the two ends of the converted system may be increased to a high value because of the fast control facility of P_{dc}. For a constant value of total power, P_{dc} may be modulated by fast control of the current controller of dc power converters. Its effect is similar to that of the FACTS controller and δ_0 may be as high as 80°.

3 Problem formulation

A conventional power system is considered with a single circuit long ac transmission line supplying power to infinite bus (Fig. 1 without dc power flow). Any 3-phase fault at the load terminal near the Gen-bus is cleared by CB4. But during the period of fault duration, power transfer through the line drops to zero as Gen-bus voltage collapses. The equal area criteria for stability study may be adopted to assess the transient stability limit of the system. Fig. 2 (a) shows that the system becomes unstable for high value of pre-fault mechanical power input P_m ($= P'_{total}$). If the fault clearing time t_1 is not very fast then the corresponding angle δ_1 becomes larger than the critical clearing angle δ_c and the system becomes unstable. Even if the system is stable,

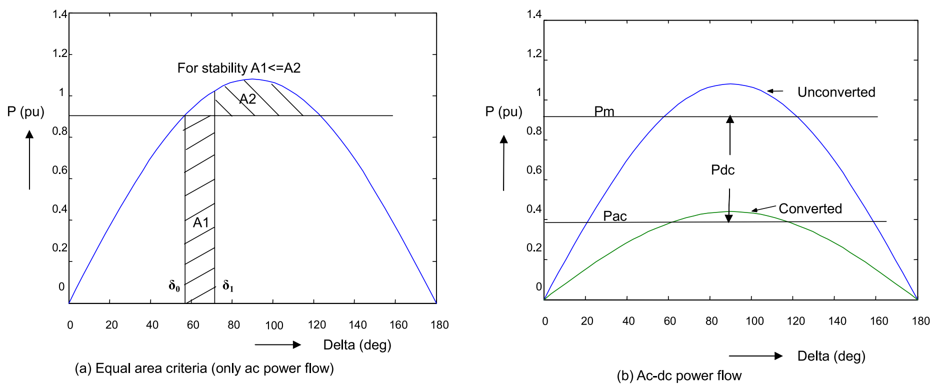

Fig. 2. P-δ curve

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a large power swing occurs without the application of stabilizers. Similar phenomenon is observed for any temporary 3-phase or 1-phase fault in the transmission line which is cleared by opening CB2 and CB5 and subsequently reclosed after the reclosure dead time t_d. The system becomes unstable due to high value of P_m and t_d.

4 Control strategy

The line is then converted for ac-dc simultaneous power flow (Fig. 1).

Under normal operating condition the power transfer through the line is

$$P_{total} = P_m = P_{ac} + P_{dc}. \text{ (refer Fig. 2 (b))}$$

When the fault occurs at the load terminal near the Gen-bus, the bus voltage reduces to a very low value. Both P_{ac} and P_{dc} become zero. The fault is cleared after t_1 second by tripping CB4. For independent control of dc power flow CB2 and CB5 are also commanded to trip at a time $t \leq t_1$, so P_{ac} remains to be zero even when the fault is cleared. But dc current is allowed to flow through the line. At the instant of tripping of CB4 rapid control of the converter system increases the dc power flow to $P_{dc}' = P_m + \Delta P_{dc}$.

Referring Fig. 3, the accelerating energy is E_1 (= Pmt1) and the power angle δ_0 swings to δ_1. At δ_1 retarding power of ΔP_{dc} ($= P_{dc}' - P_m$) is applied for t_2 second. The retarding energy is E_2 ($= \Delta P_{dc} t_2$). During the acceleration period the generator speed increases, but it gets back its steady state value after the retardation period t_2,

$$E_1 = E_2 \text{ and } t_2 = P_m t_1 / \Delta P_{dc} \tag{3}$$

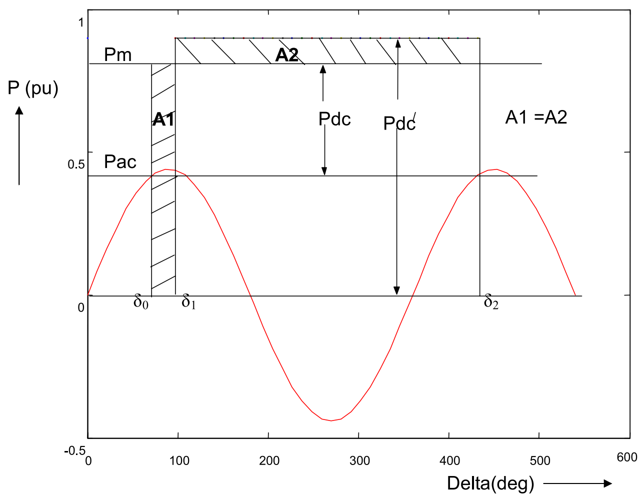

Fig. 3. Equal area criteria for dc control

During the retardation period δ_1 further swing to δ_2 and the values of δ_1 and δ_2 may be given as [5];

$$\delta_1 = \delta_0 + (\pi f_0 P_m {t_1}^2)/2H; \quad \delta_2 = \delta_1 + (\pi f_0 \Delta P_{dc} {t_2}^2)/2H \tag{4}$$

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Where, f_0 = steady state frequency and H = inertia constant of generator.

$$\Delta P_{dc} \text{ is controlled to make } \delta_2 = 2n\pi + \delta_0 \tag{5}$$

Where n is an integer. From (3), (4) and (5) one may get;

$$\Delta P_{dc} = (f_0 P_m{}^2 t_1{}^2)/(4nH - f_0 P_m t_1{}^2) \tag{6}$$

Just at the end of t_2, the dc power P_{dc}' is reduced to the pre fault value of P_{dc} and CB2 and CB5 are reclosed. The ac power flow is resumed.

$$P_{ac} = P_{max} \sin \delta_2 = P_{max} \sin \delta_0 \tag{7}$$

The new steady state is reached as the total power flow becomes $P_m = P_{ac} + P_{dc}$; the generator already regained its original speed and there is no further swing. The system is optimally damped. The total angular swing is $2n\pi$ but the power swing is only ΔP_{dc}, which is kept very small by choosing proper value of n. A low value of ΔP_{dc} also keeps P_{dc}' low.

Similar technique is adopted to clear any temporary fault in the line. The fault is cleared by tripping CB2 and CB5 and dc power flow is resumed after the auto reclosure dead time t_d, but CB2 and CB5 are reclosed only after a further time delay of t_2.

5 Case study

Classical model of the sample power system (Fig. 1) is used for the simulation study and the mechanical power input to the generator is kept constant through the transient period $(t_1 + t_2)$.

Assumed values: Gen-bus voltage = Inf-bus voltage = 1.0pu; $P_m = 0.9$pu;

For the unconverted line:

$$\delta'_0 = 56.16°;\ P'_{max} = 1.08\text{pu}.$$

For the converted line:

$$\delta_0 = 80°;\ P_{ac} = 0.384\text{pu};\ P_{max} = 0.39\text{pu};\ P_{dc} = 0.516\text{pu};$$

The upper limit of power transfer during the control of dc power is assumed not to cross 1.1pu to keep the power swing low.

Simulation Results: Faults at load terminal near Gen-bus are cleared with minimum time delay of 0.1 sec. To clear transmission line fault with 3-pole auto reclosing of circuit breakers a minimum dead time t_d of about 0.35 sec is generally used. So the total fault clearing time becomes 0.45 sec in that case.

MATLAB simulation is carried out to assess the transient stability limit of unconverted line. Solution of the swing equation shows that the system becomes unstable with as low as 0.1 second delay in the fault clearance with 0.9pu pre fault power.

Then the simulation is carried out on the converted line. The system becomes stable even with 0.45 sec. delay time. The results for the maximum fault clearing time of 0.45 sec. are given below:

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$P_m = 0.9$pu; $\delta_0 = 80°$; $t_1 = 0.45$ sec;
Total time of swing $(t_1 + t_2) = 2.77$ sec; $P'_{dc} = 1.075$pu;
Angle of swing $(\delta_2 - \delta_0) = 1080°$; $P'_{dc}/P_{dc} = 2.083$.

Though the angle of swing is high but there is no ac power flow during this period. The maximum deviation of power flow through the line after the fault clearance is also low and is 0.1749pu. The swing is optimally damped when it reaches δ_2.

Comparative study: Recent power control technologies like FACTS devices are also used to improve the stability limit. A Static Synchronous Series Compensator (SSSC) is connected in series with the line at the generator end. With the reduction of effective transfer reactance to 50% of the original value by capacitive compensation, the system becomes stable with a maximum of 0.23 second delay in the fault clearance with 0.9pu pre fault power. Even with the reduction of effective transfer reactance to 20% of the original value does not make the system stable with 0.45 sec delay time.

Similarly, a Static Synchronous Compensator (STATCOM), which is a shunt connected var compensator, is connected at the generator end of the line to improve the stability limit. Capacitive var compensation of 2 pu MVAR makes the system stable with a maximum of 0.23 second delay in the fault clearance with 0.9pu pre fault power. Even a very high value of 3.2 pu MVAR capacitive var compensation becomes unable to make the system stable with 0.45 sec delay time.

The control action of the compensators can only be activated after the fault clearance at the load terminal or after auto reclosing of CBs for transmission line faults.

It shows that the proposed simultaneous ac-dc power flow is much superior in comparison to FACTS devices for the improvement of transient stability limit.

Experimental verification of the satisfactory working of the proposed system on a laboratory model is reported in [2, 3].

6 Conclusion

A generator supplying power to infinite bus through a single circuit long ac transmission line becomes unstable after the clearance of a fault if the pre fault power transfer and/or the fault clearance time are high. Conversion of the line for simultaneous ac-dc power flow not only enhances the steady state power flow but also keeps the system stable with high values of pre fault power and fault clearance time. 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. The ac power flow is then resumed at its pre fault value by switching on the ac supply. The power swing is low and the system is optimally damped at the end of the first swing.

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