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# Enhancement of the Transient Stability of AC/DC Power System by Controlling HVDC Power Flow

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***Abstract*—HVDC power transmission employing power electronic device provides a wide range of control in power transmission. There are several possibilities to improve the transient stability in a power system. One adequate option is to use the high controllability of the HVDC if HVDC is available in the system. This paper presents a control strategy for HVDC to improve the transient stability. The strategy controls the power through the HVDC to 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 by adding 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 using a PD controller, the use of a PD controller is appropriate since it has the property of fast response. The effectiveness of the proposed controller is demonstrated by a single machine-infinite bus system example. Simulation study on SimPowerSystems toolbox in the MATLAB is carried out to validate the concept.**

*Key-Words— HVDC, Transient Stability, Power Modulation*

## I. INTRODUCTION

The power transfer capability of long AC transmission lines is usually limited by large signal stability. The development of effective ways to use transmission system close to its thermal limit has attracted much attention in recent years [1].

The central purpose of conventional HVDC transmission is to transfer a certain amount of electrical power from one node to another and to provide the fast controllability of real power transfer. If the HVDC link is operated in parallel with a critical AC line the load-flow of the AC line can be controlled directly. The HVDC link can therefore be used for improving transient stability. [2]–[3]

HVDC links, under traditional controls, do not provide synchronizing or damping effects in response to disturbance on AC side. However, the capability of an HVDC link to rapidly modulate the power flow, in response to control signals, has been utilized for some time to improve the dynamic stability of AC-DC systems [4].

For an AC–DC system, Klein et al. [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 all [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 single machine infinite bus system connected through a parallel AC and DC power transmission has been studied. In this study, the power flow in the HVDC link is modulated by adding an auxiliary signal to the current reference of the rectifier firing angle controller to improve the transient stability. The strategy is based on fast balancing of the accelerating energy. 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.

## II. MODEL DESCRIPTION

### A. HVDC Link

The HVDC considered in this paper (fig. 1) is of conventional type based on the CIGRE benchmark system [7]–[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 [7]–[8] modified to suit the necessary power.

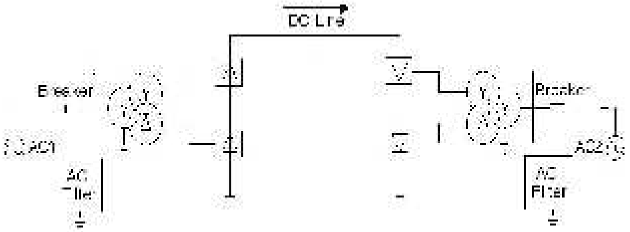


Fig.1. HVDC system

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.

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 $\alpha_{AOr}$, the power through the HVDC is controlled.

The current controller is shown in fig. 2. The limited current Iref-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 Iref (1 pu).

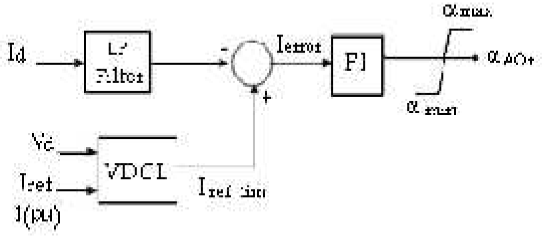


Fig.2. Current controller

## 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.

All data of the system under study can be found in appendix A.

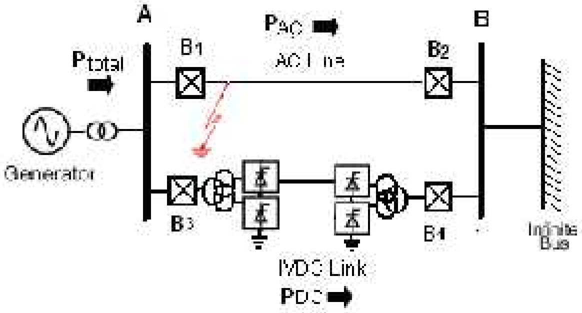


Fig.3. Parallel AC-DC system

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. Figure 4 shows the power through the HVDC ($P_{dc}$), the AC line ($P_{ac}$) and total power transfer ($P_{total}$) in steady state conditions.

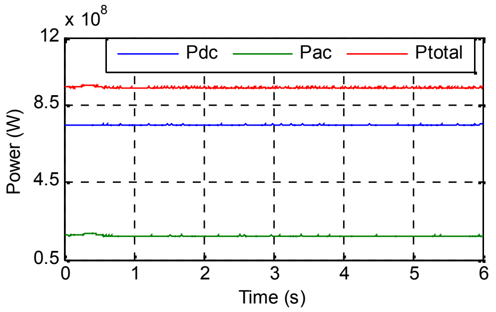


Fig.4. Ptotal, Pac and Pdc power transfer in steady state conditions

## III. CONTROL STRATEGY

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. 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. 5 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 $\delta_1$ becomes larger than the critical clearing angle and the system becomes unstable.

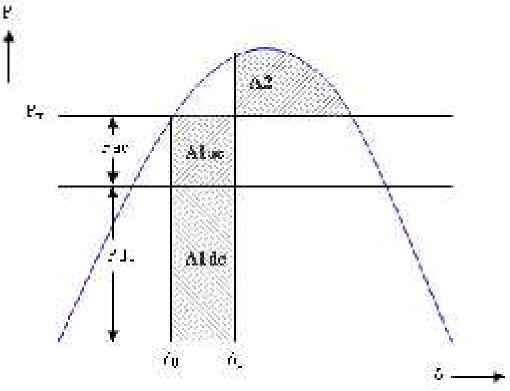


Fig.5. Equal area criteria

$P_{ac}$ steady state AC power by AC system
$P_{dc}$ steady state DC power by the DC system
$P_{total}$ total power transfer
$\delta_0$ steady state power angle
$\delta_1$ 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

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. 6, at the instant of clearing fault $t_1$ rapid control of the converter system increases the DC power flow to $P_{dc}^{/}$ :

$$P_{dc}^{/} = P_m + \Delta P_{dc} \qquad (1)$$

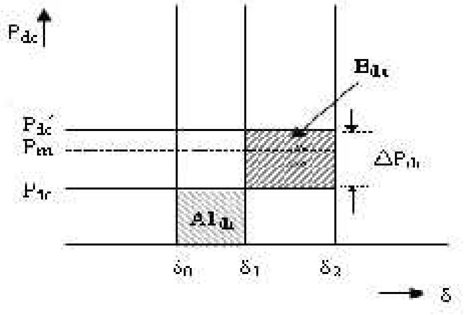


Fig.6. Equal area criteria for DC control

$B_{dc}$ 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:

$$B_{dc} = \left(A1_{ac} + A1_{dc}\right) - A_2 \qquad (2)$$

$$\Delta P_{dc} = P_{dc}^{/} - P_{dc} \qquad (3)$$

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

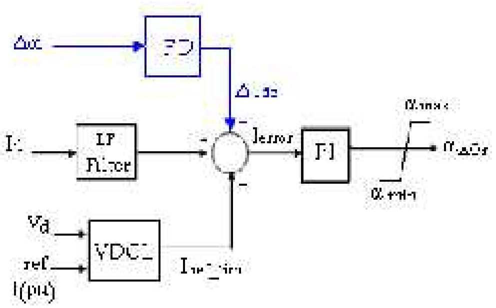


Fig.7. Current controller and auxiliary signal

The control signal ($\Delta I_{dc}$) is derived from speed deviation signal (Δω) of the generator using a PD controller as shown in fig. 7.

## IV. TRANSIENT STATE SIMULATION

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

Figure 8 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.

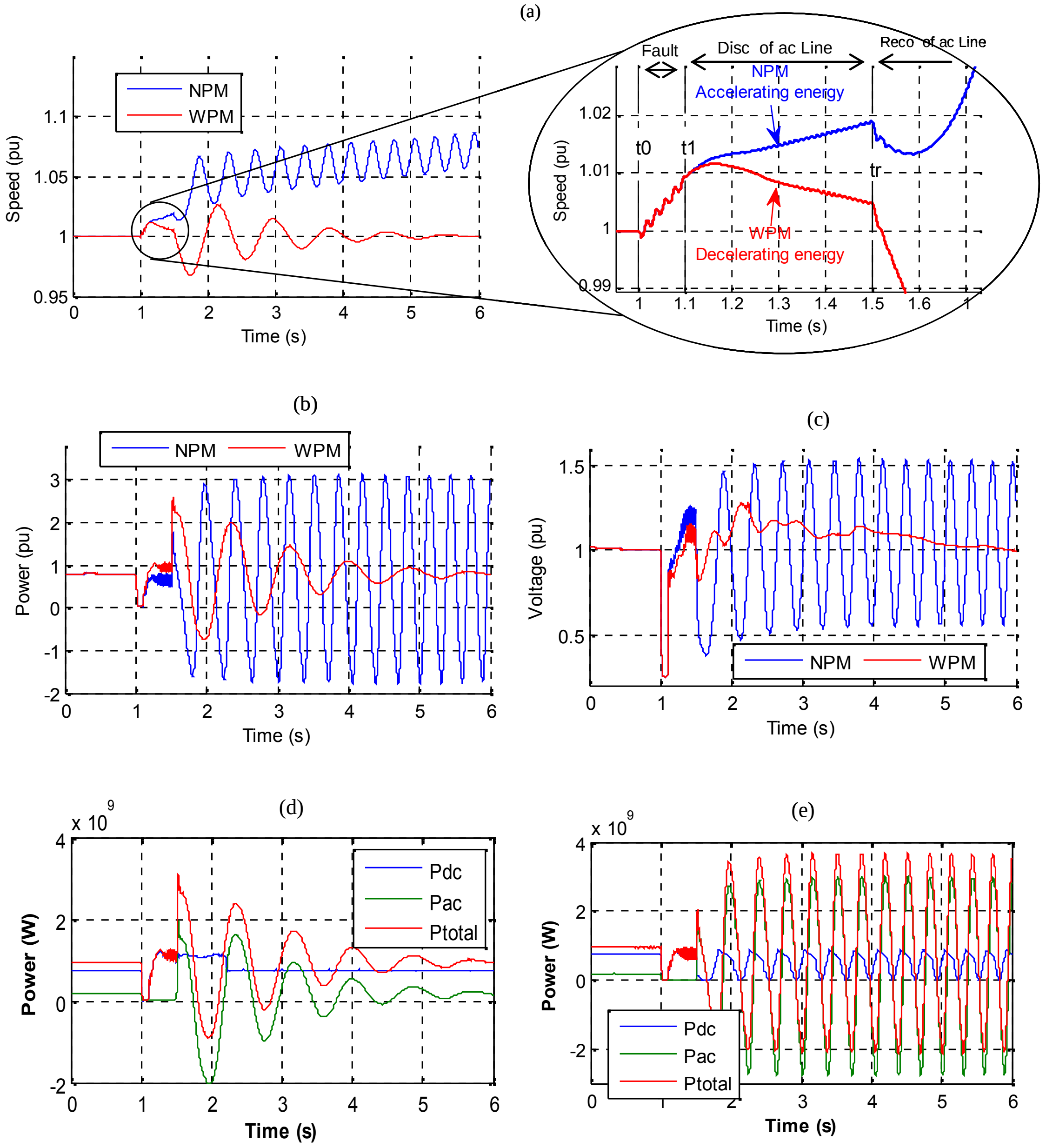
Figure 8 (a) give the variation of generator speed. As can be seen in the figure, the system falls out of synchronism when the HVDC is transferring a constant amount of power, i.e. no auxiliary power control. When the control strategy is applied, the first swing is controlled in such a way that the system remains stable.

As can be seen in Fig. 8 (i) the power through the HVDC is changing after disconnection of AC line around 1100 MW to give sufficient retarding energy to generator.

Figure 8 (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.



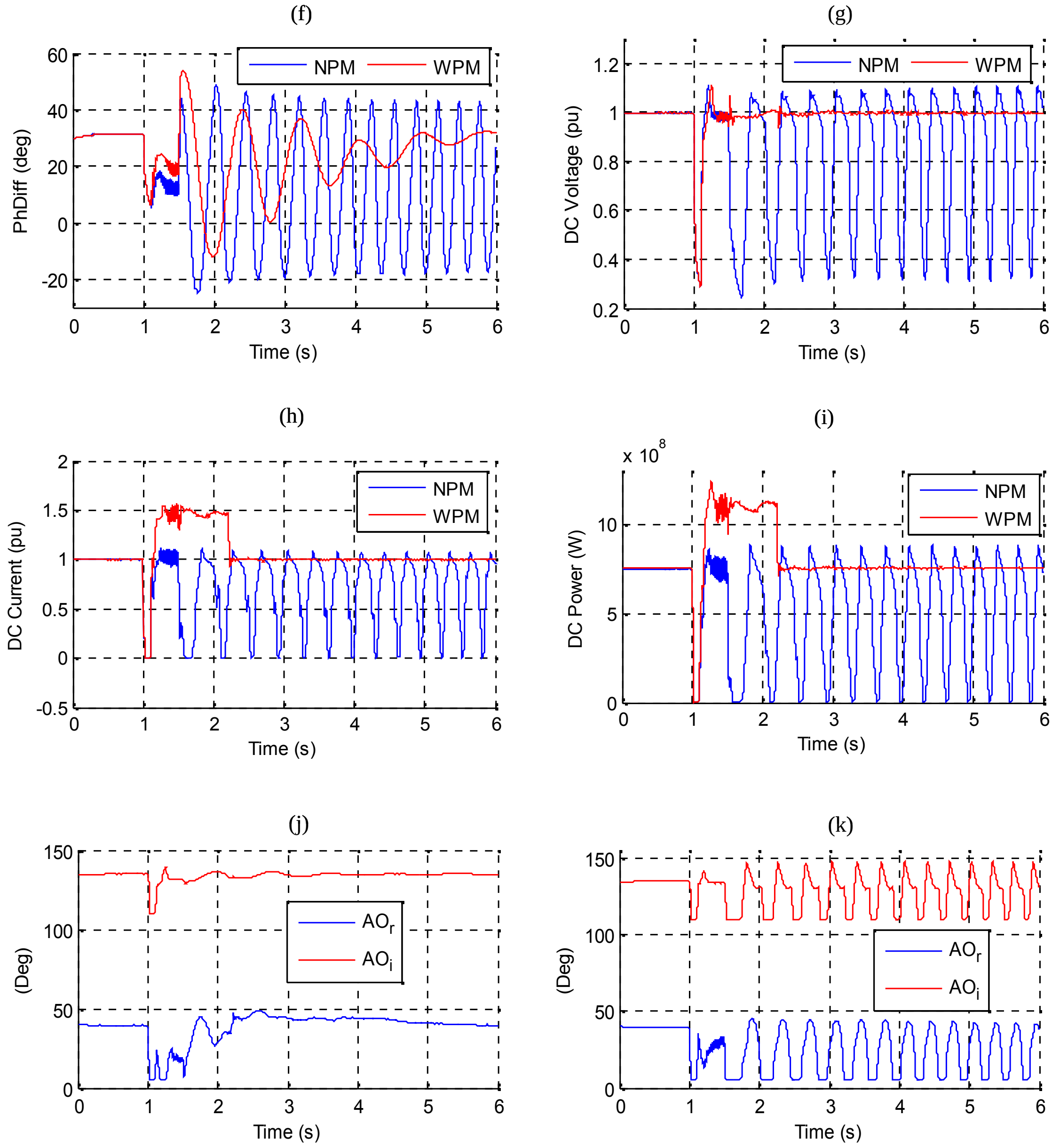

(f) (g) (h) (i) (j) (k)

Fig.8. (a) Generator speed. (b) Generator active power output. (c) Generator terminal voltage. (d) AC (Pac), DC (Pdc) and total (Ptotal) power transfer WPM. (e) AC (Pac), DC (Pdc) and total (Ptotal) power transfer NPM. (f) Transmission angle (PhDiff) between two ends. (g) DC Voltage. (h) DC Current. (i) DC power transfer (Pdc). (j) Rectifier (AOr) and inverter (AOi) firing angle order WPM and (k) NPM.

## I. CONCLUSION

This paper presents a control strategy for HVDC to improve the transient stability in power systems. The strategy controls the power through the HVDC to make the system more transient stable during disturbances. The proposed control strategy consists of the PD controller, the use of a PD controller is appropriate since 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.

A detailed study has been carried out in SimPowerSystems toolbox in the MATLAB environment to validate the proposed method. It has been demonstrated that the power flow in the HVDC link is modulated by adding an auxiliary signal to the current reference of the rectifier firing angle controller to improve 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.

## APPENDIX

### Appendix A: Parameters of the power system

*Generator*:

$S_n$ = 1200 MVA, $V_n$ = 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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