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Stability Improvement of Power System by Simultaneous Ac–Dc Power Transmission

KEYWORDS
PSCAD, MATLAB simulation; Simultaneous AC–DC power transmission; Transient stability.

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ABSTRACT *It is difficult to load long extra high voltage (EHV) ac lines to their thermal, Stability and dielectric limits as a sufficient margin is kept against transient instability. With the model proposed in this paper it will be possible to load these lines close to their thermal limits. The transmission lines are allowed to carry usual ac along with dc superimposed on it. The added dc power flow does not cause any instability. This thesis gives us the feasibility of converting a double circuit ac line into composite ac–dc power transmission line to get the advantages of parallel ac–dc transmission in order to improve stability and dampen out oscillations. The advantage of parallel ac-dc transmission for improvement of transient stability and dynamic stability and damp out oscillations has been established. Simulation has been carried out in MATLAB software package (Simulink Model). The results show the stability of power system both for natural response and response under faulty conditions*

1. Introduction

The power transfer capability of long AC transmission lines is usually limited by large signal stability. Economic factors such as the high cost of long lines and revenue from the deliv- ery of additional power provide strong incentives to explore all economically and technically feasible means of raising the stability limit. The development of effective ways to use trans- mission system close to its thermal limit has attracted much attention in recent years. The progress in the field of power electronics has already started to influence the power indus- try and the emergence of FACTS devices is the outcome of this. Very fast control of SCRs in FACTS devices like Static VAR System (SVS), Controlled Series Capacitor (CSC), and Static Phase Shifter (SPS) and controlled Braking Resistors improve stability and damp out oscillations in power system.

The transient stability criteria includes the ability of the system to withstand a three-phase fault at critical locations such as near the heavily loaded generator bus at the line carrying large amount of power in case of AC transmission and near the inverter in case of HVDC transmission .

HVDC transmission lines in parallel with EHV AC lines are recommended to improve transient and small signal stability of power system. Improvement of the stability characteristics of interconnected power system by using fast acting converter con- trol on HVDC links in the system is well established. Uhlmann has considered an idealized two-machine system with parallel AC and DC links, that proportional and integral control using the frequency signals . He has demonstrated a significant improvement in the stability. These results were obtained from a linearised system analysis with simplifying assumptions. However, subsequent work done by Peterson and Krause, confirmed the general validity of the results even for large dis- turbances. The results were based on a simplified model of the system using digital or analog simulation.

For an AC–DC system, Klein et al. have discussed the effect of DC modulation on the dynamic stability of (i) one machine, infinite bus and (ii) two machine, infinite bus configu- rations.

Vovos and Galanos have studied transient stability of a two area power system connected in two ways: (i) two parallel AC links and (ii) one AC line in parallel with DC line by simulation. Both the configurations were subjected to the same

Disturbances and faults, and their responses were assessed and compared with regards to system stability.

Hammad has introduced a generic concept of combining the transient angle and voltage stability of a parallel AC–DC transmission. The HVDC with classical DC power control even with supplementary damping signal does not con- tribute to system synchronizing torque and may increase the risk of instability. He has demonstrated the utilization of the inherent built-in short-term overload capacity of the DC converter to increase the stability margin of the AC system and allow a higher power transfer on the parallel AC transmission. Advanced HVDC large signal stabilizing control strategies can be developed to produce large amount of synchronizing and damping torques that can effectively stabilize the AC system and damp out all power oscillations on the parallel AC transmission after faults. Such controls also optimize the use of the HVDC short-term overload capacity without need for additional reactive power support. The increase in par- allel AC transmission transient stability MW transfer limit can almost be equal to the HVDC temporary overload. These features constitute large savings compared to conventional solu- tions.

Lucas et al. have utilized a small amount (2%) of con- verted DC injected into the AC line through the transformer neutral to enhance the dynamic stability of an AC power system. However, the injections of DC into the simple -Y transformer neutral will definitely saturate the transformers at both ends of the line. This is a major drawback of the scheme. Furthermore, the control proposed in this scheme adds only damping and does not contribute synchronizing torque component.

The authors of this paper have earlier shown that EHV AC line may be loaded to a very high level by simultaneous AC and DC power transmission through it. The basic proof justifying the feasibility of simultaneous AC–DC transmission has been reported in these papers.

In this paper, the improvement of transient stability by utilization of the inherent built-in short-term overloads capacity Of the DC system and rapidly modulating the DC power in case of simultaneous AC–DC line has been taken up.

A single machine infinite bus (SMIB) connected by a double circuit AC line, converted for simultaneous AC–DC power transmission has been studied. For the purpose of comparison, the same double circuit line with pure AC trans- mission was also studied. The transmission angle is varied up to 80° in case of simultaneous AC–DC power transmission system. Such a large angle is not possible in pure AC system. Both the configurations were subjected to the same types of faults at various locations of the line, and their responses were assessed and compared with regards to transient stability using PSCAD/MATLAB simulation package.

2. Simultaneous AC–DC power transmission

2.1. Basic concept

The network in Fig. 1 shows the basic scheme for simul- taneous AC–DC power flow through a double circuit AC transmission line. The DC power is obtained by converting a part of AC through line commutated 12-pulse rectifier bridge used in conventional HVDC and injected into the neutral point of the zig-zag connected secondary windings of sending end transformer. The injected current is distributed equally among the three windings of the transformer. The same is reconverted to AC by the conventional line commutated inverter at the receiving end. The inverter bridge is connected to the neutral of zig-zag connected winding of the receiving end transformer. Each transmission line is connected between the zig-zag windings at both ends. The double circuit transmission line carries both three-phase AC as well as DC power. At both ends, zig-zag connection of secondary windings of transformer is used to avoid saturation of core due to flow of DC component of current.

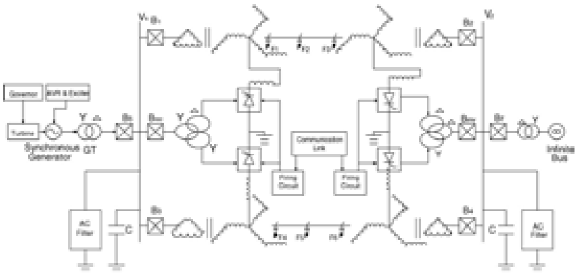


Fig. 1. Basic scheme for simultaneous AC–DC transmission.

2.2. Economic consideration

To get the advantages of parallel AC–DC transmission in order to improve stability and damping oscillations, the con- version of a double circuit AC line for simultaneous AC–DC power flow has been considered such that no alterations of con- ductor, insulator string and tower structure of the original line are required. The optimum values of AC phase and DC voltages of the converted line are 1/2 and $1/\sqrt{2}$ times the phase voltage before conversion, respectively.

The cost of transmission line includes the investment and operational costs. The investment includes costs of Right of Way (RoW), transmission tower, conductors, insulators, labor and terminal equipments. The operational costs include mainly the cost of losses. Additional costs of compensation and its terminal equipments also influences the AC line cost. DC transmis- sion does not require compensation but the terminal equipment costs are increased due to the presence of converters and fil- ters. Replacement of Y-connected transformer in simultaneous AC–DC power transmission with zig-zag transformer is not likely to increase the cost, because it transfers only 25% of total power by transformer action. Also, the AC voltage reduces to 50% of the original AC voltage. However, the neutral point of this transformer needs insulation to withstand DC voltage. The loadability is observed to get doubled or even more with the simultaneous AC–DC power flow for a line with length of 500 km or longer. When an existing AC line is converted to simultaneous AC–DC line, instead of adding separate parallel DC, the additional investment on new DC line and on AC line compensations are saved.

2.3. Protection

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 for simultaneous AC–DC power flow. In case of sym- metrical 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 inver- sion) to protect rectifier and inverter bridges. Circuit breakers (CBs) are then tripped at both ends to isolate the faulty system. Any asymmetrical faults will create inequality in the DC current flowing through the secondary of the zig-zag transformer, which will result in saturation of the transformer core. Eventually, the AC current on primary side will increase further. Primary side CBs, designed for transformer terminal and winding faults, clear these faults easily at shortest possible time. Blocking pulses to the bridges and activating the bypass valves of the bridge carry out the protection on DC side. A surge diverter connected between the zig-zag neutral and ground, protects the converter bridge against any over voltage.

DC current and voltage may be measured at zig-zag winding neutral terminals by adopting common methods used in HVDC system. AC component of transmission line voltage is measured with conventional CVTS used in EHV AC lines. Superimposed DC voltage in the transmission line does not affect the working of CVTS. Linear couplers with high air-gap core may be employed for measurement of AC component of line current. DC component of line current is not able to saturate high air-gap cores.

Electric signal processing circuits may be used to generate composite line voltage and current waveforms from the signals obtained for DC and AC components of voltage and current. Those signals are used for protection and control purposes.

3. Control principle and strategy

First swing stability in a power system refers to the ability of a power system to maintain a connected generator in synchro- nism after the system has been subjected to a major disturbance such as transmission system faults. First swing instability is caused by insufficient synchronizing torque. The criterion for the first swing stability is that the accelerating energy, occurring whenever the generator electrical power is less than the driving mechanical power, must be counterbalanced by an equal decel- erating energy, whenever generator electrical power exceeds the driving mechanical power.

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 for producing sufficient decelerating energy to solve the first swing stability.

Fig. 2 shows the power-angle characteristics of the system considered in Fig. 1

P_{ac} steady state AC power by AC system

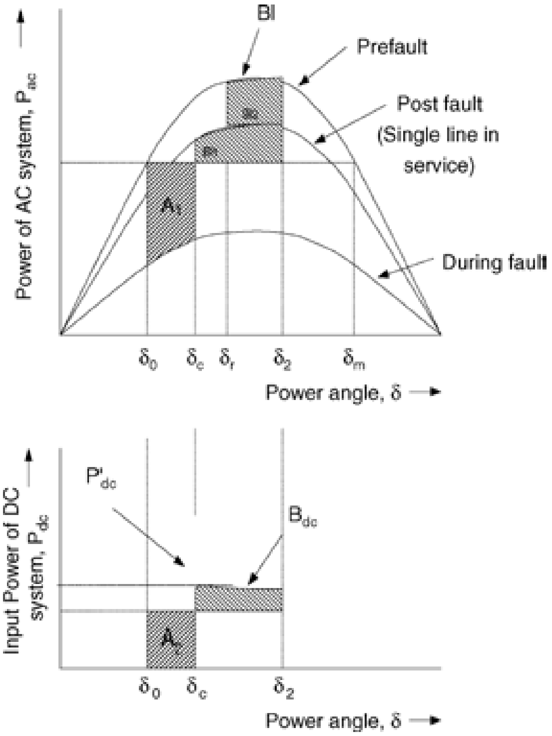


Fig. 2. Power-angle characteristics.

include constant current (CC) and constant extinction angle (CEA) and voltage dependent current order limiters (VDCOL). The converters are supplied from AC bus through Y-Y and Y- converter transformers. Each bridge is a compact PSCAD representation of a DC converter, which includes a built-in six-pulse Graetz converter bridge (can be inverter or rectifier), an internal Phase Locked Oscillator (PLO), firing and valve blocking controls and firing angle (α)/extinction angle (γ) measurements. It also includes built-in RC snubber circuits for each thyristor. AC filters at each end on AC sides of converter transformers are connected to filter out 11th and 13th harmonics. These filters and shunt capacitor supply reactive power requirements of the converters.

4. Transient state simulation

A time domain simulation study is carried out to verify the effectiveness of proposed scheme in the environment of PSCAD/EMTDC. For the purpose of comparison, simulation study was repeated for the same line with conventional HVAC system. For both cases, the real power transfer through the transmission line is kept as same. Initially, the two schemes, namely simultaneous AC–DC and AC are assumed to be operating in steady state conditions. The details of the operating conditions are mentioned in Appendix A. It has been confirmed through simulation studies, that simultaneous AC–DC transmission system without DC modulation becomes unstable in the first swing. However, with proposed control strategy of DC modulation the system remains stable after first swing.

5.1. Simultaneous AC–DC transmission

Computation and simulation studies show that in simultaneous AC–DC power flow, line delivers maximum power at transmission angle of about 60◦ [16]. The details of EHV AC line converted to simultaneous AC–DC line are given in Appendix A.

The simulation study is carried out for the following cases.

5.1.1. Case (1): fault near sending end

Initially, the simultaneous AC–DC system is assumed to be

operating in its steady state. The pre-fault power is 1.88 times the loadability of original AC line at a transmission angle of

60◦. At time t = 0.5 s a solid three-phase to ground fault occurs

near sending end F1 as shown in Fig. 1. The fault is followed by blocking of firing pulses to converter SCRs and activation of bypass valves. After a period of four cycles (80 ms), trip signals are given simultaneously to circuit breakers B1and B2 at both ends of faulty line to clear the fault. Next, pulses to SCRs are released. Thereafter, CBs are reclosed after a delay of five cycles (100 ms) from the instant of clearing fault. Fig. 3 shows the transient responses for this fault condition.

5.1.2. Case (2): fault near receiving end

Now considering a similar a solid three-phase to ground fault with the same sequence of events near the receiving end F3 of the line (near inverter).

Various transient responses for this fault condition are shown in Fig. 4.

Comparing the responses given in Figs. 5 and 6 for the case of sending end and receiving end faults the main observations are as follows:

- The magnitude of speed deviation is almost same in both cases, but speed deviation recovers faster in case of fault at receiving end.
- At the instant of the fault the generator power is subjected to much higher peak transient for sending end fault.
- The transmission angle overshoot is larger in case of sending end fault.
- After the clearance of the fault the real power oscillations have same peak values for both fault locations. However, in case of receiving end fault the oscillations subside earlier.
- The responses of DC voltage and current indicate no commutation failure for both fault conditions.

Thus, the overall comparison of simulation results of Figs. 5 and 6 indicate that the fault at the sending end is more severe than the fault at the receiving end for the system under study.

Other type of faults such as single line to ground, double line to ground, double line and three-phase faults were also studied near sending and receiving end. In all the above cases, the system is found to be stabilizing in durations, less than that for the solid three-phase to ground faults considered above.

5.2. Pure AC transmission with series compensation

The practical series capacitive compensation does not usually exceeds 75% for a number of reasons, including load balancing with parallel path, high fault current, and the possible difficulties of power flow control. In systems where sub-synchronous resonance is main concern, the compensation is limited to 30% . However, 50% compensation has been considered in the present study so that the AC system becomes comparable with simultaneous AC–DC configuration.

For the purpose of comparative study, the same network depicted in Fig. 1 is reduced to pure HVAC by deleting the

HVDC part and replacing zig-zag transformer with -Y transformer along with addition of compensation. This HVAC system is operating in its steady state and delivering same real power to the receiving end as that in the case of simultaneous AC–DC system but at a transmission angle of 30°.

The exciter is equipped with the power system stabilizer (PSS) in this case. The gain of PSS (though it is not a PI controller) is assumed to be same as that of PI controller used in simultaneous AC–DC system for DC modulation. The block diagram with its parameters of this PSS is shown in Appendix A. Fig. 7 show the transient responses when pure HVAC compensated system is subjected to a solid three-phase to ground fault F1 at one of the line near sending end. The fault is detected and circuit breakers B1, B2 of the faulty line are opened after four cycles (80 ms) to clear the fault. Five cycles (100 ms) after clearing the fault, the CBs are reclosed.

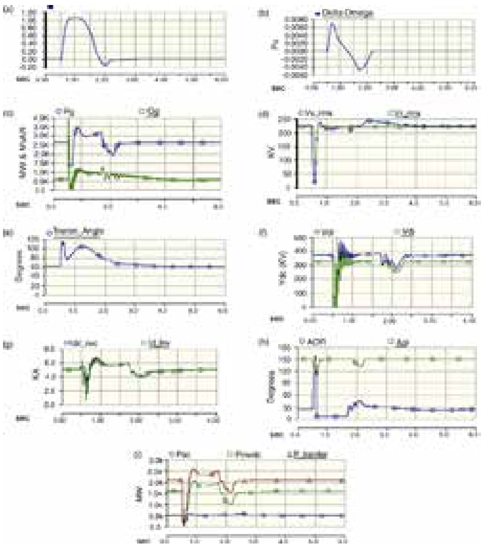


Fig. 3. (a) Control signal (Idc). (b) Generator's speed deviation (Delta Omega). (c) Generator's active (Pg) and reactive (Qg) power output. (d) Sending (Vs rms) and receiving (Vr rms) end bus voltages. (e) Transmission angle (Transm Angle) variation. (f) Rectifier (Vdr) and inverter (Vdi) DC voltages. (g) Rectifier (Idc rec) and inverter (Id inv) DC current. (h) Rectifier (AOR) and inverter (Aoi) firing angle order. (i) AC (Pac), DC (Pinvdc) and total (P tranfer) power transfer.

A similar fault condition with the same sequence of events was created for pure HVAC line with 30% compensation and 45° transmission angle. The pre-fault power level is considered to be same as that for the above cases. The response of transmission angle for this condition is shown in Fig. 8. An oscillatory response with low damping is observed. The PSS is not capable of providing an effective damping to the system at this transmission angle.

Increasing the transmission angle to 49° and reducing the compensation level in order to maintain same pre-fault real power delivery, the system is subjected to same disturbance. The transmission angle response is shown in Fig. 9 is found to be oscillatory leading to instability. A further increase of 1° in transmission angle makes the system unstable just after first swing as evident from Fig. 10a and b.

Comparison of results between simultaneous AC–DC system and pure HVAC system for the similar nature and duration of faults indicate:

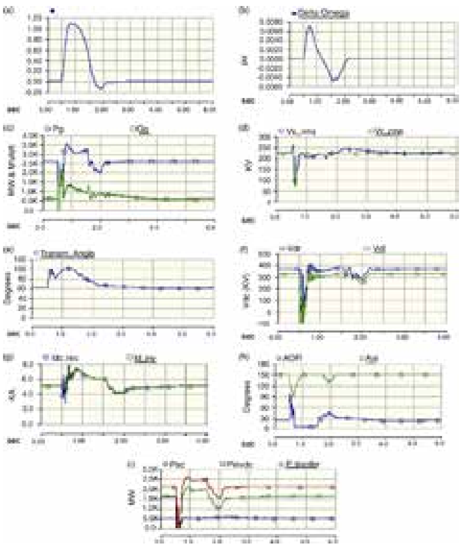
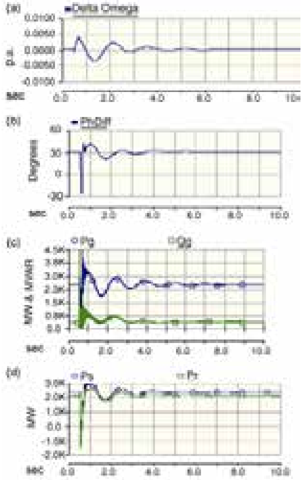


Fig. 4. (a) Control signal (Idc). (b) Generator's speed deviation (Delta Omega). (c) Generator's active (Pg) and reactive (Qg) power output. (d) Sending (Vs rms) and receiving (Vr rms) end bus voltages. (e). Transmission angle (Transm Angle) variation. (f) Rectifier (Vdr) and inverter (Vdi) DC voltages. (g) Rectifier (Idc rec) and inverter (Id inv) DC current. (h) Rectifier (AOR) and inverter (Aoi) firing angle order. (i). AC (Pac), DC (Pinvdc) and total (P tranfer) power transfer.

- The magnitude of generator speed deviation in case of simultaneous AC–DC system is longer. However, this speed deviation reduces to zero at a faster rate in the simultaneous AC–DC system as compared to pure HVAC case.
- At the inception of fault, the generator real power overshoot is larger in case of pure HVAC system. The subsequent real power oscillation magnitude as well as duration is longer in pure HVAC system. While these oscillations subside much faster in case of simultaneous AC–DC system.
- The pure HVAC system becomes oscillatory unstable at transmission angle of 49°. When angle is increased to 50°, the system looses synchronism after first swing.
- The PSS through exciter is unable to provide sufficient damping to prevent generator stepping-out in pure HVAC system.
- The most important merit of the simultaneous AC–DC system is that it remains stable even up-to transmission angle of 80° as depicted in Fig. 11. However, in the present study, the results are given for transmission angle up to 60° as the 763



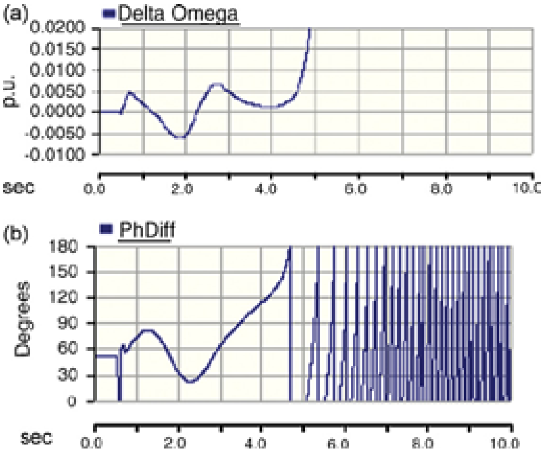


Fig. 10. (a) Generator speed deviation at a transmission of angle of 50◦. (b) Transmission angle between two buses at an initial angle of 50°.

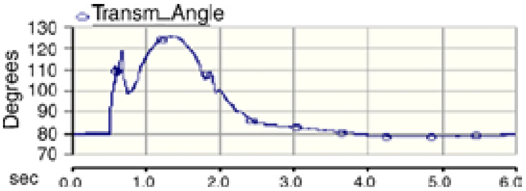


Fig. 11. Transmission angle (Transm Angle) variation..

Conclusion

system delivers maximum power at this angle. The steady state is restored just after the first swing. In pure HVAC system, the transmission angle is generally kept low for long transmission lines and seldom exceeded beyond 30◦.

A novel approach to solve the first swing stability problem by simultaneous AC–DC power transmission has been presented. A detailed study has been carried out in PSCAD/MATLAB environ- ment to validate the proposed scheme. It has been demonstrated that the stability of the system can be effectively improved by simultaneous AC–DC power transmission with fast DC power modulation.

In pure HVAC system, the transmission angle is generally kept low for long transmission lines and seldom exceeds 30◦. But in simultaneous AC–DC system we can go much beyond 30◦

transmission angle without loosing stability for transient disturbances. Satisfactory transient performance is demonstrated for transmission angle at 60◦ for the network considered in the present study.

For the purpose of study, worst location of faults (i.e. near the sending end, near inverter) and heavily loaded line (i.e. close to thermal limit) is considered. It has been demonstrated that effective control of DC component in simultaneous AC–DC power transmission considerably improves the stability of the system.

Appendix A. Parameters of the power system used as an application example

Generator:

Parameters on its own base—Xd = 1.81, Xq = 1.76, Xd = 0.3, Xd = 0.23, Xq = 0.25, Xl = 0.15, Ra = 0.003, Tdo = 8.0 s, Tdo = 0.03 s, Tqo = 0.07 s, inertia constant H = 3.5 s.

Excitation system: KA = 200.0, TA = 0.015, TC = 1.0, TB = 12.0, VRMAX = 5.64, VRMIN = −4.53, KC = 0, VIMAX = 1.0, VIMIN = −1.0.

Generator transformer (GT): Positive sequence leakage reactance = 0.15 pu, no load loss = 0.05 pu, copper loss = 0.05 pu.

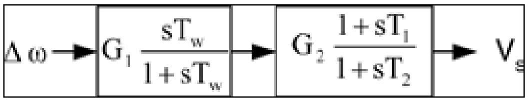
Converter transformers (CT): Positive sequence leak- age reactance = 0.10 pu; Rectifier Transformer, 220/150 KV,

1200 KVA; Inverter Transformer, 220/133 KV, 1025 KVA.

DC links: Rectifier firing angle limit (minimum) = 5◦; inverter extinction angle limit (minimum) = 15◦; DC current = 5.4 kA (rated) with short time built-in overload capacity; smoothing inductor = 0.6 H.

AC filters: 11th hormonic, C = 15.0 F, L = 0.0055582 H, R = 0.480 ; 13th hormonic, C = 15.0 F, L = 0.004 H, R = 0.408.

Power system stabilizer:



G1 = 1.0, Tw = 0.5 s, lead time constant = 0.248 s, lag time constant = 0.062 s.

Initial simultaneous AC–DC steady state conditions: Generator, Pg = 0.99 pu, Qg = 0.233 pu, Vg = 1.1 pu; AC transmission voltage Vac = 220 kV; DC transmission voltage Vd = 160 kV, i.e. bipolar DC voltage Vdc = ±320 kV; receiving end power, AC power (Pac) = 503 MW, DC power (Pdc) = 1604 MW, total power (Pr)= Pac + Pdc = 2107 MW.

Initial steady state conditions for pure AC system with compensation: Transmission voltage 400 kV; generator, Pg = 0.995 Pu, Qg = 0.133 pu. Vg = 1.1; receiving end power Pr = 2100 MW. Capacitance value for 50% compensation, C = 42.78 F.

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