Increasing the power transfer capability of an ac transmission line using a parallel small power dc link

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ABSTRACT

The paper presents a method of increasing the power transfer level of an ac transmission line by using a parallel-small power dc link to improve the ac system small-signal stability. In order to demonstrate the validity of the proposed method, computer simulated dynamic response of the parallel ac-dc power system is compared with that of the ac system alone. In this study, the power flow in the small-power dc link is modulated by adding an auxiliary signal to the current reference of the rectifier firing angle controller to improve the damping of power flow oscillations in the ac transmission line. This modulation control signal is derived in response to the frequency oscillations in the rectifier end ac system (rate of change of generator angle oscillations). The simulations performed revealed that the use of a small-parallel dc link transferring about 2% of the normal ac power substantially increases the power transfer capability of the ac line.

SYMBOLS

α_R	=	Alpha order at rectifier
β	=	Damping Constant
β_R	=	Beta at rectifier
δ_0	=	Steady state Transmission angle
$\Delta\delta$	=	Small change in Transmission angle
ω_0	=	Steady state angular frequency
H	=	Inertia Constant
$I_{dc\ meas}$	=	Measured Direct Current I_{dc}
$I_{dc\ ref}$	=	Reference value of I_{dc}
$I_{dc\ \delta}$	=	I_{dc} modulation signal
K_s	=	Synchronizing Coefficient
ΔP_{ac}	=	Small change in AC Power Transmitted
ΔP_{dc}	=	Small change in DC Control Power
ΔP_m	=	Small change in Mechanical Power
V_1, V_2	=	Bus bar voltages on AC line
V_{dc0}	=	Nominal DC voltage
X	=	Transmission system reactance

1.0 INTRODUCTION

The automatic voltage regulators present in the generating units in power systems could have an adverse effect on system small-signal stability. Hence, poorly damped oscillations of low frequency can occur which often persist for long periods of time and can sometimes limit the power transfer capability[1]. Power system stabilizers (PSS) have been widely utilized to improve damping of these oscillations, through modulation of the generator excitation [2,3].

To cause damping, PSS must provide an electrical torque on the rotor proportional to the speed variations. Additional damping is required under conditions of weak transmission and heavy load; for example, when attempting to transmit power over long transmission lines from remote generating plants or over relatively weak ties between systems. Contingencies such as line outages, often precipitate such conditions. Hence, systems which normally have adequate damping can often benefit from stabilizers during such abnormal conditions.

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[4,5]. Studies [6-9] have also shown that modulation signals incorporated to converter controls, that are derived in response to signals such as frequency deviation and rate of change of AC power transmitted provide additional damping. For example; (i) in the HVDC Intertie between Pacific North-West and South-West regions of the United States, a modulation signal derived in response to the rate of change of power in the parallel ac intertie is fed to the converter controls to improve the damping of low frequency oscillations between the two regions [4,9], (ii) in the Eel River back-to-back HVDC system which interconnects the Hydro Quebec system with the New Brunswick system in Canada, a modulation signal derived based on the frequencies of both ac systems is fed to the converter controls to improve the dynamic stability of the two systems [4] and (iii) in the CPA-UPA (CU) HVDC system between North Dakota and Minneapolis in United States, a modulation signal derived in response to rectifier end ac system frequency changes is fed to converter controls to provide damping for disturbances in the North Dakota ac system [4].

Nevertheless, due to the high cost of converters, HVDC transmission has been typically used for interconnecting asynchronous ac systems and for economic transmission of bulk power usually over long distances. However due to the availability of low cost- low power converters at low voltage, the hvdc schemes of low capacity at low voltage may now be used to improve the dynamic stability of existing AC systems. Moreover, such a DC line can be implemented using the same towers utilized for parallel AC transmission since the size/weight of the conductors are less due to the small power capacity of the DC link. Hence, such a damping improvement scheme would be economically feasible.

The use of a low power low voltage DC link to improve the ac system small-signal stability and consequently to increase the power transfer in a parallel high voltage-high power AC line is demonstrated in this paper. Modeling and Simulation of the system and controllers in this study is done with the EMTDC/ PSCAD transient simulation program.

2.0 SYSTEM MODEL

Fig. 1 shows the simplified single line diagram of the ac-dc system considered in this study.

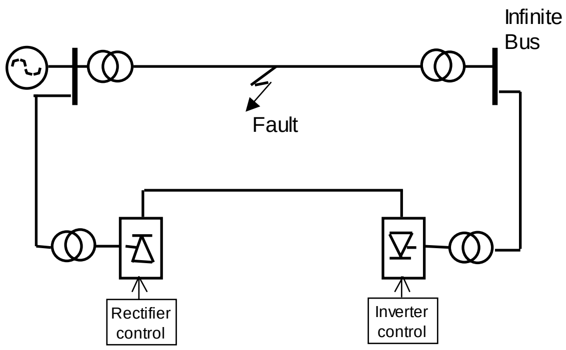

Fig 1 - Single line diagram of the parallel AC/DC system

The model represents the rectifier side ac system with a synchronous generator equipped with an excitation system and a governor-turbine (IEEE Type SCRX Exciter and IEEE Type 2 Hydro Governor & Turbine models [10]). The inverter side ac system is assumed to be larger in rating compared to the rectifier end ac system. The rectifier control in normal operation works in the constant current mode. The inverter in normal operation works in the constant gamma control mode and has incorporated in it a constant current control to cater for the condition when the rectifier has to operate at the minimum alpha limit during transient and dynamic conditions.

The nominal values of the ac system are 220 kV and 50 Hz. The ac transmission line is 200 km long and nominal rating is 500 MW. The controls used in the DC system are primarily those of the CIGRE Benchmark model [10] modified to suit the reduced voltage (20 kV) and power (5 MW).

3.0 CONTROL STRATEGY

The proposed method increases system damping and consequently the power transfer capability of the AC system by modulating the power transfer in DC line in response to the rate of change of generator angle oscillations (frequency oscillations in the rectifier end ac system). This is realised by adding a suitably derived modulation signal to the current reference of the rectifier firing angle controller (Fig. 2).

The generator-AC system behavior (linearised for small signals) is governed by the swing equation (1).

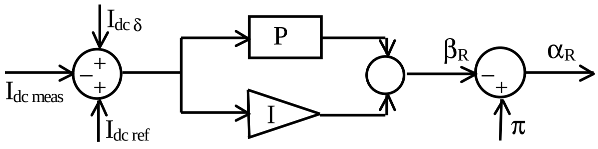

Fig. 2 - Rectifier Control

$$\Delta P_m - \Delta P_{ac} - \Delta P_{dc} = \frac{2H}{\omega_0}\frac{d^2\Delta\delta}{d\,t^2} \qquad (1)$$

The active power transfer can be written as in (2).

$$\Delta P_{ac} \cong \frac{V_1 V_2}{X}\cos\delta_0\ \Delta\delta \ = \mathrm{K_s}\,.\Delta\delta \qquad (2)$$

If the DC power is controlled proportional to the rate of change of the variation of the transmission angle δ (frequency deviation of the rectifier end ac system), and the mechanical power input assumed constant during the dynamic condition, the conditions as given in (3) and (4) can be obtained.

$$\Delta P_{dc} = \beta\ \frac{d\,\Delta\delta}{d\,t} \qquad (3)$$

$$\Delta P_m \cong 0 \qquad (4)$$

The governing equation for small changes may thus be written as in (5).

$$\frac{2H}{\omega_0}\frac{d^2\Delta\delta}{d\,t^2} + \beta\ \frac{\mathrm{d}\Delta\delta}{\mathrm{d\,t}} + \mathrm{K_s}.\Delta\delta = 0 \qquad (5)$$

4.0 CONTROLLER DESIGN

The controller to obtain the necessary damping of the AC system is designed considering the critical damping condition. Thus β can be given as in equation (6).

$$\beta = \sqrt{\frac{8K_s\,H}{\omega_0}} \qquad (6)$$

Equation (3) can be re-written in terms of the controlled change in DC current as in (7).

$$\mathrm{I_{dc\delta}} = \Delta \mathrm{I_{dc}} \cong \frac{\Delta \mathrm{P_{dc}}}{\mathrm{V_{dc0}}} = \frac{\beta}{\mathrm{V_{dc0}}}\ \frac{\mathrm{d}\,\Delta\delta}{\mathrm{d\,t}} \qquad (7)$$

This control is implemented as shown in Fig. 3.

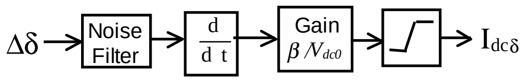

Fig. 3 - Proposed Modulation Controller

In the modified controller for the rectifier, the signal fed to the P-I controller has, in addition to the error of the DC current signal, a signal proportional to the derivative of the angle to improve the dynamic stability. A noise filter is incorporated to eliminate high frequency components interfering with the dynamic control signal. A limiter is used to prevent the signal assuming unrealistically large values during transients.

5.0 SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed controller, the system responses with and without the dc scheme are observed.

Figure 4 shows the system responses when a line-to-ground fault of 60 ms duration is occurred at the middle of the ac transmission line. Response without the dc scheme (curves NC) and with the dc scheme (curves WC) are observed.

Figures 4 (a), (b) and (c) give the variation of generator speed (rectifier end ac system frequency), real power transfer in the ac transmission line and the reactive power transfer in the ac transmission line, respectively. It can be observed that, the system becomes unstable when the dc link with the corresponding modulation control scheme is not in operation. This is due to the poor damping of the oscillations. It can also be observed that, the addition of the dc scheme improves the damping of oscillations thus stabilizing the system response.

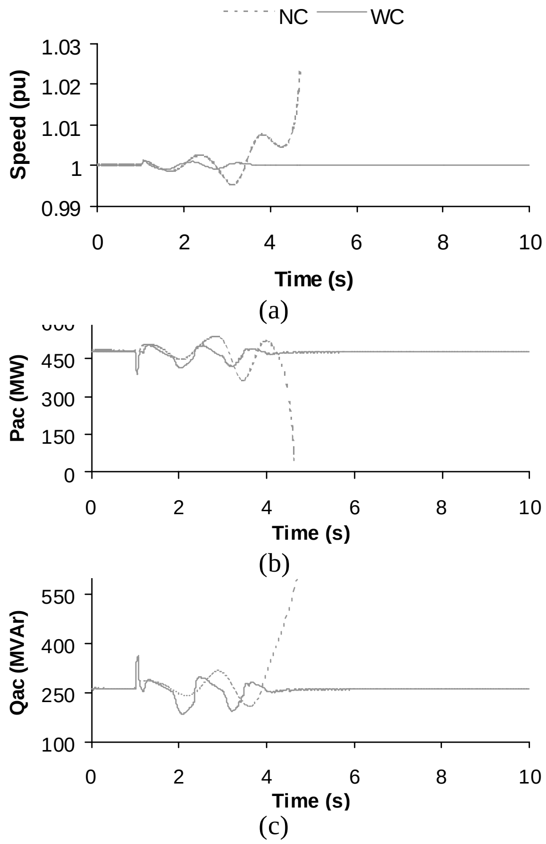

Figure 4: Comparison of system responses with and without the dc scheme

Figures 5 (a), (b), (c) and (d) give the modulation control signal added to the current reference of the rectifier firing angle control scheme, power flow in the dc link, reactive power flow in the dc link and the rectifier firing angle, respectively (when the dc scheme is in operation) with the same disturbance. 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 small-signal stability of the system.

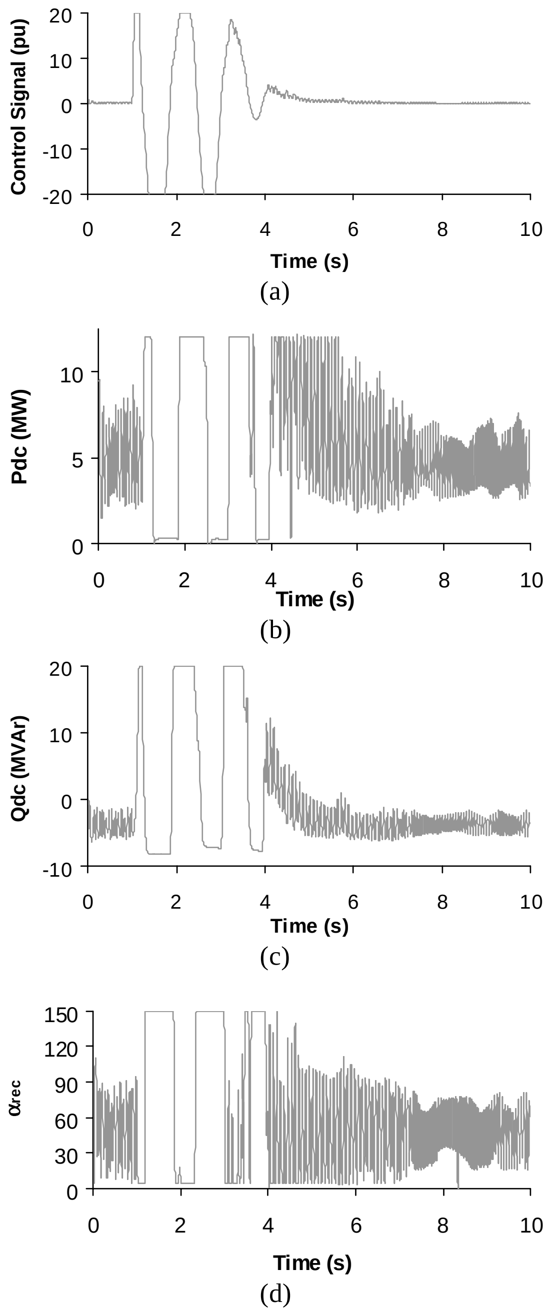

Figure 5: Response of DC scheme variables to the line-to-ground fault for 60 ms duration at the middle of the ac transmission line

6.0 CONCLUSIONS

A novel DC concept to improve the dynamic stability of an AC Power System has been presented. In order to demonstrate the validity of the proposed approach, dynamic response of the parallel ac-dc power system has been compared with that of the ac system alone. It has been demonstrated through simulations (using EMTDC/PSCAD transient simulation software) that, a very small amount of modulated DC power (about 2% of the AC power transfer) can greatly enhance the dynamic stability of the AC system.

The approach may also be adapted to damp out sub-synchronous resonance oscillations, which are otherwise not possible to remove through slow dynamic controllers such as PSS. Work is presently being continued in these areas.

7.0 ACKNOWLEDGMENTS

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8.0 REFERENCES

1) Larsen, E. V. and Swann, D. A., "Applying Power System Stabilizers, Part I, II & III", IEEE Trans., Vol. PAS-100, No. 6, June 1981, pp 3017-3046.

2) Schleif, F. R., Hunkins, H. D., Martin, G.E. and Hatton, E. E., "Excitation control to improve power system stability", IEEE Trans., Vol. PAS-87, No. 6, June 1968, pp 1426-1434.

3) Yo, K. W. V. and David, A. K., "Multivariable adaptive control of AC-DC systems", IEE Proc.-Gener. Transm. Distrib., Vol. 14, No.6, Nov 1994, pp 658-664.

4) Grund, C. E., Bahrman, M. P., Balu, N., Berstrom, L., Long, W. F., Newell, R.J., Osborne, D. and Pohl, R. V., "Dynamic Performance Characteristics of North American HVDC Systems for Transient and Dynamic Stability Evaluations", IEEE Committee Report, IEEE Trans, PAS-100, No. 7, July 1981, pp 3356-3364.

5) Lee, R. L., Zollman, D., Tang, J. F., Hsu, J. C., Hunt, J. R., Burton, R. S. and Fletcher, D. E., "Enhancement of AC/DC System Performance by Modulation of a Proposed Multiterminal DC System in the Southwestern U.S.", IEEE Trans on Power Delivery, Vol. 3, No. 1, Jan 1988, pp 307-316.

6) Dash, P. K., Liew, A. C. and Routray, A., "High-performance controllers for HVDC transmission links", IEE Proc. Gener. Transm. Distrib., Vol. 141, No. 5, Sept 1994, pp 422-428.

7) To, K. W. V., David, A. K. and Hammad, A. E., "A Robust Co-ordinated Control Scheme for HVDC Transmission with Parallel AC Systems", IEEE Trans on Power Delivery, Vol. 9, No. 3, July 1994, pp 1710-1716.

8) Hsu, Y. and Wang, L., "Damping of a Parallel AC-DC Power System using PID Power System Stabilizers and Rectifier Current Regulators", IEEE Trans on Energy Conversion, Vol. 3, No. 3, Sept 1988, pp 540-547.

9) Cresap, R.L. and Mittelstadt, W.A., "Small-signal modulation of the Pacific HVDC intertie", IEEE Trans on PAS, Vol. 95, 1976, pp 536-541.

10) EMTDC/PSCAD Users' Manual, Manitoba HVDC Research Centre, Canada, 1994.

APPENDIX

System Parameters:

Synchronous Generator

H = 4.0 s, Xp = 0.130 pu, X_d = 0.92 pu, X_d' = 0.30 pu, X_d"=0.22pu, X_q = 0.22 pu, X_q' = 0.22 pu, R_a is neglected (0.00001 pu), T_{do}' = 5.2 s, T_{do}" =0.0234 s, T_{qo}"=0.029 s V_{base} = 7.967 kV, S_{base} = 500 MVA

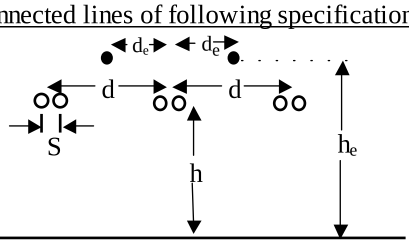
Generator Exciter Model (IEEE Type SCRX)

T_1 = 0.02 s, T_a = 1.5 s, T_b = 1.0 s, T_e = 0.02 s, K = 20, E_{max} = 5 pu, E_{min} = - 5 pu

Generator Governor-Turbine Model (IEEE Type 2)

T_1 = 0.88 s, T_2 = 3.7 s, T_3 = 0.44 s, T_4 = 0.02 s, T_5 = 0.8 s, T_6 = 0.4 s, T_s = 0.05 s, C_1 = 4.8 s/pu, C_2 = 0.1 s, C_3 = 0.04 pu/s, C_5 = 0.0, C_6 = 1.0 s, T_{max} = 0.95

Transmission Lines (the line used in the system has two series connected lines of following specifications)



Line Configuration

r_e (radius of earth conductors)=5.525mm, d_e=5m, h_e=35m, $R_{dc,e}$=2.865Ω/km, r (radius of line conductors)=20.35 mm, d=10m, h=30m, R_{dc}=0.032Ω/km, S =457.2mm, Sag at mid span=10m, Length=100km

AC Line Transformers (s.e. and r.e.)

500 MVA, 13.8/220 kV, x=0.12 pu

Rectifier and Inverter Transformers

10 MVA, x=0.18 pu, 13.8/9 kV (rectifier transformer), 13.8/8 kV (inverter transformer)

Converters

$V_{dc\ nom}$ = 20 kV, $I_{dc\ nom}$ = 250 A, $P_{dc\ nom}$ = 5 MW

α_{Rmin}= 5°, α_{Rmax}= 150°, α_{Imin}= 30°, α_{Imax}=110°, γ_{Imin}=15°

Additional Rectifier Control

Noise filter T = 0.01 s, Gain = 5 pu, limits = -1 to 1 pu