Versatile PID-HVDC Controls for Enhancement of Power System Stability

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Abstract: *In this paper, the investigation is carried out on the improvement of power system stability by utilizing auxiliary controls for controlling power flow in HVDC link. Transient stability analysis is done on a multi-machine system, where, conventional controllers P, PI, PD and PID etc. are developed to improve the stability of the power system. Simulated results show for a multi machine system it is necessary to employ control signals derived from relative angle deviation, speed deviation and acceleration and different combinations of these signals. The performance of the system at different locations of HVDC link and fault locations is studied to optimize the location of HVDC link.*

Key words: *HVDC; Power System Stability; Multi – Machine Stability; P, PI, PID controllers.*

1. Introduction.

HVDC power transmission system offers several advantages, one of which is to rapidly control the transmitted power. Therefore, they have a significant impact on the stability of the associated AC power systems. Moreover, HVDC link is effective for frequency control and improve the stability of the system using fast load-flow control. The importance of AC-DC power transmission system regarding improvement of stability has been subject to much research. An HVDC transmission link is highly controllable. It is possible to take advantage of this unique characteristic of the HVDC link to augment the transient stability of the ac systems.

A proper design of the HVDC controls is essential to ensure satisfactory performance of overall AC/DC system [1]. In recent years, the HVDC systems model used are simpler models; such models are adequate for general purpose stability studies of systems in which the DC link is connected to stronger parts of the AC system. But the preference is to have a flexible modeling capability with a required range of detail [2, 3].

Supplementary controls are often required to exploit the controllability of a DC links for enhancing the AC system dynamic performance. There are a variety of such higher level controls used in practice. Their performance objectives vary depending on the characteristics of the associated AC systems.

The supplementary controls make use of signals derived from the ac systems to modulate the dc quantities [4, 5]. The modulating signals in case of a multi machine system may be derived from relative angular deviations of the machines, relative speed deviations of the machines and average difference in accelerations of the machines. The particular choice depends on the system characteristics and the desired results. The placement of the HVDC line is also a big issue in a power system. The system response at different location of the HVDC and faults gives us the optimized location of HVDC line. For transient stability the rate of change of the generator angles should come to zero within a particular interval of time. The system response can be evaluated by observing the time when the rate of change of generator angle first comes to zero, and the peak overshoot of generator angles.

2. AC/DC Transient Stability

In transient stability studies it is prerequisite to do AC/DC load flow calculations in order to obtain system conditions prior to the disturbance. While the conventional approaches are available for conducting the calculations, the eliminated variable method is used here which treats the real and reactive powers consumed by the converters as voltage dependent loads. The dc equations are solved analytically or numerically and the dc variables are eliminated from the power flow equations. The method is however unified in the sense that the effect of the dc- link is included in the Jacobian. It is, however, not an extended variable method, since no dc variables are added to the solution vector [6].

2.1 DC System Model

The equations describing the steady state behavior of a mono polar DC link can be summarized as follows [4].

$$V_{dr} = \frac{3\sqrt{2}}{\pi} a_r V_{tr} cos\alpha_r - \frac{3}{\pi} X_c I_d \quad (1)$$

$$V_{di} = \frac{3\sqrt{2}}{\pi} a_i V_{ti} cos\gamma_i - \frac{3}{\pi} X_c I_d \quad (2)$$

$$V_{dr} = V_{di} + r_d I_d \quad (3)$$

$$P_{dr} = V_{dr} I_d \quad (4)$$

$$P_{di} = V_{di} I_d \quad (5)$$

$$S_{dr} = k \frac{3\sqrt{2}}{\pi} a_r V_{tr} I_d \quad (6)$$

$$S_{di} = k \frac{3\sqrt{2}}{\pi} a_i V_{ti} I_d \quad (7)$$

$$Q_{dr} = \sqrt{S_{dr}^2 - P_{dr}^2} \quad (8)$$

$$Q_{di} = \sqrt{S_{di}^2 - P_{di}^2} \qquad (9)$$

Where, V_{dr} and V_{di} are voltages at rectifier and inverter end resp.; V_{tr}, and $V_{ti}$are terminal voltages at rectifier and inverter ends resp.; Id is dc link current; X_c and r_d are dc link reactance and resistance resp.; α and □ are firing and extinction angle resp.; a is tap ratio; P_{dr} and P_{di} are real power at rectifier and inverter ends resp.; Q_{dr} and Q_{di} are reactive power at rectifier and inverter ends resp.; S_{dr} and S_{di} are apparent power at rectifier and inverter ends resp.

2.2 The Eliminated Variable Method

The real and reactive powers consumed by the converters are expressed as function of their ac terminal voltages, V_{tr} and V_{ti}. Their partial derivatives with respect to V_{tr} and V_{ti} are computed and used in modification of Jacobian elements of the Newton Raphson power flow solution as shown below [7],

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \qquad (10)$$

$$N'(tr,tr) = V_{tr}\frac{\partial P_{tr}^{ac}}{\partial V_{tr}} + V_{tr}\frac{\partial P_{dr}(V_{tr},V_{ti})}{\partial V_{tr}} \qquad (11)$$

$$N'(tr,ti) = V_{ti}\frac{\partial P_{tr}^{ac}}{\partial V_{ti}} + V_{ti}\frac{\partial P_{dr}(V_{tr},V_{ti})}{\partial V_{ti}} \qquad (12)$$

$$N'(ti,tr) = V_{tr}\frac{\partial P_{tr}^{ac}}{\partial V_{tr}} - V_{tr}\frac{\partial P_{di}(V_{tr},V_{ti})}{\partial V_{tr}} \qquad (13)$$

$$N'(ti,ti) = V_{ti}\frac{\partial P_{tr}^{ac}}{\partial V_{tr}} - V_{ti}\frac{\partial P_{di}(V_{tr},V_{ti})}{\partial V_{ti}} \qquad (14)$$

L' is also modified analogously. Thus, in the eliminated variable method, four mismatch equations and up to eight elements of Jacobian have to be modified, but no new variables are added to solution vector, when a dc – link is included in the power flow.

2.3 Representation of HVDC Systems

Each dc system has unique characteristics tailored to meet the specific needs of its application. Hence, standard models of fixed structures have not been developed for representation of dc systems in stability studies. The current controller employed is a proportional integral controller and the auxiliary controller is taken to be a constant gain controller [8].

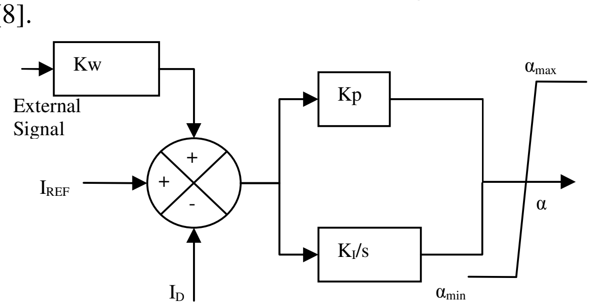

Fig. 1. Block diagram of current controller.

The HVDC link can be represented as transfer function model [9] as,

$$I_d = I_{ref}/1 + sT_d \qquad (15)$$

Where, I_d is dc link current; I_{ref} is reference value of current; Td is Time constant of the system.

2.4 Generator Representation

The synchronous machine is represented by a voltage source, in back of a transient reactance, that is constant in magnitude but changes in angular position neglecting the effect of saliency and assumes constant flux linkages and a small change in speed [6]. The classical generator model can be described by following set of differential and algebraic equations,

Differential equations,

$$\frac{d\delta}{dt} = \omega - 2\pi f \qquad (16)$$

$$\frac{d^2\delta}{dt^2} = \frac{d\omega}{dt} = \frac{\pi f}{H}(P_m - P_e) \qquad (17)$$

Algebraic equations,

$$E' = E_t + I_t r_a + jx'_d I_t \qquad (18)$$

Where E' is voltage at back of transient reactance; E_t is machine terminal voltage; I_t is machine terminal current; r_a is armature resistance; x'_d is Transient reactance; δ is rotor angle; ω is speed; P_m and P_e are mechanical and electrical power resp.; H is inertia constant.

2.5 Load Representation

The static admittance Y_{po} used to represent the load at bus P, can be obtained from,

$$Y_{po} = I_{po}/E_p \qquad (19)$$

2.6 Steps of AC-DC Transient Stability Study

The basic structure of transient stability program is given below [10]

1 The initial bus voltages are obtained from the ac/dc load flow solution prior to the disturbance.

2 After the ac/dc load flow solution is obtained, the machine currents and voltages behind transient reactance are calculated.

3 The initial speeds and the initial mechanical powers are obtained for each machine prior to the disturbance.

4 The network data is modified for the new representation. Extra nodes are added to represent the generator internal voltages. Admittance matrix is modified to incorporate the load representation.

5 The time is set as t = 0;

6 If there is any switching operation or change in fault condition, the network data is modified accordingly to run the ac/dc load flow.

7 Using Runge-Kutta method, solution of the machine differential equations are obtained to find the changes in the internal voltage angle and machine speeds.

8 Internal voltage angles and machine speeds are updated.

9 Advance time, t = t + Dt.

10 The time limit is to be checked, if t £ tmax, then

the process has to be repeated from step 6; else the process has to be stopped.

In case of multi machine system stability analysis the relative angles are plotted to evaluate the stability of the power system.

3 Conventional Controller

A WSCC-9 system is taken for stability analysis; it is shown in the figure 2. A fault is assumed to occur on Line 4-6, at initial time zero. It is assumed that a grounded fault occurred near to Bus 6 and the line from Bus 4 to Bus 6 is removed after 4 cycles. The HVDC line is located between buses 4 –5. Under these conditions, the impact of HVDC on system stability is presented. Initially, a case in which the HVDC line maintains the same control as in the normal state, in which the post-fault HVDC power flow setting remains the same as before, is investigated. From the plot of relative angles of generators it was found that, the system becomes unstable. Then a controller is designed to stabilize the system.

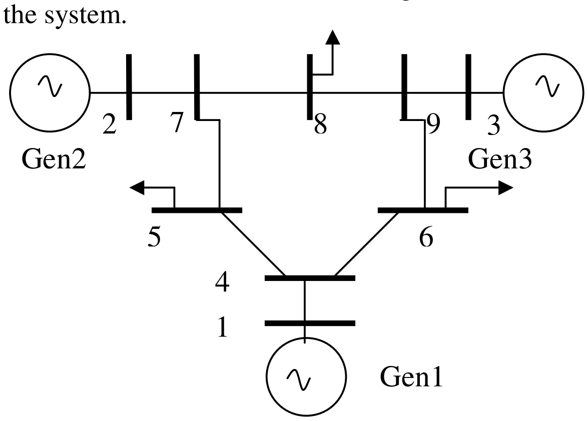

Fig. 2. WSCC 9 bus System

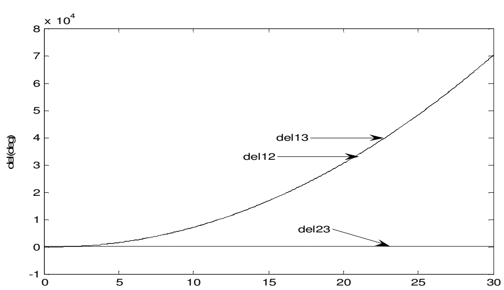

Fig.3. Plot of relative angles without control signal

It is clearly seen from figure 3, the system is becoming unstable, generator 2 and generator 3 are moving together whereas generator 1 falling out of synchronism, with this group. To stabilize the system, it is necessary to make equal accelerations of all the generators. So an error signal representing average difference in accelerations of the generators is considered. In case of multi machine system, the relative angles are to be maintained within limits to maintain the stability of the system. So, error signals derived from the average difference in the relative angles and average difference in the relative speeds of the generators are considered.

These error signals are shown below.

(20)

(21)

(22)

Combination of the above three signals are considered, in order to improve the stability. Gains of the signals are varied in order to get better transient and dynamic performance. The signal $error_2$ is the equivalent to the integral of the signal $error_1$ and the signal $error_3$ is equivalent to the differential of the signal $error_1$. Hence, the controller is equivalent to a PID controller [6]. Then the control signal can be equivalently represented as,

(23)

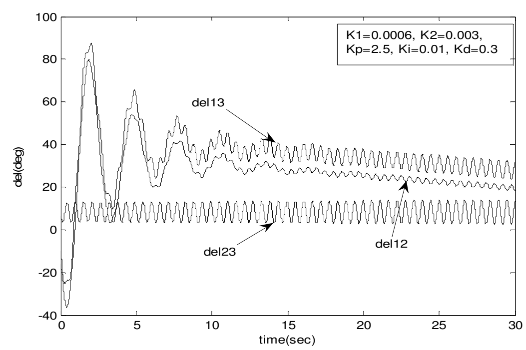

Fig.4. Plot of relative angles with PID controller.

4 Optimization of HVDC Location

HVDC link rapidly controls the power flowing through it, so the location of HVDC link in AC power system must be at the best suitable place for the best transient stability of the system. In the above mentioned WSCC-9 Bus system the possibilities of HVDC link and fault locations are, 1) HVDC link 4-5 and fault at 4-6, 7-8 and 8-9; 2) HVDC link 4-6 and fault location at 4-5, 7-8 and 8-9; 3) HVDC link 7-8 and fault at 4-5 and 4-6; 4) HVDC link 8-9 and fault location at 4-5 and 4-6.

For each of the above mentioned possibilities the following procedure is followed,

- HVDC system is modeled and eliminated variable method is used to solve the power flow equations.
- Y-bus matrix is modified after the fault is cleared.
- Newton - Raphson AC/DC load flow is run with different control modes.
- AC/DC transient stability algorithm is run with different control signals applied.

- The relative and absolute angles of generators are observed and plotted.

When HVDC locations are 4-5 and 4-6 the system responses are obtained, but in case of HVDC location 7-8 and 8-9, system response cannot be obtained as the N-R AC/DC load flow is not converged for determination of initial conditions. The reason behind not converging could be,

- The inertia constant of generator-2 and generator-3 is less as compared to generator-1.
- The diagonal elements of Y-bus are not dominating over off-diagonal elements.

5 Results

5.2 System response without controller

The system response without controller is observed for different locations of HVDC and faults. Without control means the control of the HVDC is left open so the uncontrolled power will flows through the HVDC link. It is clear from figures 5-8 that one of the generators will be out of synchronism whenever the fault occurs and other two will be in synchronism.

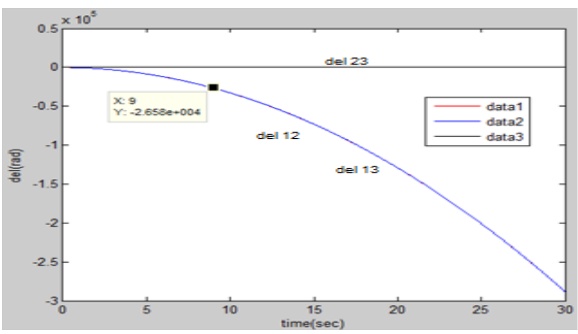

Fig.5. HVDC link is 4-5 & Fault at 4-6

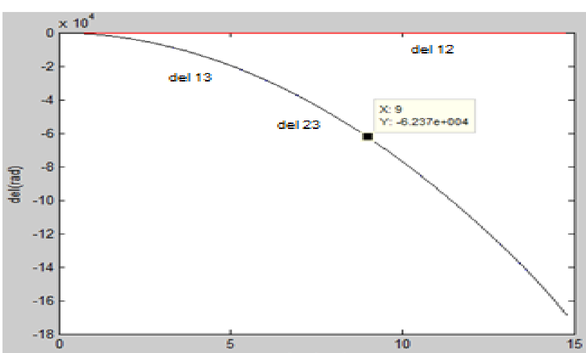

Fig.6 When HVDC link is 8-9 & Fault at 4-6

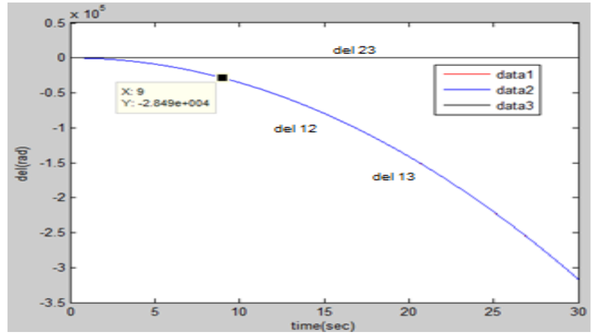

Fig.7. When HVDC link is 4-6 & Fault at 4-5

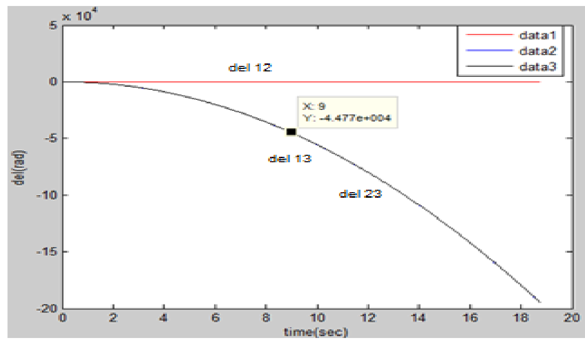

Fig.8. When HVDC link is 4-6 & Fault at 8-9

5.3 System Response with P-Controller

Figures 9 and 10 show the transient responses of the system with only one control signal i.e. P control is applied. From the responses it is clear that only P controller is not sufficient to stabilize the system.

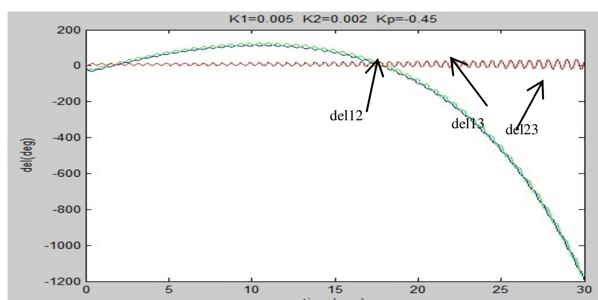

Fig.9. When HVDC link is 4-5 & Fault at 4-6

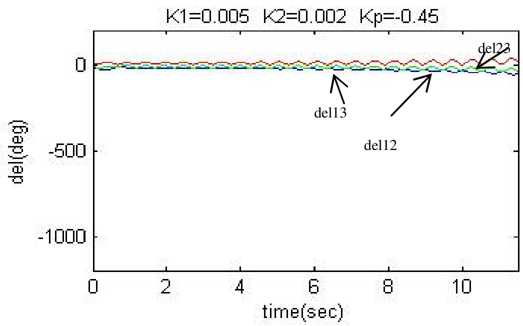

Fig.10. When HVDC link is 4-6 & Fault at 4-5

5.4 System Response with PI-Controller

Figures 11 - 14 show the transient responses of the system with PI controller. PI controller provides sufficient damping to the system but still not enough to reduce the settling time of the response.

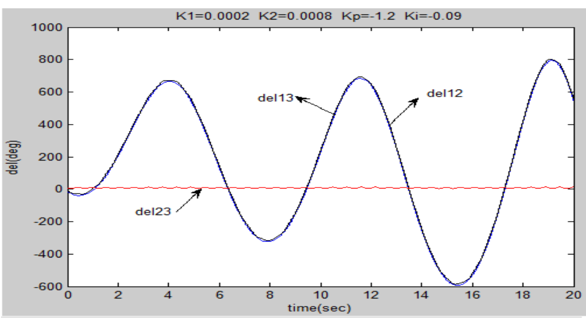

Fig.11. When HVDC link is 4-5 & Fault at 4-6

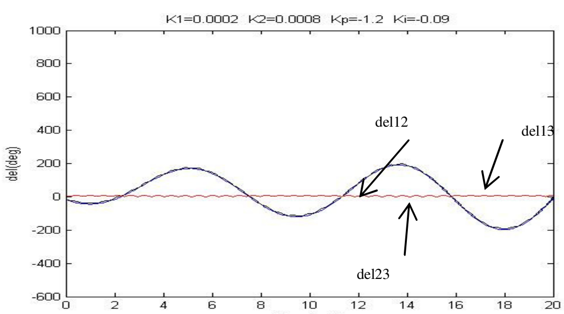

Fig.12. When HVDC link is 4-6 & Fault at 4-5

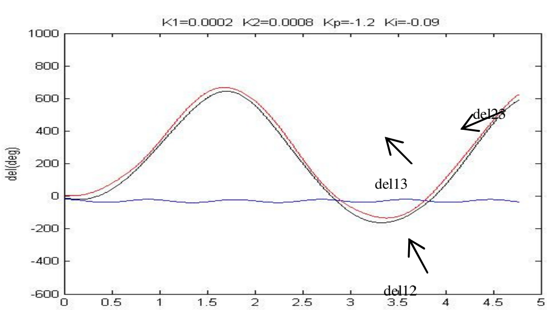

Fig.13. When HVDC link is 4-6 & Fault at 7-8

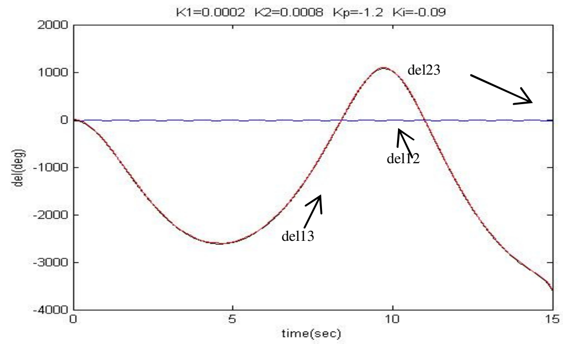

Fig.14. When HVDC link is 4-6 & Fault at 8-9

5.5 System Response with PD-Controller

Figures 15 and 16 show the transient responses of the system with PD controller. For HVDC location in line 4-6 and fault at location 4-5, figure 18, the PD controller provides better results than other condition.

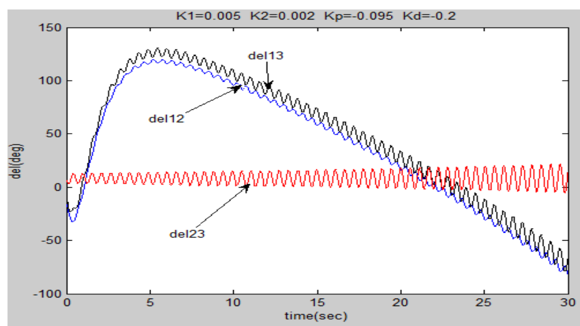

Fig.15. When HVDC link is 4-5 & Fault at 4-6

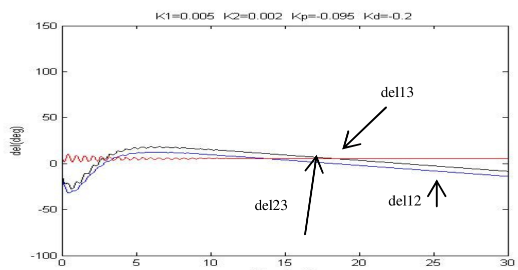

Fig.16. When HVDC link is 4-6 & Fault at 4-5

5.6 System response with ID-controller

Figures 17 - 20 show the transient responses of the system with ID controller. The performance of ID controller varies with change in fault location and HVDC link location. For HVDC location in line 4-6 and fault in 4-5 and vice versa, figure 19 and 20, the system oscillates severely as time increases but in other cases figure 21 and 22, system oscillations are completely damped.

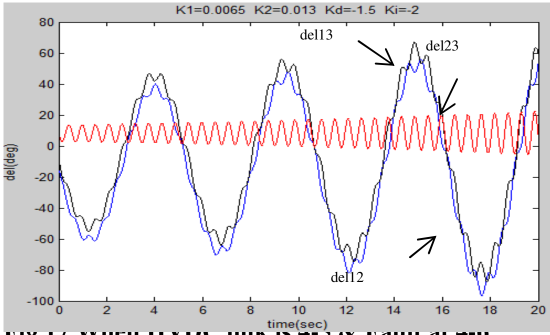

Fig.17 When HVDC link is 4-5 & Fault at 4-6

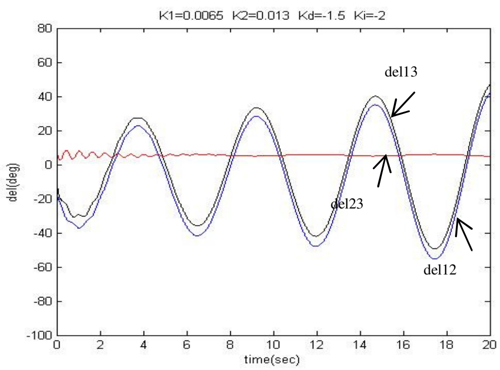

Fig.18. When HVDC link is 4-6 & Fault at 4-5

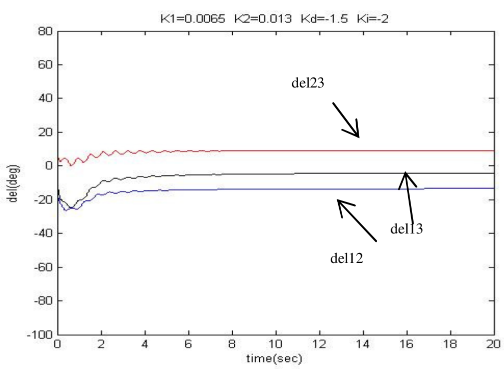

Fig.19. When HVDC link is 4-6 & Fault at 7-8

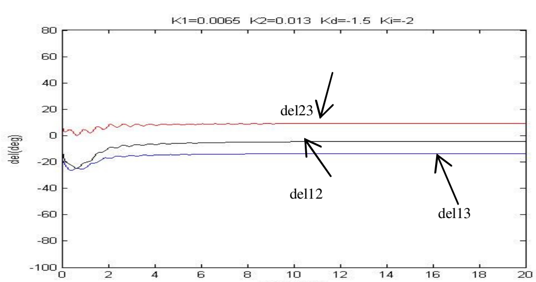

Fig.20. When HVDC link is 4-6 & Fault at 8-9

5.7 System Response with PID-Controller

Figures 21 - 24 show the transient responses of the system with PID controller. Among all controllers discussed above PID controller gives better results for all possible locations of HVDC link and faults. The system damping is reduced and transient response settles down in minimum time.

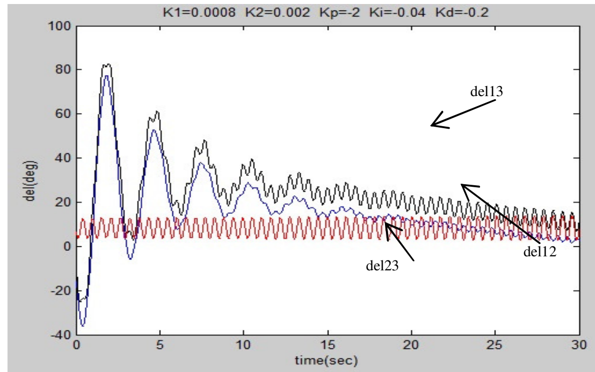

Fig.21. When HVDC link is 4-5 & Fault at 4-6

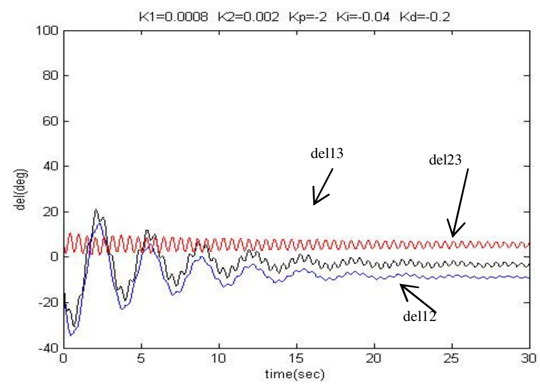

Fig.22. When HVDC link is 4-6 & Fault at 4-5

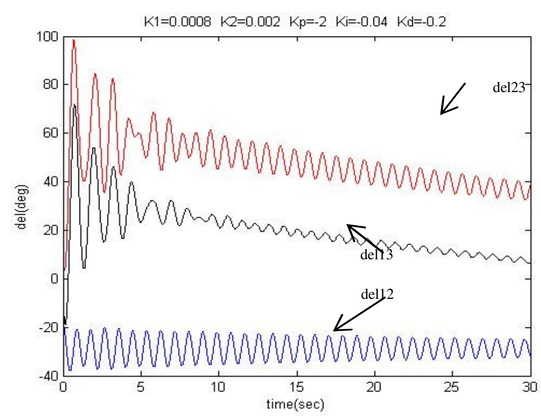

Fig.23. When HVDC link is 4-6 & Fault at 7-8

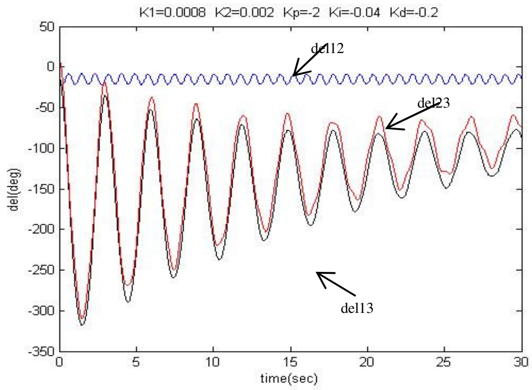

Fig.24. When HVDC link is 4-6 & Fault at 8-9

The summary about absolute angles of each generator and relative angles of the generators is tabulated in Table 1. From optimization strategy discussed in section 5 above and comparing system responses for HVDC link in line 4-6 and 4-5, it is found that HVDC link at 4-6 controls the system effectively for all possible fault locations. Thus, for HVDC link in line 4-6, the comparison of transient responses of PI, PD, ID and PID controllers, for all possible fault location with respect to the peak overshoot is tabulated in Table 2. Also the comparison of transient responses of PI, PD, ID and PID controllers, for all possible fault locations with respect to the settling is tabulated in Table 3.

5.8 Analysis of the results

a) Absolute and relative angles of generators are severely affected in post fault condition. Generator near the fault location falls out of synchronism with other generators and remaining two generators maintain the synchronism among themselves. This indicates the need of proper control strategy for generator falling out of synchronism.

b) Comparison of peak overshoot in Table 2 shows that PID controller provides necessary damping in all cases to reduce the overshoot in acceptable range.

c) Comparison of settling time in Table 3 shows that the use of PID controller settles down the response quickly.

6 Conclusions

Transient response of the WSCC 9 bus system is studied and the optimized location of HVDC link is found by observing the response of the system with different control signals applied. Considering the HVDC current controller and line dynamics, it is observed that the transient stability of the multi-machine system is improved only if the combination of all the three signals derived from relative speed (P), rotor angle (D) and average acceleration (I) is used.

The system response is relatively stable when HVDC link is located in line 4-6 for all possible fault locations as compared to other locations of HVDC link, when PID controller is employed.

7 References

[1] P. Kundur, Power System Stability and Control, McGraw- Hill, Inc., 1994.

[2] Garng M. Huang, VikramKrishnaswamy, HVDC Controls for Power System Stability, IEEE Power Engineering Society, pp 597-602, 2002.

[3] C.S. Rao and T. K. Nag Sarkar, Half Wave Thyristor Controlled Dynamic Brake to Improve Transient Stability, IEEE Trans., vol. PAS-103, no. 5, pp. 1077-1083, May 1984.

[4] K. R. Padiyar, HVDC Power Transmission Systems, New Age International (P) Ltd., 2004.

[5] V.S. Reddy, P.V.R Rao, Supplementary HVDC Controls for Multi-machine System Stability Improvement.

[6] P.M.Anderson and A.A.Fouad, Power System Control and Stability, 1st ed.,Iowa State University Press, 1977.

[7] T. Smed, G. Anderson, A New Approach to AC/DC Power Flow, IEEE Trans. on Power Systems., Vol. 6, No. 3, pp 1238- 1244, Aug. 1991.

[8] Jos Arrillaga and Bruce Smith, AC- DC Power System Analysis, The Institution of Electrical Engineers, 1998.

[9] A. Ekstrom and G. Liss, A refined HVDC control system, IEEE Trans. Power Apparatus and Systems, vol. PAS-89, no. 536, May/June 1970.

[10] Stagg and El- Abiad, Computer Methods in Power System Analysis, International Student Edition, McGraw- Hill, Book Company, 1968.

Table 1

Absolute and relative angles of generators for various HVDC link and fault locations

HVDC Location	Fault Location	del1	del2	del3	del12	del13	del23
Line 4-5	Line 4-6 near bus 6	-0.50	2.00	2.00	-2.60	-2.60	0.00
Line 4-5	Line 7-8 near bus 8	-2.00	8.40	-2.00	-10.0	0.00	10.0
Line 8-9	Line 4-6 near bus 6	-0.38	-0.38	5.80	0.00	6.18	6.18
Line 8-9	Line 4-5 near bus 5	0.40	-0.81	0.40	-0.48	0.00	-0.48
Line 4-6	Line 4-5 near bus 5	-0.64	2.20	2.20	-2.80	-2.80	0.00
Line 4-6	Line 8-9 near bus 9	-0.29	-0.29	4.18	0.00	-4.47	-4.47

Table 2

Comparison of peak overshoot (degrees) for PI, PD, ID, PID controller for all possible fault locations.

HVDC Location	Fault Location	PI Controller	PD Controller	ID Controller	PID Controller
Line 4-6	Line 4-5 near bus 5	183.50	22.100	28.530	20.800
Line 4-6	Line 7-8 near bus 8	658.40	--	-23.000	98.300
Line 4-6	Line 8-9 near bus 9	1139.0	--	-23.200	-321.00

Table 3

Comparison of settling time (s) for PI, PD, ID, PID controller for all possible fault locations

HVDC Location	Fault Location	PI Controller	PD Controller	ID Controller	PID Controller
Line 4-6	Line 4-5 near bus 5	5.04	6.34	3.45	1.96
Line 4-6	Line 7-8 near bus 8	1.63	--	0.42	1.06
Line 4-6	Line 8-9 near bus 9	9.23	--	0.42	1.54