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HVDC Controls for Multi-Machine System Stability Improvement

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Abstract–This paper deals with the improvement of multi-machine power system stability, utilizing the rapid power controllability of HVDC. A fuzzy logic controller is then proposed, which utilizes a set of control rules to vary the gains of the conventional controller to further strengthen the system stability. Here, the current controller and line dynamics of the HVDC system are considered in the stability analysis. Initially, a study has been conducted to determine the control signal required for the HVDC power modulation in order to improve the power system stability.
Keywords – HVDC, Power System Stability, Multi – Machine Stability, Fuzzy Logic controller

I. INTRODUCTION

HVDC systems have the ability to rapidly control the transmitted power. Therefore, they have a significant impact on the stability of the associated AC power systems. More importantly, 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].

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 following are the major reasons for using supplementary control of DC links:

- Improvement of damping of AC system electromechanical oscillations.
- Improvement of transient stability.
- Isolation of system disturbance.
- Frequency control of small isolated systems.
- Reactive power regulation and dynamic voltage support.

The controls used tend to be unique to each system. To date, no attempt has been made to develop generalized control schemes applicable to all systems.

The supplementary controls use signals derived from the AC systems to modulate the DC quantities. The modulating signals can be frequency, voltage magnitude and angle, and line flows. The particular choice depends on the system characteristics and the desired results.

Apart from conventional controllers, a fuzzy logic based variable gain controller is also developed to modulate the power order of the DC control, which in turn modulates the DC power.

II AC/DC Stability Analysis

In transient stability studies, it is prerequisite to do AC/DC load flow calculations in order to obtain system conditions prior to the disturbance. The eliminated variable method proposed in [3] 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 unified, since 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.

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DC System Model

The equations describing the steady state behavior of a monopolar DC link can be summarized as follows.

$$V_{dr} = \frac{3\sqrt{2}}{\pi} a_r V_{tr} \cos\alpha_r - \frac{3}{\pi} X_c I_d \quad (2.1)$$

$$V_{di} = \frac{3\sqrt{2}}{\pi} a_i V_{ti} \cos\gamma_i - \frac{3}{\pi} X_c I_d \quad (2.2)$$

$$V_{dr} = V_{di} + r_d I_d \quad (2.3)$$

$$P_{dr} = V_{dr} I_d \quad (2.4)$$

$$P_{di} = V_{di} I_d \quad (2.5)$$

$$S_{dr} = k \frac{3\sqrt{2}}{\pi} a_r V_{tr} I_d \quad (2.6)$$

$$S_{di} = k \frac{3\sqrt{2}}{\pi} a_i V_{ti} I_d \quad (2.7)$$

$$Q_{dr} = \sqrt{S_{dr}^2 - P_{dr}^2} \quad (2.8)$$

$$Q_{di} = \sqrt{S_{di}^2 - P_{di}^2} \quad (2.9)$$

The Eliminated Variable Method

The real and reactive powers consumed by the converters are written as functions of V_{tr} and V_{ti}. The expressions for 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 as shown

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \left[\begin{array}{c|c} H & N \\ \hline J & L \end{array}\right] \begin{bmatrix} \Delta\delta \\ \Delta V / V \end{bmatrix} \quad (2.10)$$

$$N'(tr,tr) = V_{tr} \frac{\partial P_{tr}^{ac}}{\partial V_{tr}} + V_{tr} \frac{\partial P_{dr}(V_{tr}, V_{ti})}{\partial V_{tr}} \quad (2.11)$$

$$N'(tr,ti) = V_{ti} \frac{\partial P_{tr}^{ac}}{\partial V_{ti}} + V_{ti} \frac{\partial P_{dr}(V_{tr}, V_{ti})}{\partial V_{ti}} \quad (2.12)$$

$$N'(ti,tr) = V_{tr} \frac{\partial P_{ti}^{ac}}{\partial V_{tr}} - V_{tr} \frac{\partial P_{di}(V_{tr}, V_{ti})}{\partial V_{tr}} \quad (2.13)$$

$$N'(ti,ti) = V_{ti} \frac{\partial P_{ti}^{ac}}{\partial V_{ti}} - V_{ti} \frac{\partial P_{di}(V_{tr}, V_{ti})}{\partial V_{ti}} \quad (2.14)$$

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

Representation of HVDC Systems

Each DC system tends to have unique characteristics tailored to meet the specific needs of its application. Therefore, standard models of fixed structures have not been developed for representation of DC systems in stability studies. The current controller employed here (fig.1) is a proportional integral controller and the auxiliary controller is taken to be a constant gain controller.

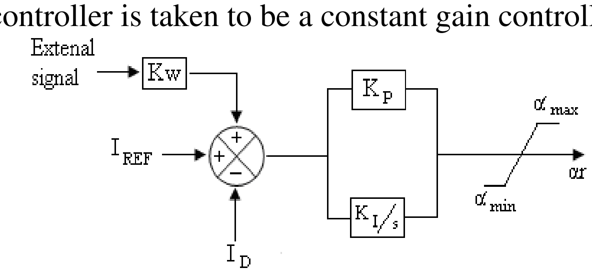

Fig 1 Current controller and auxiliary controller

HVDC line is represented using transfer function model [4] as shown in the figure 2.

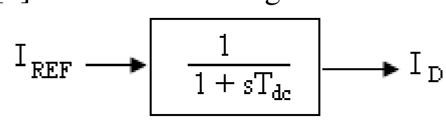

Fig.2 Transfer function model.

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.

$$\frac{d\delta}{dt} = \omega - 2\pi f$$

$$\frac{d^2\delta}{dt^2} = \frac{d\omega}{dt} = \frac{\pi f}{H}(P_m - P_e) \quad (2.15)$$

Representation of loads

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

$$Y_{po} = \frac{I_{po}}{E_p} \quad \text{where,} \quad I_{po} = \frac{P_{lp} - jQ_{lp}}{E_p^*}$$

Steps of the AC-DC Transient Stability Study

The basic structure of transient stability program is given below [5]:

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) Set time, t=0;
6) If there is any switching operation or change in fault condition, modify network data accordingly and run the AC/DC load flow.
7) Using Runge-Kutta method, solve the machine differential equations to find the changes in the internal voltage angle and machine speeds.
8) Internal voltage angles and machine speeds are updated and are stored for plotting.
9) AC/DC load flow is run to get the new output powers of the machine.
10) Advance time, $t=t+\Delta t$.
11) Check for time limit, if $t \leq$ tmax repeat the process from step 6, else plot the graphs of internal voltage angle variations and stop the process.

Basing on the plots, that we get from the above procedure it can be decided whether the system is stable or unstable. In case of multi machine system stability analysis the plot of relative angles is done to evaluate the stability of the power system.

III Conventional controller

The WSCC – 9 Bus system [6] is considered for the stability analysis and is given in the figure 3 .

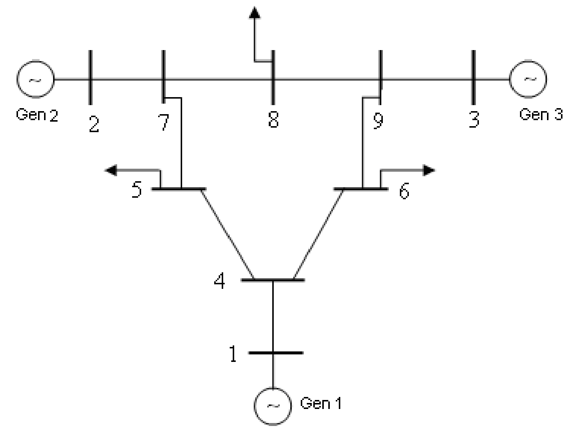

Fig 3 WSCC nine bus system

A HVDC line is assumed to be present between lines 4 – 5. A fault is assumed to occur on the line 4 – 6, near to bus 6, at initial time zero. It is cleared after 4 cycles, by removing the line and to reflect this removal the admittance matrix is modified. Initially, HVDC line is assumed to maintain same control as it had in the normal condition. The power flowing through the HVDC link is maintained constant and equal to prefault value. Then the plot of relative angles is as shown in figure 4.

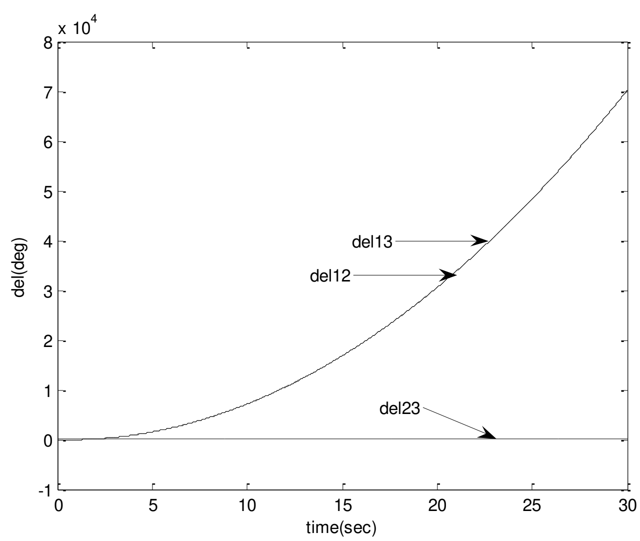

Fig .4 Plot of relative angles without any control.

From the figure it is clear that the system is unstable as the relative angles are increasing. It can be examined that the generator 1 is going out of step with respect to the generators 2 and 3. To stabilize the system it is necessary to make the accelerations of all the generators equal. So an error signal representing average difference in

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accelerations of the generators is considered. Incase of multi machine systems 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 as shown below.

$$error_1 = \left[\left[\frac{(\omega(2)-\omega(1))+(\omega(3)-\omega(1))}{2}\right] - [\omega(2)-\omega(3)]\right] \quad (2.16)$$

$$error_2 = \left[\left[\frac{(del(2)-del(1))+(del(3)-del(1))}{2}\right]\right] - [del(2)-del(3)] \quad (2.17)$$

$$error_3 = \left[\frac{\frac{P\_mis(3)}{H(3)}+\frac{P\_mis(2)}{H(2)}}{2}\right] - \left[\frac{P\_mis(1)}{H(1)}\right] \quad (2.18)$$

Different combinations 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. When $error_3$ signal is considered for improving the stability of the system as suggested in [2], the plot of relative angles is shown in figure 5. This reveals that the considered signal is inadequate to improve the stability of the system.

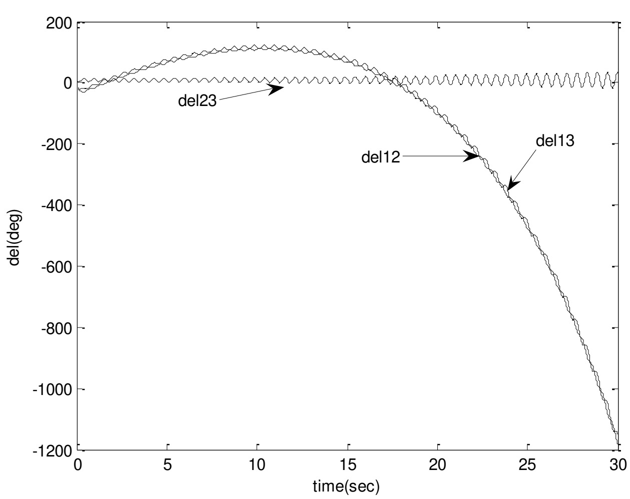

Fig.5 Plot of relative angles with $error_3$ as control signal

Considering the different combinations of the signals, in varied proportions, as the control input, the plot of relative angles is as shown in figure 6.

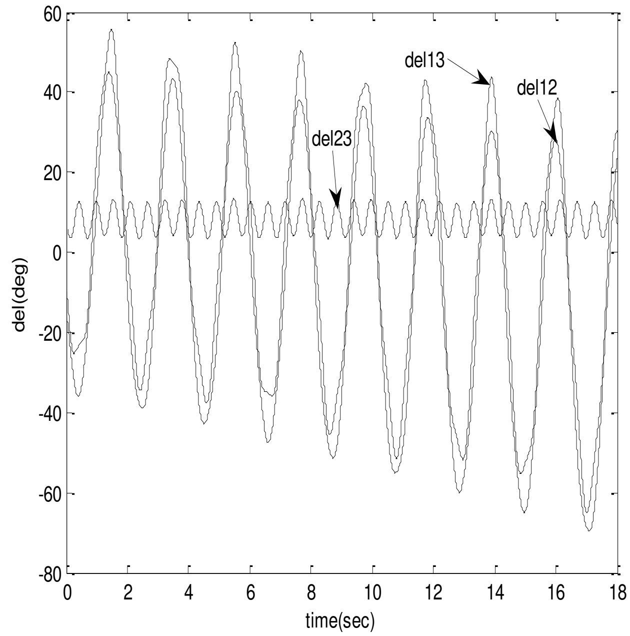

Fig.6.a Plot of relative angles with control signal $K_p*error_1+K_i*error_2$.

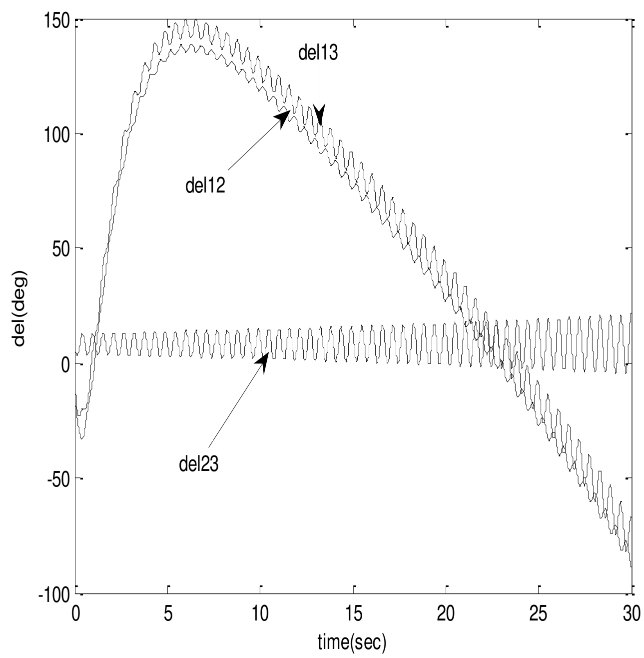

Fig.6.b Plot of relative angles with control signal $K_p*error_1+K_d*error_3$.

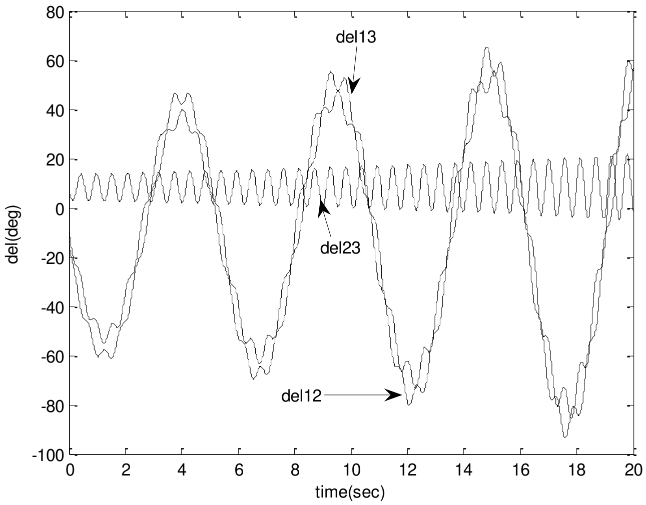

Fig. 6.c Plot of relative angles with control signal K_i*error$_2$+K_d*error$_3$.

In the above cases it can be seen that either the system is unstable or there is no considerable improvement in the stability of the system. When all the three signals are considered, the plot of the relative angles is as shown in figure 7. It can be seen that the stability of the system is improved and by the end of the study time the action of AGC will come into picture which will further improve the system stability.

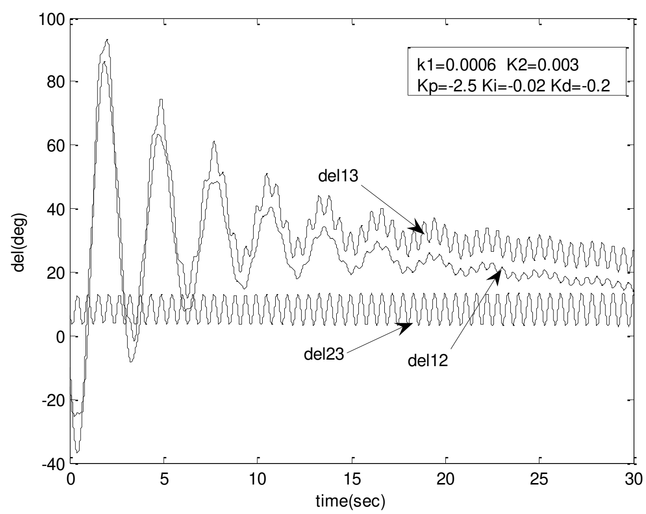

Fig .7 Plot of relative angles with control signal K_p*error$_1$+ K_i*error$_2$+K_d*error$_3$.

Control signal,
error = K_p*error$_1$+ K_i*error$_2$ + K_d*error$_3$

So, for this formulation of the system and for this disturbance scenario it is essential to use all the three signals, to have a considerable improvement in the stability of the system.
Here 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 proposed above is equivalent to a PID controller. Then the control signal can be equivalently represented as in equation 2.19.

error= K_p e(t)+K_i Ie(t)+K_d De(t) (2.19)

Considering this, the methodology used in variable gain PID controller scheme can be applied to the above controller, to improve its performance.

IV Fuzzy logic controller

One approach to enhance the performance of the conventional controller of (2.19) is to vary its gains K_p, K_i and K_d as a function of |e(k)|, |Ie(k)| and |De(k)|, respectively. Thus if |e(k)| is large/medium/small then change Kp by a large/medium/small amount in order to reduce e(t) to zero as fast as possible. This rule is also applicable to |Ie(k)| and |De(k)| by changing K_i and K_d , respectively[7].
Therefore, in fuzzy logic terminology, it is possible to associate three linguistic labels, viz., large, medium and small, to each of the variables |e(k)|, |Ie(k)| and |De(k)|.

Control rules

Based on above rules and the fact that the controller output of (2.19) has three terms, there are altogether 27 linguistic control rules, which can modify the conventional controller gains to get a better performance. These rules are summarized in table 1.

Table1: Rule Base

Rule No: (labels of universes; weighted outcome)	
i: (|e|, |Ie|, |De|; wu_i)	for i = 1 to 27

1: (S, S, S; wu_1),	2: (S, S, M; wu_2),	3: (S, S, L; wu_3)
4: (S, M, S; wu_4),	5: (S, M, M; wu_5),	6: (S, M, L; wu_6)
7: (S, L, S; wu_7),	8: (S, L, M; wu_8),	9: (S, L, L; wu_9)
10: (M, S, S; wu_{10}),	11: (M, S, M; wu_{11}),	12: (M, S, L; wu_{12})
13: (M, M, S; wu_{13}),	14: (M, M, M; wu_{14}),	15: (M, M, L; wu_{15})
16: (M, L, S; wu_{16}),	17: (M, L, M; wu_{17}),	18: (M, L, L; wu_{18})
19: (L, S, S; wu_{19}),	20: (L, S, M; wu_{20}),	21: (L, S, L; wu_{21})
22: (L, M, S; wu_{22}),	23: (L, M, M; wu_{23}),	24: (L, M, L; wu_{24})
25: (L, L, S; wu_{25}),	26: (L, L, M; wu_{26}),	27: (L, L, L; wu_{27})

The rules in the table 1 are to be used in the following manner

If |e(k)| is small and |Ie(k)| is small and |De(k)| is small then

$$Wu_1(k) = K_p\mu_s(|e(k)|)e(k) + K_i\mu_s(|Ie(k)|)Ie(k) + K_d\mu_s(|De(k)|)De(k)$$

Similarly, rule 22 is read as

If |e(k)| is large and |Ie(k)| is medium and |De(k)| is small then

$$Wu_{22}(k) = K_p\mu_L(|e(k)|)e(k) + K_i\mu_m(|Ie(k)|)Ie(k) + K_d\mu_s(|De(k)|)De(k)$$

In the above rules, $\mu_L(|z|)$, $\mu_m(|z|)$ and $\mu_s(|z|)$ are membership functions when |z| is large, medium and small, respectively, and z is either e(k), Ie(k) or De(k). Figure 8 shows the type of membership functions used in this formulation. Briefly, a membership function $\mu_{LL}(x)$ is used to indicate to what degree, in a scale ranging from 0 to 1, the variable x satisfies the linguistic label LL.

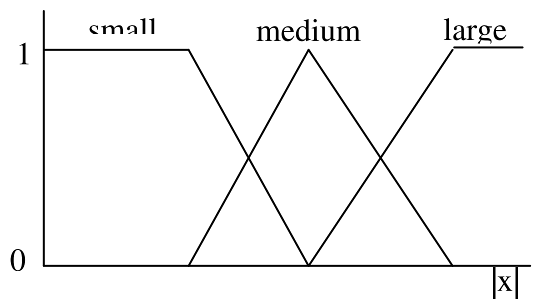

Figure.8: Membership function

Variable gain Fuzzy logic controller

For a given set of |e(k)|, |Ie(k)| and |De(k)| all the 27 rules shown in Table 1 will be active. Furthermore, there is a degree of fulfillment μ_i, also known as the truth value, of each rule for i=l to 27. This degree of fulfillment is determined by applying the AND operation to the condition part of the rule. Thus, for Rule 1, it is given by

$$\mu_1 = \min\left[\mu_s(|e(k)|), \mu_s(|Ie(k)|), \mu_s(|De(k)|)\right]$$

For Rule 22, its degree of fulfillment is

$$\mu_{22} = \min\left[\mu_L(|e(k)|), \mu_m(|Ie(k)|), \mu_s(|De(k)|)\right]$$

Therefore, for a given set of |e(k)|, |Ie(k)| and |De(k)|, there are 27 weighted outcomes $wu_i(k)$ and each outcome has μ_i as its degree of fulfillment for i=1 to 27. One commonly used method to determine the net outcome $U_F(k)$ is based on the weighted average approach. Here, this approach is adopted and thus

$$U_F(k) = \frac{\sum_{i=1}^{27} Wu_i}{\sum \mu}, \qquad (2.21)$$

$$\text{Where, } \sum \mu = \sum_{i=1}^{27} \mu_i \qquad (2.22)$$

Applying, the above formulation to the conventional controller scheme proposed in the previous section, the plot of the relative angles is shown in figure 9.

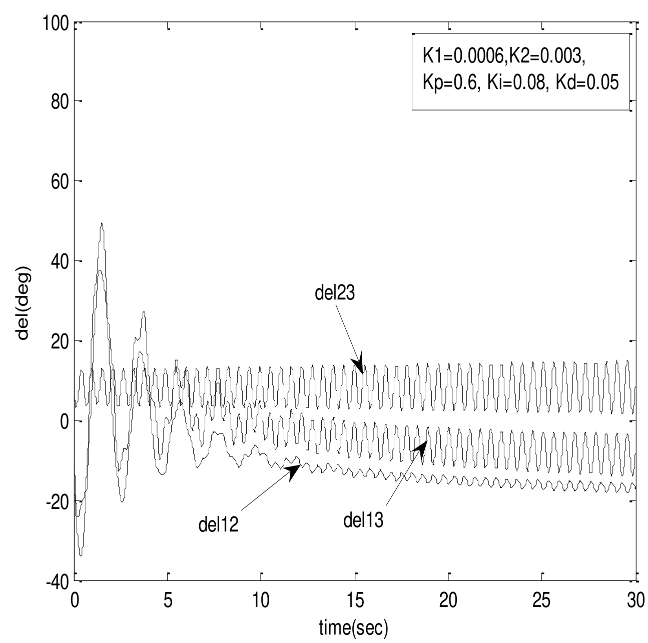

Fig. 8 Plot of relative angles of generators with fuzzy controller

V Conclusions

Considering the HVDC current controller, 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, phase angle and average acceleration is used.
Fuzzy Logic Based variable gain controller has been implemented successfully for HVDC power modulation to augment the transient stability. The fuzzy logic controller gives better performance than the conventional controller as expected.

VI References

[1] Prabha Kundur, "*Power System Stability and Control*", McGraw- Hill, Inc., 1994.
[2] Garng M. Huang, Vikram Krishnaswamy, "*HVDC Controls for Power System Stability*", IEEE Power Engineering Society, pp 597- 602, 2002.
[3] T. Smed, G. Anderson, G.B.Sheble, L.L.Grisby "*A New Approach to AC/DC Power Flow*", IEEE Trans. on Power Systems., Vol. 6, No. 3, pp 1238- 1244, Aug. 1991.
[4] K. R. Padiyar, "*HVDC Power Transmission Systems*", New Age International (P) Ltd., 2004.
[5] Stagg and El- Abiad, "*Computer Methods in Power System Analysis*", International Student Edition, McGraw-Hill, Book Company, 1968.
[6] P.M.Anderson and A.A.Fouad, Power System Control and Stability, 1st ed.,Iowa State University Press, 1977.
[7] Choo Min Lim, Takashi Hiyama, "Application of A Rule-Based Control Scheme for Stability Enhancement of Power Systems", pp 1347- 1357, IEEE 1995.