# FUZZY TUNING OF DC LINK CONTROLLERS

**P.K.Dash, Aurobinda Routray**
**Dept. of Electrical Engineering**
**Regional Engineering College**
**Rourkela-769 008**
**INDIA**

**S.K.Panda & A.C.Liew**
**Electrical Engineering Department**
**National University of Singapore**
**SINGAPORE**

**ABSTRACT** The paper introduces different types of Fuzzy tuning methods for the controller parameters of the firing and extinction angle controller of an HVDC link. The test system, a point to point DC link has been subjected to various small and large disturbances to examine the effectiveness of the proposed schemes. The current error and it's derivative in case of rectifier and the gamma error and it's derivative in case of the inverter are taken as the two principal signals to generate the change in the proportional and the integral gains according to a definite rule base. The results obtained have been compared graphically to prove the superiority of the proposed controllers.

**Keywords : DC Link Controller, Fuzzy Logic, Variable PI gains**

## I. INTRODUCTION

For multi-input-multi-output non-linear dynamic systems the simplest yet robust controllers are P-I type. Very often in such systems, under certain circumstances, with fixed values of proportional and integral gains, these controllers are prone to instability. However, with proper tuning of the controller parameters the above situations can be easily overcome. Therefore, the prime objective of all the controller designs is to adjust the effective integral, proportional and the derivative gains for reliable operation of the plant under all possible situations.

The operation and control of an HVDC link connected to weak AC system is too complex to visualise from a system point of view. The main objective of DC link controllers at either end (rectifier and inverter) is to operate the link efficiently, under normal and abnormal conditions.

To circumvent the abnormal problems occuring in HVDC links, extensive research has been carried out in the area of HVDC control. Elaborate literature available in DC adaptive control are inconclusive for practical applications. The absence of insight into system's performance with large disturbances where the adaptive control not only may be ineffective, but may degrade performance rather than enhance it[1,2]. Reeve et.al have tried a gain scheduling adaptive control where the effect of large disturbances has been taken into account[3]. Hammad et.al have proposed a Robust co-ordinated control scheme for a parallel AC-DC system[4]. The paper describes the derivation and validation of a co-ordinated controller based as on-line identification of the AC/DC system. Alexandris etal have used Kalman filtering approach for designing the rectifier current regulator in the presence of unknown inputs[5].

Most of the above controllers, although superior to the conventional PI type, need either an accurate plant model or a reliable instrumentation scheme. The noise rejection property of these controllers are rather limited.

Recently, extensive research in the area of Fuzzy logic control throws some light on it's application to large non-linear systems such as HVDC links. Till-date such type of controllers have proven themselves successful in controlling small non-linear plants. For large systems still it remains a challenge to replace the conventional controllers completely. However, the adjustment of the gains can be done by a scheme based on Fuzzy logic.

In order to account for sensor noise, model uncertainties, and shifts in operating points, the linguistic characteristics of Fuzzy control provide a very good approach to the uncertainty problem[6]. Fuzzy logic control proves to be highly effective in controlling plants whose detailed and accurate mathematical descriptions are not available. On the otherhand, Fuzzy rule derivation, by principle, relies on the experience of a human expert; which some times limits the Fuzzy logic controller to low order system.

The paper presents a Fuzzy logic based approach for the on-line tuning of the control parameters for a point to point HVDC link connected to weak AC system. In one part of this paper normalised values of current error and it's derivative (gamma error and it's derivative) have been taken as the input signals for Fuzzy inference. The output derived by a simple non-linear defuzzification method tunes the various gains of the pole controller (gamma controller). In the other part, a Lyapunov energy function has been taken instead of the DC link current. The magnitude and sign of the function and it's derivative with the changing values of gains determine the future path of the change in gains. At last a comparative study has been taken up to demonstrate the feasibility and effectiveness of the proposed schemes with the conventional fixed gain controllers.

## II. HVDC SYSTEM MODEL

A two pole point-to-point HVDC system has been simulated with the help of EMTDC package. The filters and transformers on either side of the DC link and the transmission line are represented in detail. The system shown in Fig.1 is divided into four subsystems:

*IEEE Catalogue No. 95TH8130*
*0-7803-2981-3/95/$4.00©1995 IEEE*

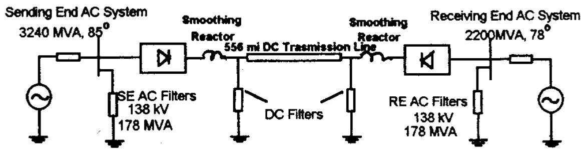

Fig.1(i) HVDC System Model

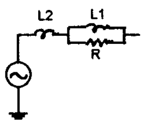

Fig.1(ii) Details of AC System Representation

**1. Subsystem 1** : The rectifier side subsystem consists of a constant voltage and constant frequency source behind an impedance that comprises of inductances and resistances to represent a simplified AC system. The short circuit ratio (SCR) for the system is fairly high as compared to the Inverter side AC system. AC filters for 5th, 7th, 11th and 13th harmonics have been provided.

**2. Subsystem 2** : The rectifier is connected to the DC transmission line through a large inductor and a 12th harmonic filter has been connected to take care of the ripples in the DC voltage.

**3. Subsystem 3** : It is identical with the subsystem 2 except for the fact that it comes in-between the inverter and the DC link.

**4. Subsystem 4** : The inverter side AC system representation is identical to that of rectifier side. The same filters are also present here. But the voltage ratings and SCR are different. The inverter AC side is weaker having an SCR around 2.5.

### A. Inverter Control System

The inverter is subjected to constant extinction angle (CEA) control Fig.2. The pole controller (i.e. current controller) has been provided for rectifier operations under transient conditions. However, in steady state normal operating conditions it operates with CEA control.

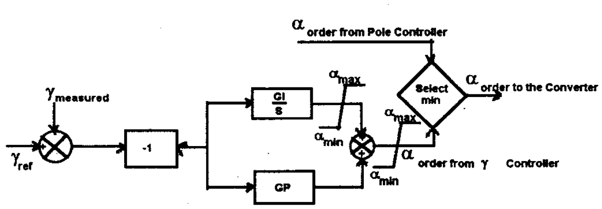

Figure 2 Inverter Gamma Controller

### B. Rectifier Control System

The DC-link current is maintained constant by subjecting the rectifier with constant current control Fig.3. The firing angle is adjusted with current error, to maintain the DC current constant. It is also provided with a valve controller (Gamma controller) to operate it as an inverter during transient and abnormal situations.

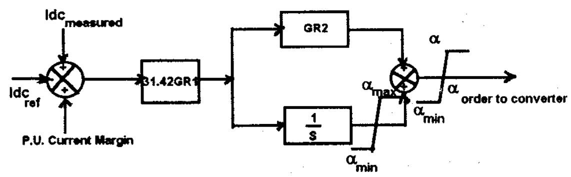

Fig.3 Rectifier Pole Controller

The SCR at the rectifier end AC system is approximately 35 representing a strong system. While the inverter end AC system is made weaker (SCR=2.5) by choosing suitable resistance and inductance parameters.

## III. DESIGN IMPLEMENTATION

The rectifier side current regulator has been replaced by a Fuzzy self-tuning controller as shown in Fig.4(ii). The structure remains the same except that the gain GR1 (which takes care of both $K_p$ and $K_i$ ) is adjusted through Fuzzy inference. The gains of the inverter side gamma controller has also been tuned in a similar way Fig 4(iii).

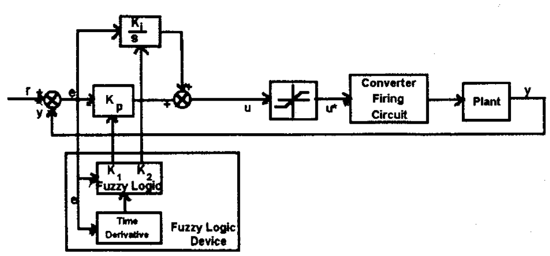

Fig.4(i) Fuzzy Tuning Strategy

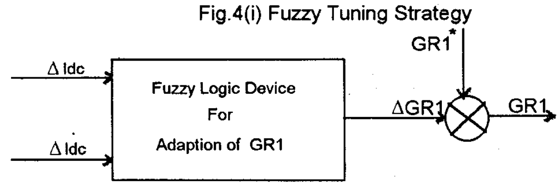

Fig.4(ii) Fuzzy Tuning for the Pole Controller

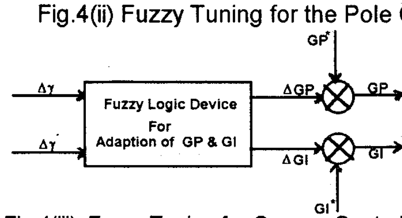

Fig.4(iii) Fuzzy Tuning for Gamma Controller

**Part I : Simple Fuzzy Tuner**

The normalised values of the current error and its derivative are used as the two principal variables for the adjustment of the gains in the rectifier pole controller.

Let

$$\Delta I_{dc} = I_{dcrf} - I_{dc} \quad (1)$$

$$\Delta \dot{I}_{dc} = \left(\Delta I_{dc} - \Delta I_{dcp}\right) / \Delta T \quad (2)$$

$$Er = GE.\left(\Delta I_{dc}\right) \quad (3)$$

$$Rt = GR.(\Delta \dot{I}_{dc}) \quad (4)$$

Where $I_{dcrf}$ =Reference current

$I_{dc}$ = measured current

$\Delta$T = Sampling rate

$\Delta I_{dcp}$= Previous value of error

GR, GE = gains for normalisation.

The inputs $Er$ and $Rt$ are fuzzified into three sets i.e. P, Z and N (Positive, Zero, Negative). The rule table Table-1 is formed from the results of the conventional controller. The membership grades (Fig.5) are taken as triangular and symmetrical. The Fuzzy procedure to adapt $GR_1$ starts from it's nominal value $GR_1^*$, and assumes that its variations span in a limited range. The tuned value of the control parameter can be indicated as

$$GR_1 = GR_1^* + \Delta GR_1 \quad (5)$$

The value of $\Delta GR_1$ is worked out in terms of

- it's nominal value $GR_1^*$
- the value of $K_1$ derived from the Fuzzy logic device
- Coefficient $C_R$ that fix the min-max range of the parameter variations. For example $C_R = 4$ means that $GR_1$ will vary between $0.25GR_1^*$ and $4GR_1^*$.

The variation of $\Delta GR_1$ is given by

$$\Delta GR_1 = K_1 . GR_1^* . C_R \quad \text{if } K_1 \geq 0 \quad (6)$$

$$\Delta GR_1 = K_1 . GR_1^* . \frac{1}{C_R} \quad \text{if } K_1 \leq 0 \quad (7)$$

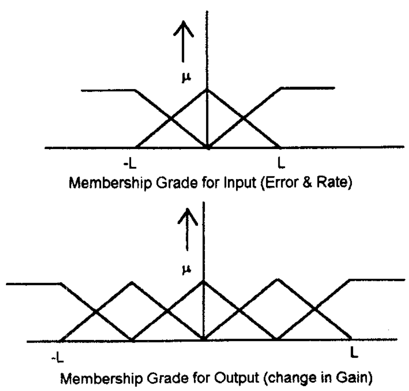


Fig.5 Membership Grade for input and output

The advantage of this adaptation scheme can be seen from the following equations.

For this controller the integral action is given by

$$\int_0^t GR_1(z)\Delta I_{dc}(z)dz \quad (8)$$

where as for the conventional controller the integral action is given by

$$GR_1^* \int_0^t \Delta I_{dc}(z)dz \quad (9)$$

Equation (8) represents as to how the gain parameter varies with the dc link operating conditions.

The Fuzzy device output $K_1$ can be derived by different defuzzification methods. However, a simple non-linear defuzzification is used here :

$$K_1 = \frac{\sum \mu_i y_i}{\sum \mu_i} \quad (10)$$

where, $\mu_i$ =membership grades of the $i^{th}$ output Fuzzy set;

$y_i$ = numerical value of the output for which the membership grade for the $i^{th}$ Fuzzy set is 1.

The output membership grades for different Fuzzy sets are derived by Zadeh's AND, OR rules from the rule table

**Table 1**

| **Error→ ↓Rate** | **P** | **Z** | **N** |
|---|---|---|---|
| **P** | **PL** | **PM** | **Z** |
| **Z** | **PM** | **Z** | **NM** |
| **N** | **Z** | **NM** | **NL** |

*The Fuzzy sets for Inputs are :P-Positive , N-Negative, Z-Zero. The Fuzzy sets for Output are :PL-Positive Large, PM-Positive Medium, Z-Zero,NL-Negative Large & NM-Negative Medium*

For the tuning of the gamma controller, the inverter extinction angle and it's derivative have been used. In this case, instead of tuning only one parameter unlike the rectifier pole controller, both the proportional and integral gains have been adjusted with a fixed proportion (Fig.4(iii)).

**Part II: Lyapunov Fuzzy Tuner**

The following Lyapunov function is formulated from the current error and it's derivative for adjusting the gains of the rectifier pole controller. Unlike simple Fuzzy-tuning, only the proportional gain has been tuned here. The integral gain has been kept at a fixed value. The Lyapunov function $V$ is defined as

$$V = EAE^T \quad (11)$$

where,

$$E = [\Delta I_{dc} \;\; \Delta \dot{I}_{dc}] \quad (12)$$

and $A = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix}$ is a positive definite matrix for normalising $V$.

The rate of change of $V$ is obtained as,

$$\dot{V} = \left(V - V_p\right) / \Delta T \quad (13)$$

where,

$V_p$=previous value of $V$

In order satisfy the stabilisation objective, we require,

$$\dot{V} \leq 0 \text{ or } \Delta V \leq 0 \quad (14)$$

To satisfy the condition stated in (14) by tuning $K_p$, one must find an expression that relates $\Delta V$ to the desired change in $K_p(\Delta K_p)$. A sensitivity function is introduced to obtain,

$$S = \partial V / \partial K_p \qquad (15)$$

which leads to

$$\Delta V = \left(\partial V / \partial K_p\right)\Delta K_p \qquad (16)$$

Based on (16), for a given $\left(\partial V / \partial K_p\right)$, the objective of the Fuzzy tuner is to generate an appropriate $\Delta K_p$, which in turn should produce a $\Delta V$ that satisfies (14).

The next value of $\Delta K_p$ i.e. $\Delta K_p(t_{k+1})$ (the output of the Fuzzy tuner) depends only on the present value of $\Delta V(t_k)$ (the performance index at time $t_k$) and on the present sign of $\left(\frac{\partial V}{\partial K_p}\right)(t_k)$ (the sensitivity function at time $t_k$) which can be estimated by

$$\frac{\partial V}{\partial K_p}(t_k) \approx \frac{\Delta V(t_k)}{\Delta K_p(t_k)} = \frac{V(t_k)-V(t_{k-1})}{K_p(t_k)-K_p(t_{k-1})} \qquad (17)$$

The guideline to chose the sign for $\Delta K_p$ is given as

$$sign(\Delta K_p(t_{k+1})) = -sign\left(\frac{\partial V}{\partial K_p}(t_k)\right) \qquad (18)$$

The algorithm to choose the magnitude is as follows :

(1) If $\Delta V(t_k)$ is positive, then the magnitude for $\Delta K_p(t_{k+1})$ must be large. The reason behind this action is that if $\Delta V(t_k)$ is positive, then the system is diverging from the desired trajectory and a drastic action must be taken to quickly bring the system back to the desired condition.

(2) If $\Delta V(t_k)$ is negative then the magnitude for $\Delta K_p(t_{k+1})$ must be medium. The reason behind this is if that $\Delta V(t_k)$ is negative, then the system is converging towards the desired trajectory, and only a medium action must be taken in order to avoid large overshoot (or undershoot) of the trajectory.

(3) If $\Delta V(t_k)$ is zero, then the magnitude for $\Delta K_p(t_{k+1})$ must be small. The reason is that if $\Delta V(t_k)$ is near zero, the system almost reaches the desired trajectory and only a very small action needs to be taken.

For example the following Fuzzy rule is formed :

$R_1$: IF $\Delta V(t_k)$ is positive and $\left(\frac{\partial V}{\partial K_p}\right)(t_k)$ is negative $\Delta K_p(t_{k+1})$ is Positive Large

The complete Fuzzy decision tree for $\Delta K_p(t_k)$ is shown in Fig.6. After the Fuzzy inference, a simple non-linear defuzzification scheme as given in equation (10) is used to find out $\Delta K_p(t_k)$.

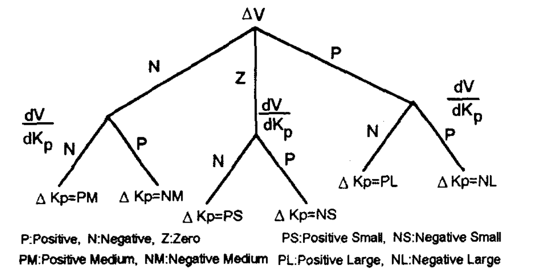


Fig.6 Fuzzy Decission Tree for Lyapunov Type Fuzzy Tuning

Finally the change in GR1 is given by

$$\begin{aligned} \Delta GR_1 &= \Delta K_p . GR_1^{*} . C_R && \text{if } \Delta K_p(t_k) \geq 0 \\ &= \Delta K_p . GR_1^{*} . 1/C_R && \text{if } \Delta K_p(t_k) < 0 \end{aligned} \qquad (19)$$

**A. Procedure**

From the sampled values of the DC link current error, the derivative $\Delta \dot{I}_{dc}$ is calculated. A filter can be used to remove the high frequency components in the derivative signal. The DC current which is measured in subsystem 2 is passed through a lag network to make it ripple free. After calculating the derivatives, the signals are normalised by multiplying by two gains "GE" and "GR" (for simple Fuzzy Tuning).

The optimal values of these gains are found out from the ITSE (integral time square error) criterion. A performance index given by

$$\int_0^t z^2\left(\Delta I_{dc}(z)\right)^2 dz \qquad (20)$$

has been minimised by the multiple run feature of EMTDC. Prior to it, the steady state optimal values of the conventional control gains have been found out.

## IV. CASE STUDIED

The following cases have been studied for the four different controller actions. They are

(a) Lyapunov Fuzzy Tuning of GR1 (Rectifier Pole Controller)

(b) Simple Fuzzy Tuning of GR1(Rectifier Pole Controller), GP & GI(Inverter Gamma Controller)

(c) Simple Fuzzy Tuning of GR1 (Rectifier Pole Controller)

(d) Conventional Controller

**Pole Controller :**

For the conventional pole controller on the either side :
$GR_1$=5.88, $GR_2$ = 0.0136,

Rectifier pole controller : $\alpha_{min} = 5^{\circ}$, $\alpha_{max} = 155^{\circ}$

Inverter pole controller : $\alpha_{min} = 108^{\circ}$, $\alpha_{max} = 178^{\circ}$

For the rectifier side Fuzzy tuned pole controller normalized input values of the DC current and its derivative have been used.

The value of $C_R$ is 2 in this case.

For valve control conventional PI type gamma controller on either side of the DC link is used.

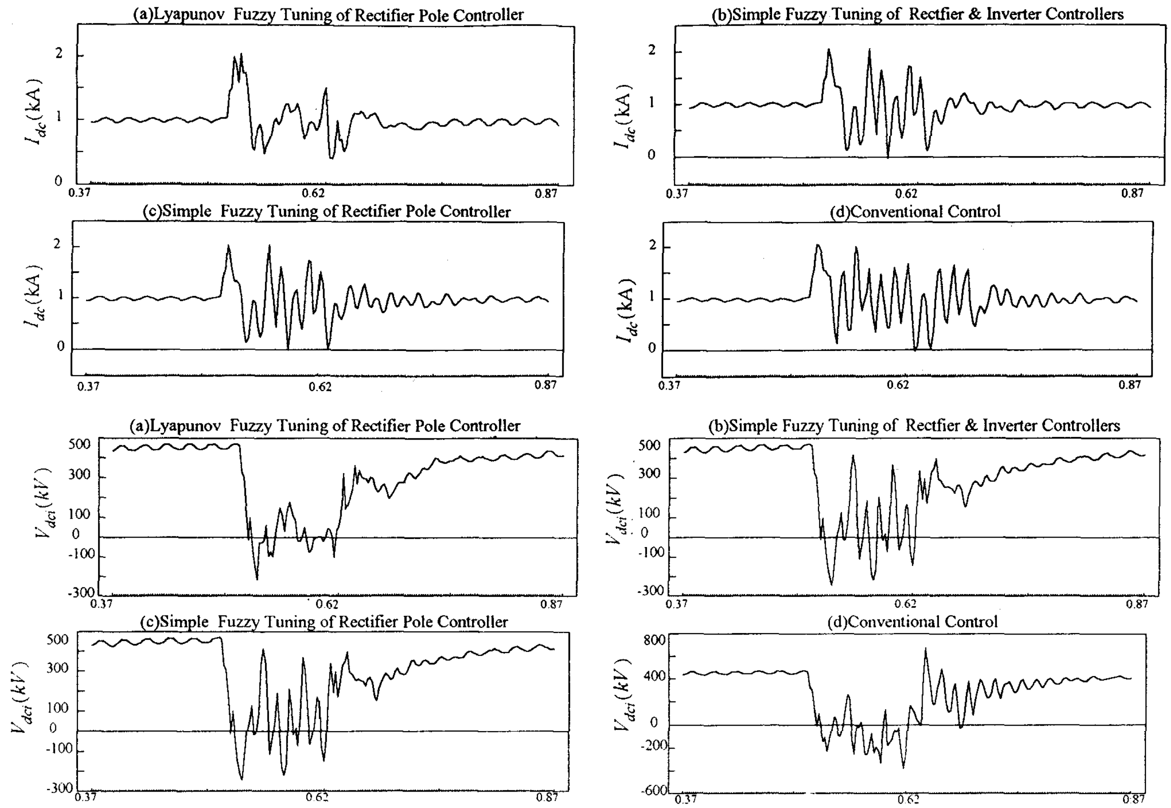


**Fig.7 DC Current and Voltage waveforms after Single Line-to-Ground Fault at Inverter AC bus**

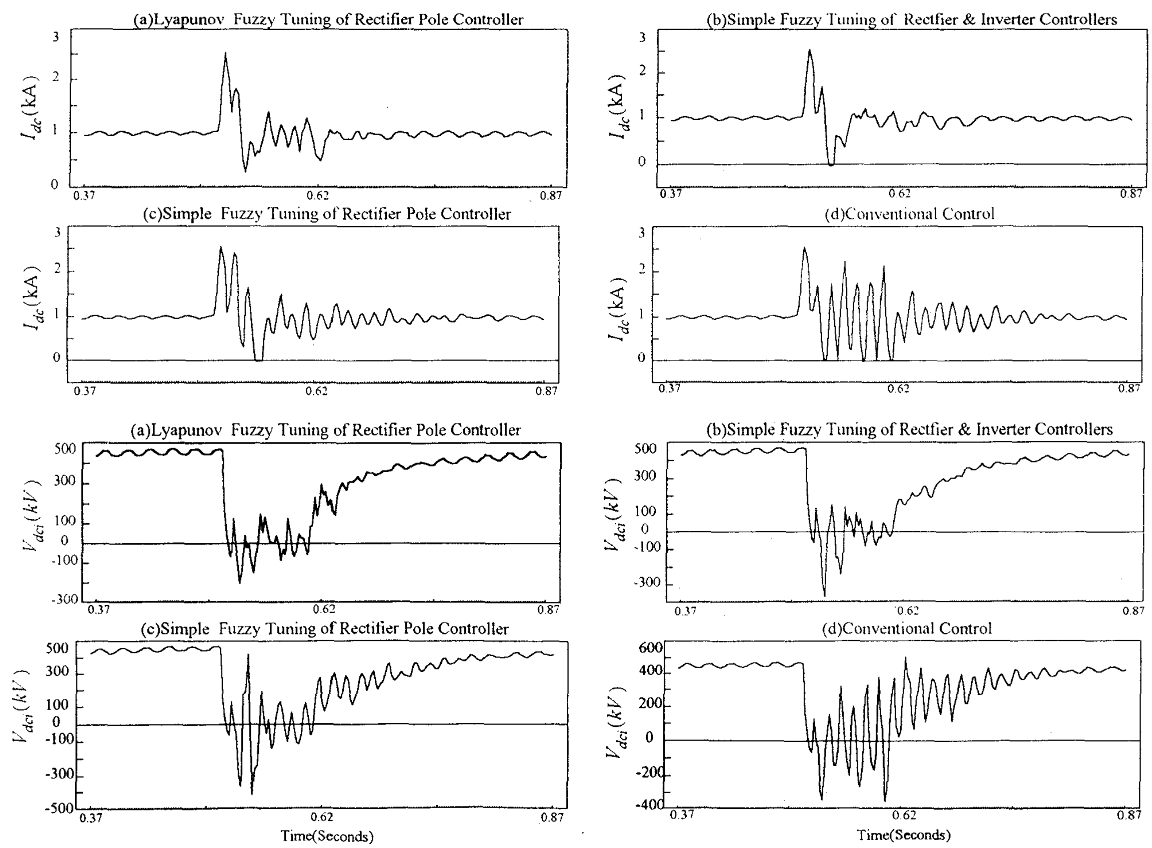


**Fig.8 DC Current and Voltage waveforms after DC Line-to-Ground Fault at Inverter**

The rectifier side AC-system being strong, recovers very fast after any disturbances, overriding the effect of most of the controller actions. Therefore, for any fault on the rectifier AC or DC bus, much difference is not observed in the current and voltage waveforms for most of the controller actions.

For the faults in the inverter side the proposed controllers make the system recover much faster than the conventional PI controller does. Especially the Lyapunov type Fuzzy Tuning displays extremely good results while recovering from the Inverter DC line to ground fault. The commutation failures, power oscillations and high di/dt which are detrimental to the converter operation have been minimised in case of the proposed controllers.

The relevant waveforms in Figs.7 and 8 demonstrate this.

**A. Single line-to-ground fault at Inverter AC bus**

The wave forms resulting from a 5 cycle single line-to-ground fault at inverter AC bus have been shown in Fig.7. Being a weaker system, the oscillations in the voltage and current are primarily decided by the controller action. The current wave form in case of a conventional controller has a lot of crests and dents and suffers from prolonged oscillations, whereas, for a simple Fuzzy controller the DC current fast returns to it's nominal value. For Lyapunov type Fuzzy Controller the oscillations are further minimised. Similarly from the DC voltage waveform at the inverter side it is clear that the valves undergo commutation failure several times in case of a conventional controller, whereas for other types of controllers it has been minimised.

**B. DC line-to-line fault at the Inverter**

Fig.8 shows the waveforms after a 5 cycle DC line-to-line fault at the inverter. A large number of oscillations has been observed in DC link current and voltage magnitudes in case of a conventional controller. From the inverter DC voltage plots it is clear that in case of conventional control the inverter valves undergo commutation failure several times as compared with the simple Fuzzy & Lyapunov type Fuzzy Controllers.

## V. CONCLUSION

For HVDC links where very large transient conditions are involved in the plant operation, it is more convenient to improve the PI control strategy rather than to work out complicated dynamic models which require sophisticated control strategies. The application of the linguistic rules is in fact simpler than sophisticated identification and optimization procedures. The implementation of Fuzzy controllers is also less complicated than that of optimization algorithms. The results obtained display the superiority of such controllers over the conventional one. A little modification in the simple Fuzzy tuning methodology makes the controller performance better.

## VI. ACKNOWLEDGMENT

The authors acknowledge the funds received from Department of Science & Technology, Govt. of India.

## VII. REFERENCES

[1] S.Lefebvre, M.Saad, and AR.Hurteau, "Adaptive Control for HVDC Power Transmission Systems," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No.9, 1985, pp.2329-2335.

[2] W.J.Rugh, "Analytical Framework for Gain Scheduling," IEEE Control Systems Magazine, Vol.II, No.1, 1991, pp.79-84.

[3] John Reeve, and M.Sultan, "Gain Scheduling Adaptive Control Strategies for HVDC Systems to Accommodate Large Disturbances", IEEE Trans. on Power Systems, Vol.9, No.1, 1994, pp.366-372.

[4] K.W.V.To, A.K.David and A.E.Hammad, "A Robust Co-ordinated Control Scheme for HVDC Transmission with Parallel AC Systems", IEEE 94WM 061-2 PWRD.

[5] A.T.Alexandridis, and G.D.Galanos, "Design of an Optimal Current Regulator for weak AC/DC Systems Using Kalman Filtering in the Presence of Unknown Inputs", IEE Proceedings, Vol.136, Pt.C, No.2, 1989, pp.57-63.

[6] A. De carli, P. Ligouri and A. Marroni, " A Fuzzy-PI Control Strategy", Control Eng. Practice, Vol.2, No.1, 1994, pp 147-153.

[7] V.K. Sood, N. Kandil, R.V. Patel & K. Khorasani, " Comparative Evaluation of Neural Network based and PI Current Controllers for HVDC Transmission" IEEE Trans. on Power Electronics, Vol.9, No.3, 1994, pp 288-295.

[8] H.Chris Tseng, Victor Hwang, and Sung Lep Lui, "Fuzzy Servocotroller : The Hierarchical Approch", 0-7803-0236-2/92 ©IEEE , pp.623-631.

[9] H.Chris Tseng and Victor Hwang, " Servocontroller Tuning with Fuzzy Logic", IEEE Trans. on Control System Technology, Vol.1, No.4, 1994, pp 262-269

[10] "EMTDC User's Manual." Manitoba HVDC Research Center, Winnipeg, MB, Canada.