A Fuzzy Self-Tuning PI Controller for HVDC Links

Aurobinda Routray, P. K. Dash, and Sanjeev K. Panda

Abstract—**This paper introduces a fuzzy logic-based tuning of the controller parameters for the rectifier side current regulator and inverter side gamma controller in a high voltage direct current (HVDC) system. A typical point-to-point system has been taken with the detailed representation of converters, transmission links transformers, and filters. The current error and it's derivative and the gamma error and it's derivative are used as the principal signals to adjust the proportional and integral gains of the rectifier pole controller and the inverter gamma controller, respectively, for the optimum system performance under various normal and abnormal conditions. Finally, a comparative study has been performed with and without tuning, to prove the superiority of the proposed scheme.**

I. INTRODUCTION

WITH GROWING industrialization, power generation and demand are increasing very fast. To handle large bulk of power, the ac power transmission is not economical over large distances. High voltage direct current (HVDC) transmission is the only alternative to it. The advantages gained by dc power transmission outweighs the complexity of its operation and maintenance. Not only are they used for long distance power transmission, but also they are being used as a part of the ac network to enhance the stability of the system.

But the operation and control of HVDC links as already mentioned poses a challenge for the designers to choose the proper control strategy under various operating conditions. The tuning of the converter controls for dc transmission is a compromise between the speed of response and stability for small disturbances on the one hand and robustness to tolerate large signal disturbances due to faults and switching on the other hand. Furthermore, the highly nonlinear nature of the control loops require careful selection of control constants that will accommodate a range of operating conditions. It has been found in actual dc projects that control with fixed parameters fails under abnormal circumstances.

To circumvent the above problem, extensive research has been carried out in the area of HVDC control. Elaborate literature available in dc adaptive control is inconclusive for practical applications because of the absence of insight into performance with large disturbances where the adaptive control not only may be ineffective but may degrade the performance rather than enhance it [1], [2].

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Reeve *et al.* have tried a gain scheduling adaptive control strategy where the effect of large disturbances has been taken into account [3]. Hammad *et al.* have proposed a robust coordinated control scheme for a parallel ac–dc system [4]. The paper describes the derivation and validation of a coordinated controller based as on-line identification of the ac–dc system. Alexandridis and Galanos have used the 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 types, need either an accurate plant model or a reliable instrumentation scheme. The noise rejection property of these controllers is rather limited.

Recently, extensive research in the area of fuzzy logic control throws some light on its application to large nonlinear systems. To date, such types of controllers have proven themselves successful in controlling small nonlinear plants. For large systems it still 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. Furthermore, fuzzy rules derivation, by principle, relies on the experience of a human expert; which sometimes limits the fuzzy logic controller to lower order systems.

The paper presents a fuzzy logic-based approach for the on-line tuning of control parameters for large systems like HVDC transmission links. A satisfactory accuracy of the parameter adaptation is obtained by referring the fuzzy subsets to the normalized values of the variables involved in the fuzzy logic.

An electromagnetic transient simulation program (EMTDC) [7] was used in the study. The program has the capability of detailed modeling of transmission lines for coupling effects as well as the capability to represent HVDC converters in full detail and to represent transformer saturation nonlinearities. It is important to properly model the dc controls because the overvoltages can be affected by the control response.

II. HVDC SYSTEM MODEL

Particularly in the last ten years, a wide variety of HVDC converter control strategies have been tested and optimized with the help of various digital simulation programs. In 1985, the great interest in HVDC system simulation led to the idea of establishing an HVDC benchmark model [8]. In the following years, a comparison of one physical simulator and four digital

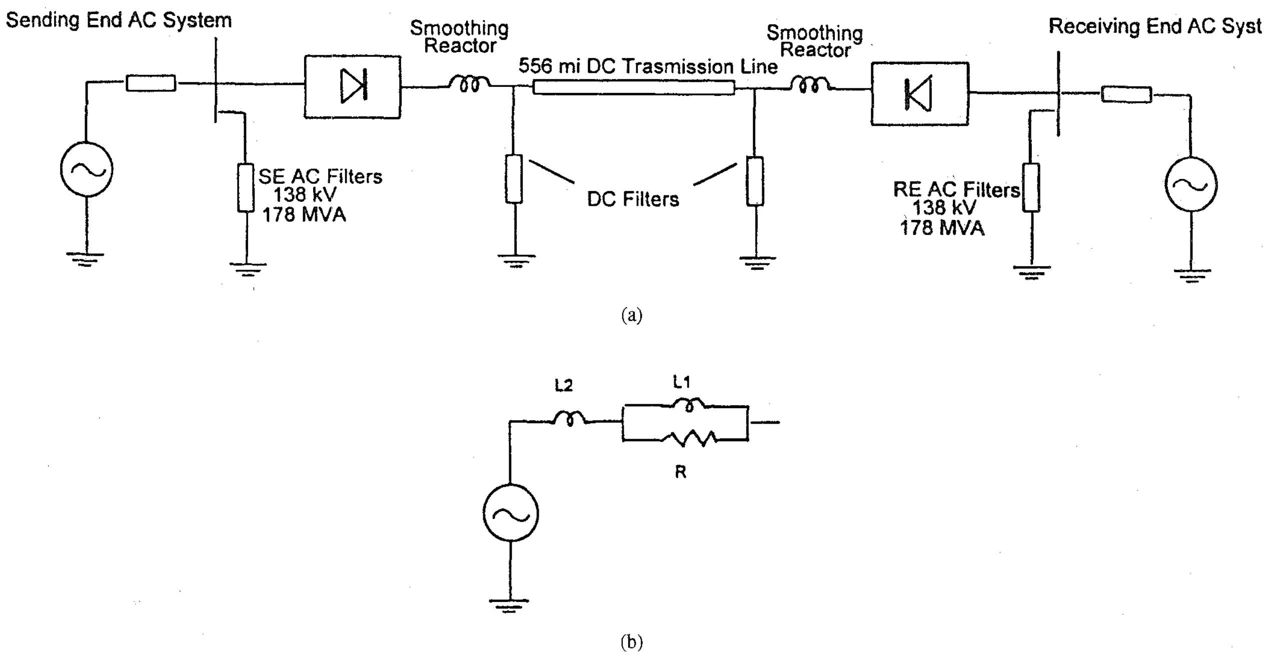


Fig. 1. (a) HVDC system model. (b) Details of ac system representation on either side.

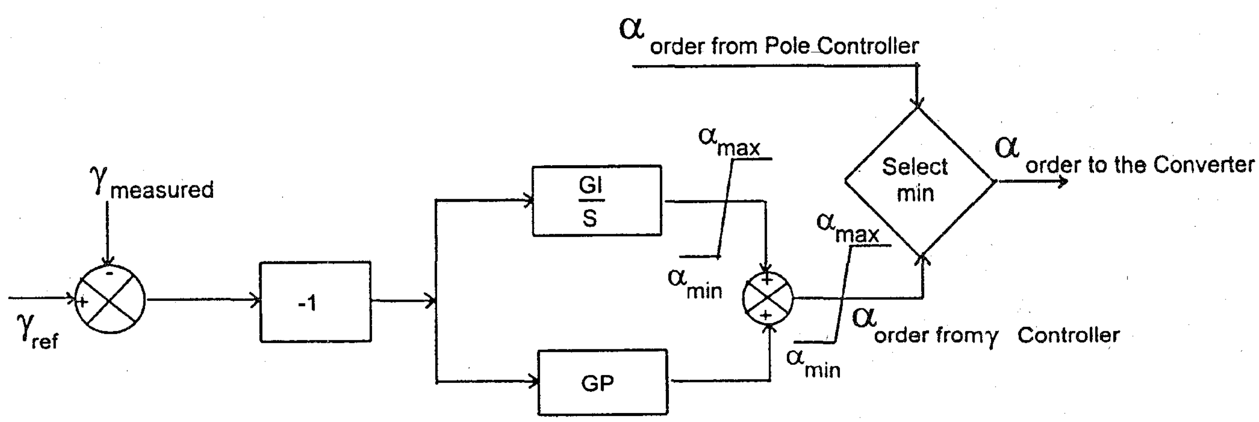


Fig. 2. Inverter gamma controller.

simulation models was carried out [9], [10]. Computed results from the various simulation programs all agreed quite well with the reference simulator results.

For HVDC control and system fault studies, a time-step of 50 μs is customarily chosen. This time-step is slightly more than 1° for a 60-Hz waveform and can result in the generation of noncharacteristic harmonics. This difficulty is eliminated if the thyristors switching are interpolated to within a fraction of a time-step. We, therefore, chose to use an electromagnetic transient program (EMTP)-type program capable of such interpolation as EMTDC.

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

Subsystem 1: The rectifier-side subsystem consists of a constant voltage and constant frequency source behind impedances that comprise inductances and resistances to represent a simplified ac system. The short circuit ratio (SCR) (shown in the Appendix) for the system is fairly high as compared to the inverter-side ac system. AC filters for fifth, seventh, eleventh, and thirteenth harmonics have been provided.

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

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

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 3.8.

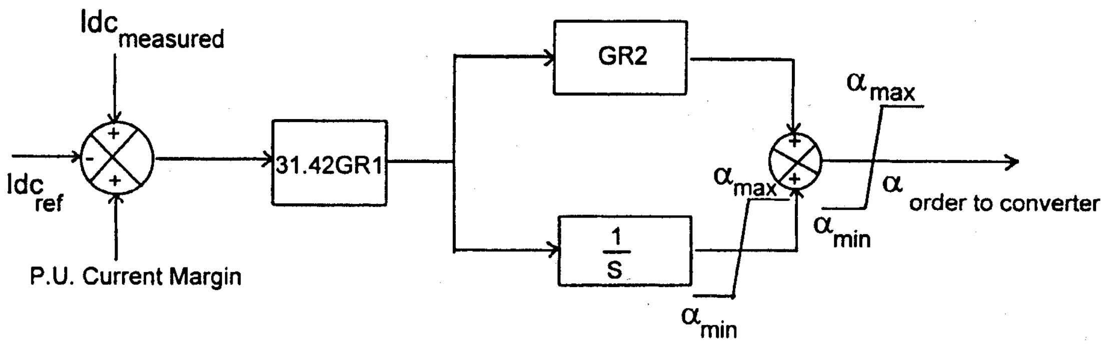


Fig. 3. Rectifier pole controller.

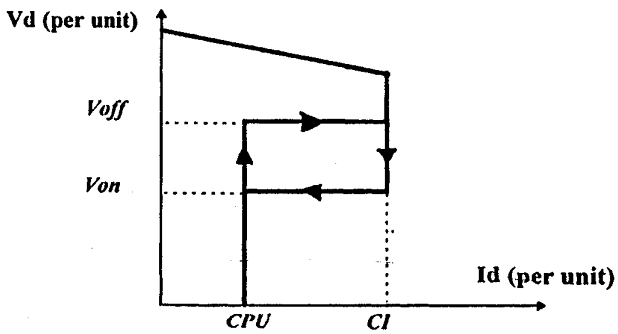


Fig. 4. Hysteresis-type VDCOL.

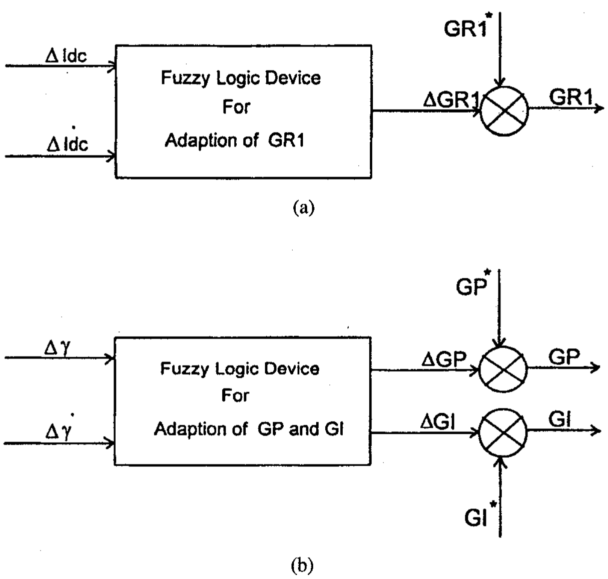


Fig. 5. (a) Fuzzy tuning for rectifier pole controller. (b) Fuzzy tuning for inverter gamma controller.

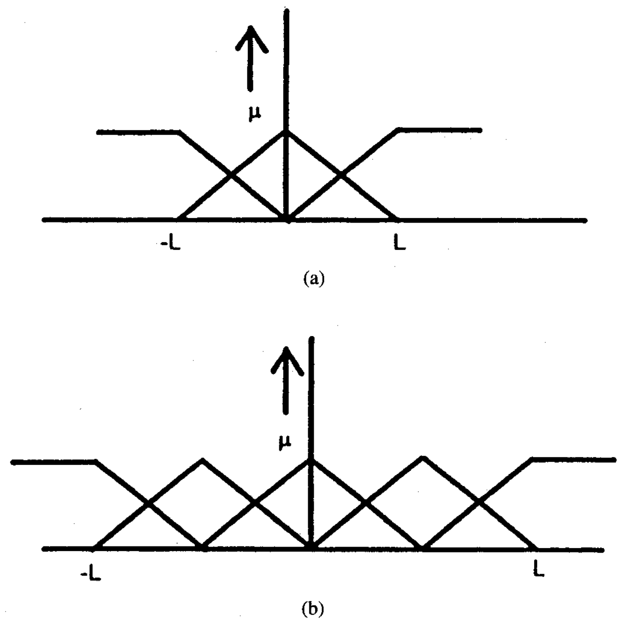


Fig. 6. Membership grades of (a) input (error and rate) and (b) output (change in gain) of the fuzzy tuner.

TABLE I
THE FUZZY SETS FOR INPUTS ARE: P-POSITIVE, N-NEGATIVE, Z-ZERO. THE FUZZY SETS FOR OUTPUT ARE: LP-LARGE POSITIVE, MP-MEDIUM POSITIVE, Z-ZERO, LN-LARGE NEGATIVE, AND MN-MEDIUM NEGATIVE

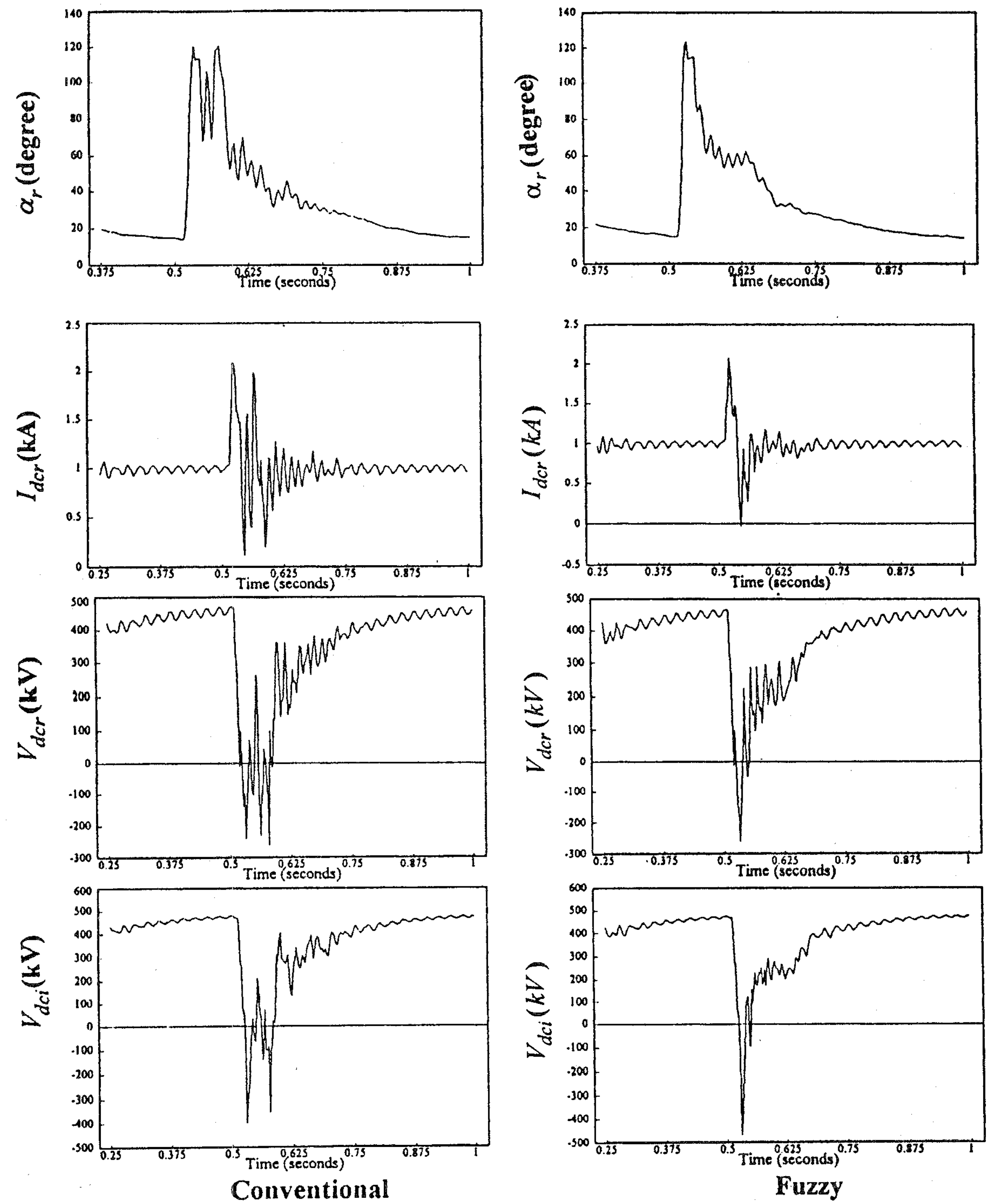
error→ rate↓	P	Z	N
P	LP	MP	MN
Z	MP	Z	MP
N	MN	MP	LP

A. Inverter Control System

The inverter is in constant extinction angle (CEA) control (Fig. 2). A pole controller, i.e., constant current controller, has also been provided for rectifier operation under transient and power reversal conditions. However, in steady state normal operating conditions it operates with CEA control (valve control).

B. Rectifier Control System

The dc link current is maintained constant by subjecting the rectifier with constant current control (pole control) as shown in 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 or CEA Controller) to operate it as an inverter during transient and power reversal situations.



(a)

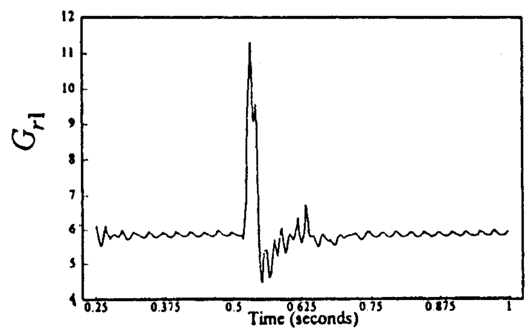
Fig. 7. Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (a) Waveforms for single line-to-ground fault at inverter ac bus.

C. VDCOL

A hysteresis-type voltage dependant current order limiter (VDCOL) as shown in Fig. 4 has been provided at the sending end of the dc system to reduce the current order under low ac bus voltage conditions. This is done to take care of the power reversal under small disturbances. This also takes care of the abnormally high current order when the rectifier is subjected to constant power control.

III. Design Implementation

The rectifier-side current regulator has been replaced by a fuzzy self-tuning controller as shown in Fig. 5(a). Here the gain *GR1* (which takes care of K_p and K_I both) is adjusted through fuzzy inference. The inverter-side gamma controller has also been tuned in the similar lines [Fig. 5(b)] but the signals used here are the extinction angle deviation and it's derivative after proper normalization and filtering.



(b)

Fig. 7. (*Continued.*) Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (b) Variation of Gr_1 due to fuzzy tuning.

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

$$\Delta I_{\rm dc} = I_{\rm dcrf} - I_{\rm dc} \tag{1}$$

$$\Delta \dot{I}_{\rm dc} = \frac{(\Delta I_{\rm dc} - \Delta I_{\rm dcp})}{\Delta T} \tag{2}$$

$$E = GE \cdot (\Delta I_{\rm dc}) \tag{3}$$

$$R = GR \cdot (\Delta \dot{I}_{\rm dc}) \tag{4}$$

where

$I_{\rm dcrf}$ reference current;
$I_{\rm dc}$ measured current;
ΔT sampling rate;
$\Delta I_{\rm dcp}$ previous value of error;
GR, GE gains for normalization.

The inputs E and R are fuzzified into three sets, i.e., P, Z, and N (Positive, Zero, Negative). The membership grades (Fig. 6) are taken as triangular and symmetrical. The fuzzy procedure to adapt GR_1 starts from it's nominal value GR_1^*, and assumes that their variation span is a limited range. The tuned value of the control parameter can be indicated as

$$GR_1 = GR_1^* + \Delta GR_1. \tag{5}$$

The value of ΔGR_1 is worked out in terms of

—its nominal value GR_1^*;
—the value of K_1 derived from the fuzzy logic device;
—coefficient C_R that fixes 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 ΔGR_1 is given by

$$\Delta GR_1 = K_1 \cdot GR_1^* \cdot C_R \quad \text{if } K_1 \geq 0 \tag{6}$$

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

The advantage of this adaptation scheme can be seen from the following equations. For this controller, the integral action is given by

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

Where as for the conventional controller, the integral action is given by

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

Equation (8) represents the variation of the integral gain with the plant operating conditions.

The fuzzy device output K_1 can be derived by different defuzzification methods. However, here a simple nonlinear defuzzification is used

$$K_1 = \frac{\sum \mu_i y_i}{\sum \mu_i} \tag{10}$$

where μ_i = membership grades of the ith output fuzzy set; y_i = numerical value of the output for which the membership grade for the ith fuzzy set is one. The output membership grades for different fuzzy sets are derived by Zadeh's AND, OR rules from the rule table.

For designing the rule base (Table I) for tuning both the rectifier and inverter controllers, the following important factors have been taken into account.

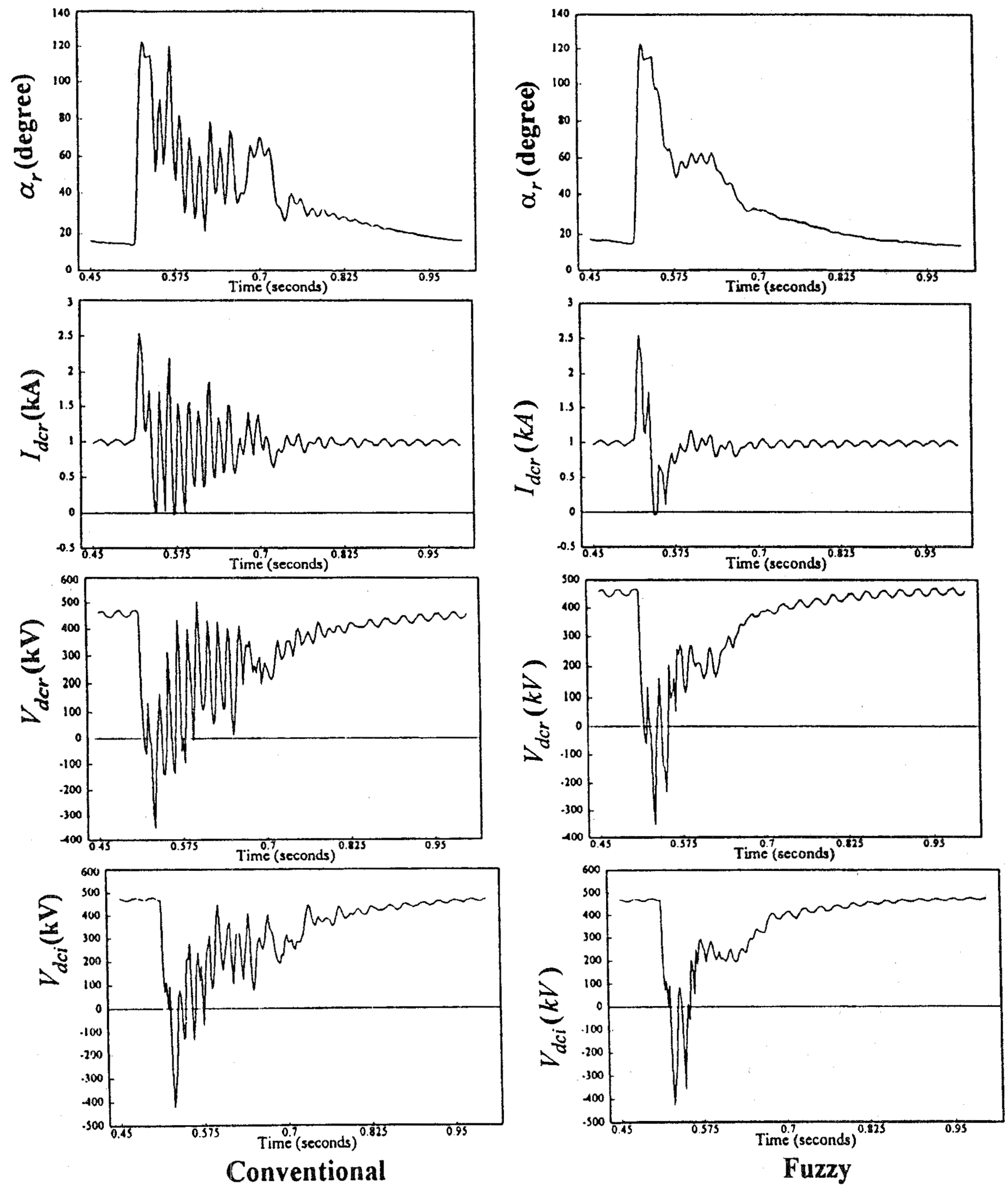
1) For large positive/negative values of the error and it's derivative (same sign) the system is diverging away from the equilibrium point. Therefore, a large control action is required which is accomplished by a positive increase in the controller gains.
2) When the error is positive and its derivative is negative and vice-versa, the system is converging toward the equilibrium point. Therefore, the controller action should be minimized to prevent the system from oscillating further. This is achieved by lowering the values of the controller gains.
3) For small/zero values of the error and its derivative, the system is assumed to be near the equilibrium point. Therefore, the controller should operate with the nominal values of the gains, which is manifested as zero increase/decrease in the gains in the rule table.

For the tuning of the gamma controller [Fig. 5(b)] the inverter extinction angle deviation and it's derivative have been taken. But here in this case, instead of tuning only one parameter unlike the rectifier pole controller, both the proportional and integral gains of the inverter gamma controller have been adjusted.

IV. Application of Self-Tuning Fuzzy PI Controller

As the EMTDC software package is expected to produce similar results as that of a physical HVDC simulator, both conventional and fuzzy control of power converters are tested using this package. The EMTDC based digital simulator produces the dc link current error from the discrete values of the dc link currents as shown in (2).

A filter can be used to abandon the high frequency components in the derivative signal. The dc current, which is obtained in Subsystem 2, is passed through a lag network to make it ripple free: After calculating the derivatives, the signals are normalized by premultiplying with two gains "GE" and "GR."



(a)

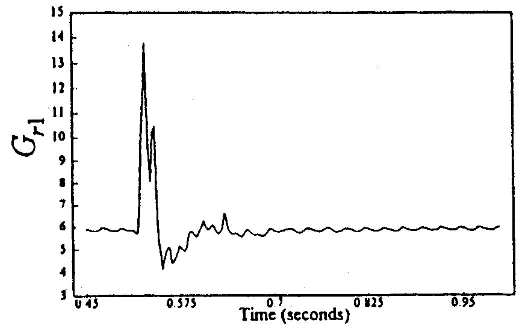
Fig. 8. Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (a) Waveforms for dc line-to-line fault at inverter.

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

$$\text{P.I.} = \int_0^t z^2(\Delta I_{\text{dc}}(z))dz \qquad (11)$$

has been minimized by the multiple run feature of EMTDC. Prior to it, the steady-state optimum values of the conventional fixed gain (GR_1, GR_2, GP, and GI all have fixed value) control parameters have been found out by the same procedure.

The following cases have been studied for the tuning of the rectifier-side pole controller. The relevant waveforms demonstrate the superiority of the proposed scheme. Waveforms for a particular case (i.e., inverter-side dc line-to-ground fault) have been also shown to compare the performance of the fuzzy tuner while operating at one end (only rectifier pole controller) and operating at both the ends (the inverter gamma controller



(b)

Fig. 8. (*Continued.*) Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (b) Variation of Gr_1 due to fuzzy tuning.

TABLE II
DATA FOR AC FILTERS AT RECTIFIER (177 MVA)

n	5th	7th	11th	13th
R(Ω)	2.0	3.0	2.0	2.0
L(H)	0.0614	0.0614	0.0152	0.0152
C(μF)	4.58	2.337	3.84	2.749

TABLE III
DATA FOR AC FILTERS AT INVERTER (177 MVA)

n	5th	7th	11th	13th
R(Ω)	8.0	8.0	3.0	3.0
L(H)	0.168	0.168	0.0444	0.0444
C(μF)	1.67	0.852	1.310	0.938

and rectifier pole controller). As anticipated, tuning both sides gives better result in terms of settling time, peak overshoot, and commutation failures.

A. Single Line-to-Ground Fault at Inverter

The waveforms resulting from a 2.5-cycles 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 urrent waveform in case of a conventional controller has a lot of crests and dents and suffers from prolonged oscillations, whereas, in case of a fuzzy logic controller, the dc current fast returns to its nominal value. 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. In case of a fuzzy logic controller, the power reversal is only momentary.

B. DC Line-to-Line Fault at the Inverter

Fig. 8 shows the waveforms after a 2.5-cycle dc line-to-line fault at inverter. Several oscillations have been observed in dc link current, voltage, and power in case of a conventional controller. From the inverter dc voltage plots it is clear that the inverter valves undergo commutation failure several times as compared with the fuzzy controller.

C. Single Line-to-Ground Fault at Rectifier

A 2.5-cycle single line-to-ground fault has been created on the rectifier ac bus. The relevant waveforms are shown in Fig. 10. The oscillations in dc current are as such low. Since the ac system is strong enough, the waveforms are least affected by the controller actions. The VDCOL comes into play as soon as the rectifier dc voltage falls below 0.7 pu, thereby reducing the current order. That is why there are two steps in the dc current; one for the low dc voltage during fault and other after the recovery.

The change in the dc power level is within ±50%. There is no power reversal. The change in gain GR_1 for the proposed controller has been shown in Fig. 10.

D. DC Line-to-Line Fault at Rectifier

A dc line-to-line fault has been created at the rectifier dc bus after the inductor for about 2.5 cycles. This is in a way similar to a three-phase fault on the ac bus as the net power flow becomes zero. VDCOL comes into play as soon as $V_{\rm dcr}$ drops below a certain level. Similar to the 1-ϕ single-phase fault the voltage and current waveforms are not much affected by the controller actions due to the fact that the rectifier-side ac system is strong enough to recover from any kind of fault as soon as the latter is removed. There is no power reversal. However, during the fault, momentarily the dc power flow becomes zero followed by oscillations. The relevant waveforms are shown in Fig. 11.

E. Step Change in the Current Order

The rectifier current order has been increased by 40%. The overshoot in case of the fuzzy controller is slightly less than that of conventional controller. The resulting current waveform is shown in Fig. 12.

F. Tuning Both Sides

A five-cycle dc line-to-ground fault has been created at the inverter while tuning both the pole controller as well as gamma controller. The current and voltage waveforms shown in Fig. 9 display the superiority of this scheme. The recovery is much faster in this case. The peak overshoots and frequent commutation failures have also been minimized.

V. DISCUSSIONS

From the above simulation results, the following can be concluded.

1) The rectifier-side ac system being strong, it recovers very fast after any disturbances, overriding the effect of any controller. Therefore, for any fault on the rectifier ac or dc bus, not much difference is observed in the current and voltage waveforms for either type of controller actions.

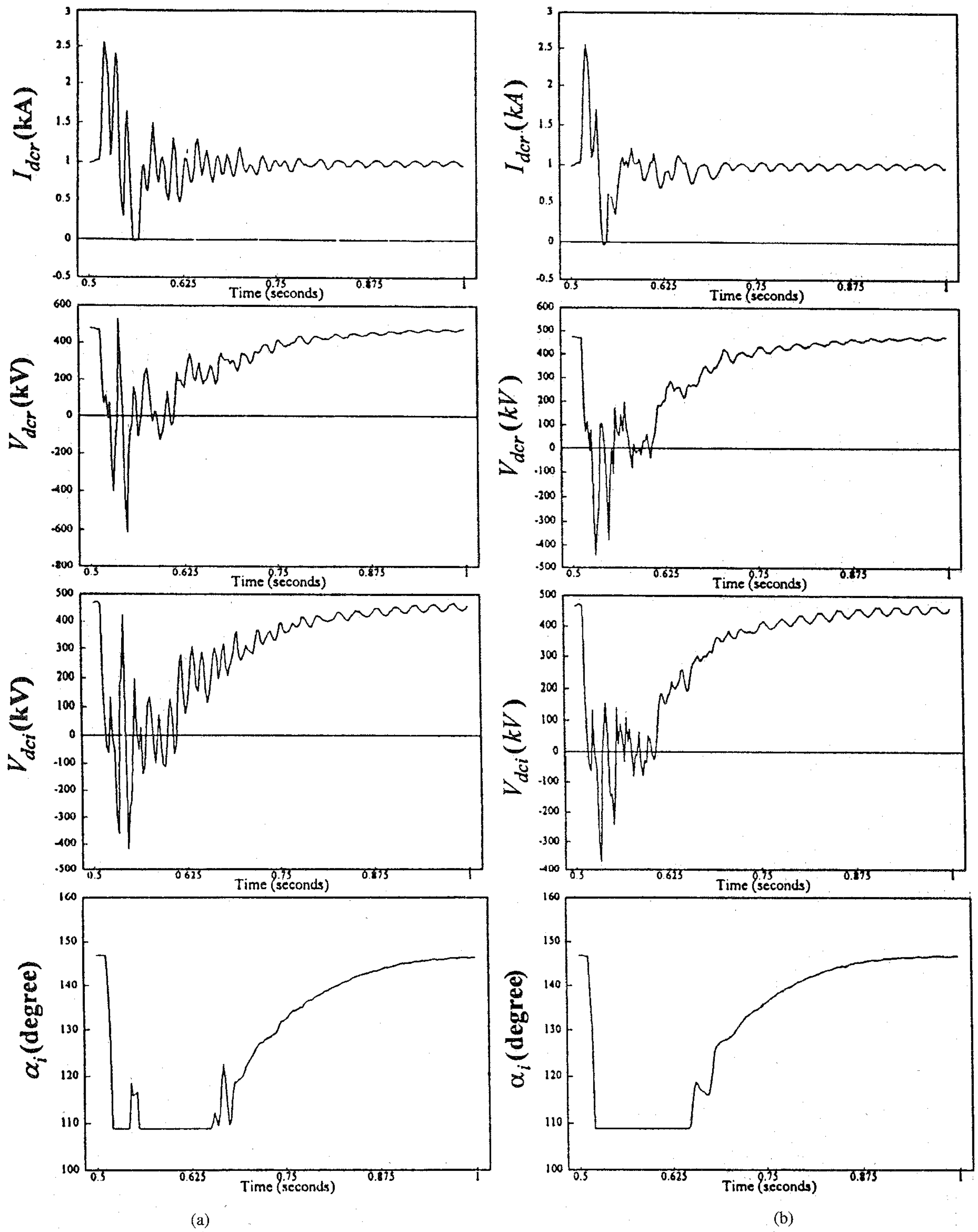
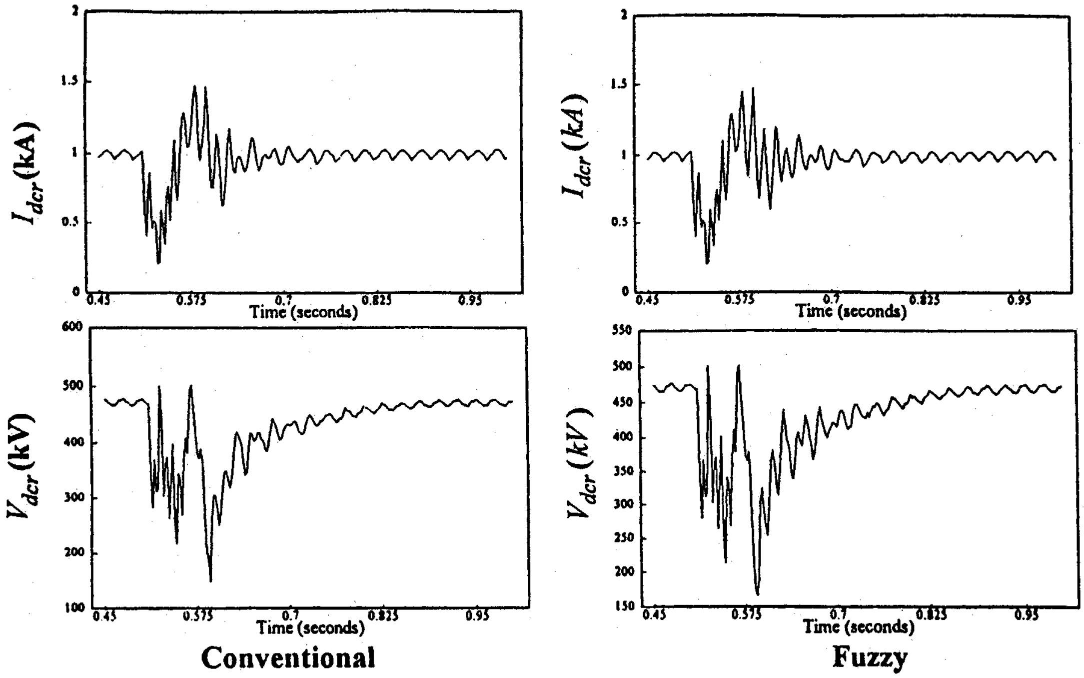


Fig. 9. Performance comparison of tuning (a) one side and (b) tuning both sides by fuzzy rule base. Waveforms for dc line-to-line fault at inverter.

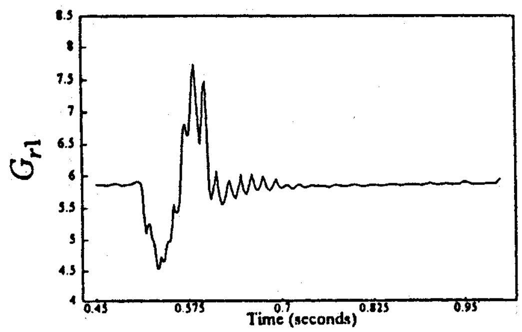
2) For the faults in the inverter side, the proposed controller makes the system recover much faster than the conventional PI controller does. The commutation failures, power oscillations, and high di/dt which are detrimental to the converter operation have been minimized in case of the fuzzy controller.
3) For small disturbances, the proposed controller may not be much better than the conventional fixed gain one as it is for large disturbances.
4) Tuning both sides gives better results as anticipated.

VI. 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



(a)



(b)

Fig. 10. Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (a) Waveforms for single line-to-ground fault at rectifier ac bus. (b) Variation of Gr_1 due to fuzzy tuning.

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 fixed gain controllers.

APPENDIX

Data for the system model are provided below.

A. Rectifier End

Data for the ac filters at the rectifier end (200 kV) are shown in Table II. The rectifier-end ac system consists of a constant voltage and constant frequency source behind an L-LR [Fig. 1(b)] network which represents the equivalent Thevenin impedance of the ac network. The impedance network consists of

$$R = 1.267\ \Omega, \quad L_1 = 0.002\,735\ \text{H}, \quad L_2 = 0.007\,67\ \text{H}.$$

B. Inverter End

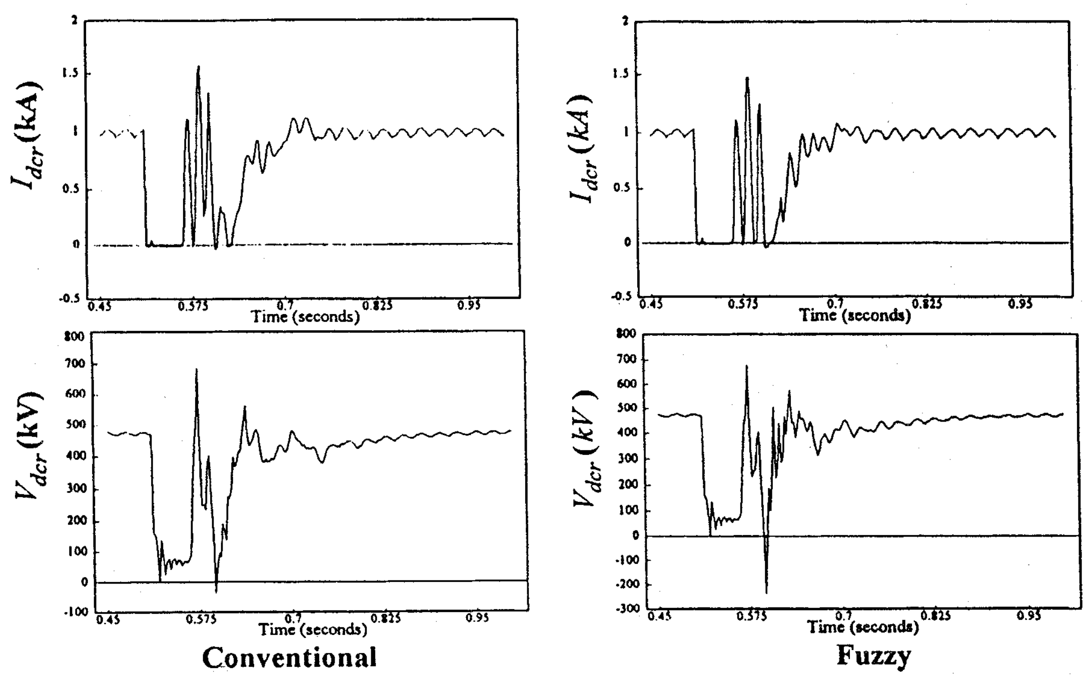
The data for the ac filters at the inverter end (340 kV) are shown in Table III. The inverter-end ac system consists of a constant voltage, constant frequency source behind an L-LR [Fig 1(b)] network. The impedance network consists of

$$R = 14.2\ \Omega, \quad L_1 = 0.0277\ \text{H}, \quad L_2 = 0.0443\ \text{H}.$$

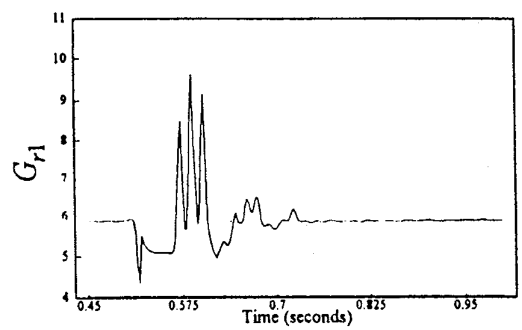
C. DC Subsystems

Both the inverter- and rectifier-side subsystems are identical. Each consists of a large inductor in series between the converter and dc transmission line. A dc filter has been connected in parallel to take care of dc voltage harmonics.

Smoothing inductor: $L_d = 0.75$ H,
Filter data: $R = 12.0\ \Omega$, $L = 0.1222$ H, $C = 0.4\ \mu$F (for 12th harmonic).



(a)



(b)

Fig. 11. Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller). (a) Waveforms for dc line-to-line fault at rectifier. (b) Variation of Gr_1 due to fuzzy tuning.

D. DC Transmission Line

A 556-mile long transmission line connects the rectifier and inverter dc subsystems. The following data pertains to the details of the line:

Steadystate lower frequency = 5 Hz;

High frequency transient = 90 Hz;

Mode traveling time = 3.037 ms;

Characteristic impedance = 300 Ω;

Mode resistance per unit length at the lower frequency = 0.025 Ω;

Mode resistance per unit length at the higher frequency = 0.03 Ω.

E. Pole Controller

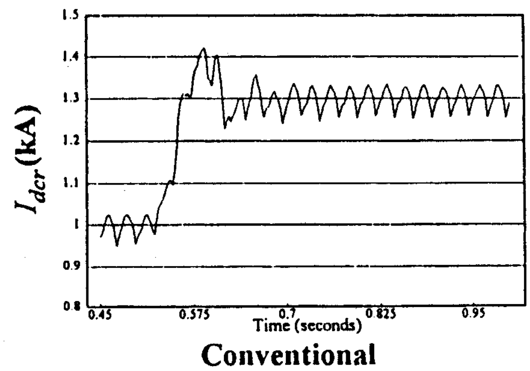
For the conventional pole fixed gain controller on the either side:

$$GR_1 = 5.88, \; GR_2 = 0.0136$$

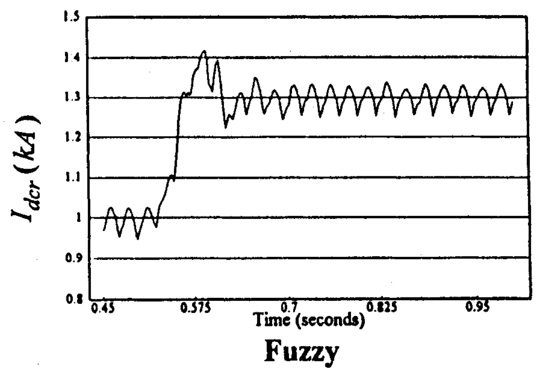
$$\text{SCR} = \frac{\text{Short Circuit Level (MVA) of the ac system at the Converter Bus}}{\text{Rated dc Power (MW)}}$$

$\text{SCR}_{\text{rectifier}} = 14.41$ at a power factor of 0.58

$\text{SCR}_{\text{inverter}} = 3.84$ at a power factor of 0.43.



(a)



(b)

Fig. 12. Performance comparison of conventional and fuzzy controller (tuning the rectifier pole controller—40% step change in rectifier current order).

Rectifier pole controller: $\alpha_{\min} = 5°$, $\alpha_{\max} = 155°$;
Inverter pole controller: $\alpha_{\min} = 108°, \alpha_{\max} = 178°$;
(operates during transient conditions)
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 two in this case.

F. Valve Controller

For the conventional PI type gamma controller on the either side:

$GP = 0.27, GI = 15.0$ (rectifier gamma controller operates during transient conditions). For the inverter-side fuzzy-tuned gamma controller, normalized input values of the inverter extinction angle and its derivative have been used. The value of C_r is also two in this case.

G. Short Circuit Ratio

The short circuit ratio (SCR) is defined as the equations shown at the bottom of the previous page.

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