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Power Transfer Capability Improvement to HVDC Transmission System using Artificial Neural Network and Inference System (ANFIS) Controller

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Abstract–High Voltage Direct Current (HVDC) Transmission systems traditionally employ PI controllers with fixed proportional (P) and integral (I) gains K_p and K_i respectively. Although such controllers are robust and simple, they are not easily optimized to obtain the best performance under all conditions. In the field of intelligent control systems, fuzzy logic control and artificial neural network based control are the two most popular control methodologies being used. Neuro-fuzzy systems, as the name suggests combine ANNs and fuzzy logic into one system. The aim of such a combination is to inherit advantages of both the intelligent control techniques and shunt out their individual disadvantages. The CIGRÉ model as one of the conventional methods has been studied and new complementary characteristics have been added to improve its stability and damping rate of voltage and current oscillations during the disturbance in the AC Systems and to increase the efficiency of the proposed model.

Keywords–HVDC transmission, CIGRÉ Benchmark model, faults in HVDC system, proportional integral (PI) Controller, ANFIS controller.

I. INTRODUCTION

High Voltage Direct Current (HVDC) Transmission is the preferred method for bulk Transmission of power over long distances [1]. HVDC System is a mature Technology [2], starting from mercury-arc to thyristors and presently to IGBT and IGCT valves, from conventional PI Controllers to more advanced Control Techniques. Further work needs to be done particularly on the Control aspects to further improve the Transmission performance and efficiency of such Systems. The performance of these systems depends on the control method being used. Furthermore, the control of a HVDC System remains a formidable challenge because of various factors such as changes in system conditions, converter Transformer saturation characteristics, presence of AC/DC filters, and the generation of harmonics by converter units which makes the HVDC System highly complex and non-linear [3]. Since fuzzy logic uses intuitive rules for the control of the system, a detailed system model is not required. This makes Fuzzy Logic well-suited for use with complex and nonlinear systems, such as HVDC Systems. Earlier research on the use of Fuzzy Logic to tune the PI Controller parameters employed constant triangular Membership functions [4]–[7]. The past work generally concluded that fuzzy logic could improve the performance of HVDC systems under various fault conditions or operating point changes, by decreasing the number of commutation failures, improving the commutation margin, or dampening oscillations.

The use of properly-designed neuro-fuzzy logic controllers has been widely shown to provide at least marginal improvement in the operation of HVDC systems compared to the use of conventional constant-parameter PI controllers [4]–[9]. This is explained by the fact that the tuning of constant-parameter PI controllers is a compromise between the speed of response and stability after small disturbances, and the robustness to tolerate large signal disturbances due to faults.

II. HVDC TEST SYSTEM

The CIGRE benchmark HVDC system model [10], used here as the test system, has been designed for conducting performance comparisons between different HVDC system control strategies. The system is shown in Fig. 1.

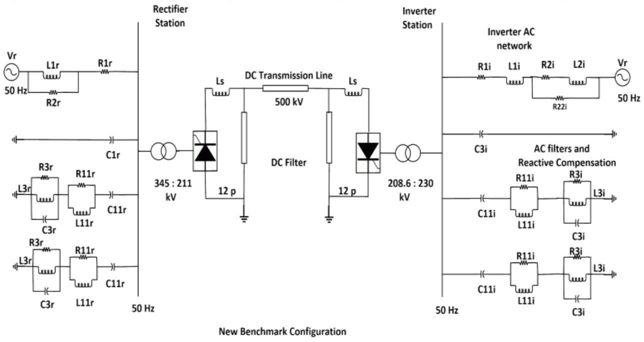

Fig. 1: Single-line diagram of the CIGRÉ benchmark HVDC system.

The short circuit ratios (SCRs) and Effective Short Circuit Ratios (ESCRs) for the CIGRE model are:

$$SCR = \frac{Short\ Circuit\ MVA\ of\ \mathrm{AC}\ System}{\mathrm{DC}\ Converter\ MW\ Rating}$$

(i) Rectifier: $SCR = 2.5\angle 84^o$

(ii) Inverter: $SCR = 2.5\angle 75^o$

These short circuit ratios characterize a weak system, and it is well-known that an HVDC System converter feeding into a weak AC System is prone to commutation failures. There is also a DC side resonance at near fundamental frequency and an AC-side resonance near the second harmonic frequency. Overall, the system has been specifically designed to be particularly onerous for DC control operation, and thus, it is a good choice for the test system in HVDC system control studies [8]. The control system must control a quantity such as the DC current or

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transmitted power, ensure stable operation in the presence of small system disturbances, and minimize the consequences of large disturbances or faults. To obtain these objectives while consuming minimum reactive power, the firing angles must be minimized [11]. The rectifier operates under constant current (CC) control to control the DC current and the inverter usually operates under constant extinction angle (CEA) control to regulate the DC voltage. For nominal conditions, the CEA control ensures the extinction angle stays at its nominal value of 150, resulting in small reactive power consumption while providing ample commutation margin to prevent commutation failures. In a two terminal HVDC System, the current margin control method is normally utilized whereby the rectifier is kept in current control (CC) and the inverter is in constant extinction angle (CEA) control. An error signal, I_e, which is the difference between the reference current, I_d, and the measured current, Id, from the system, is fed to the PI-controller. The error output of the controller is acted upon by the PI gains to provide the required alpha order for the HVDC converter. Due to uncertainties in system parameters, the optimal choice of gains is quite difficult. Proportional Integral (PI) controllers are commonly used in HVDC System in addition to AI controllers. A mathematical model of the real plant is required for the controller design with conventional methods. The difficulty of identifying the accurate parameters for a complex nonlinear and time-varying nature of real plants may render, in many cases, the fine tuning of parameters which is time consuming. Fig. 2 shows the structure of PI controller.

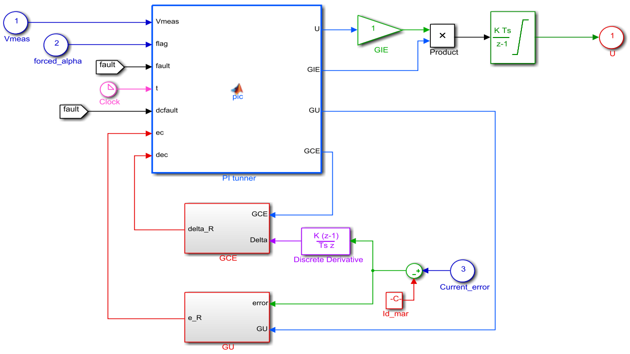

Fig. 2: Structure of PI controller.

III. ARTIFICIAL NEURAL NETWORK AND INFERENCE SYSTEM CONTROLLER (ANFIS)

Previously, control techniques assumed a fixed mathematical model of the plant but since HVDC systems are highly uncertain, obtaining an accurate mathematical model of the plant is not possible. Consequently, a lot of research is being conducted in the application of intelligent control techniques such as fuzzy logic, neural networks and genetic algorithms to the control of HVDC systems. Fuzzy logic (FL) based controllers have been successful in improving the performance of the HVDC system [11] ,However a combination of fuzzy logic and artificial neural networks (ANNs) were used. Artificial Neural Network and Inference System (ANFIS) is developed from sugeno-type fuzzy inference system (FIS) for effective data processing. The development is a simple data learning technique by using configuration of neuro-fuzzy model with hybrid learning rule. FIS processes a given input mapping to get a target output. This process involves membership function, fuzzy logic operators and if-then rules. It has multiple inputs and a single output with the capability in handling highly non-linear functions and predicting future value of a chaotic time series. Compared to the capabilities of the approaches such as cascaded-correlation ANN, back propagation ANN, sixth-order polynomial and other earlier methods, the result obtained from the ANFIS gives a better performance in non-dimensional error index [10]. Every stage of ANFIS shown in Fig. 3 has a particular function which is used to calculate input and output parameter sets as described below [10].

Stage 1: In the process of input fuzzification, the following equations are utilized:

$$X_i(x) = 1/[1+((x-c_i)/a_i)^\wedge 2]^\wedge(b_i) \qquad i = 1,2 \qquad (1)$$

$$Y_i(x) = 1/[1+((y-c_i)/a_i)^\wedge 2]^\wedge(b_i) \qquad i = 1,2 \qquad (2)$$

where Xi and Yi are fuzzified input values, whereas a_i, b_i and c_i are the parameter sets from the Gaussian input membership function.

Stage 2: Application of fuzzy operators involves the use of the product (AND) to the fuzzified input. (3) to (6) represent the fuzzy relations obtained from the product of fuzzy operators.

$$R1 = X1(x) \times Y1(y) \qquad (3)$$

$$R2 = X1(x) \times Y2(y) \qquad (4)$$

$$R3 = X2(x) \times Y1(y) \qquad (5)$$

$$R4 = X2(x) \times Y2(y) \qquad (6)$$

Stage 3: In the application method of rules, the activation degree and normalization is implemented by using the following equations:

$$G_i = R_i / RT \qquad i = 1,2,3,4 \qquad (7)$$

where

$$RT = R1 + R2 + R3 + R4 \qquad (8)$$

Stage 4: Aggregation of all outputs are obtained by using (9) which is the product of the normalized activation degree and individual output membership function,

$$O_i = G_i(pi \cdot x + gi \cdot y + ri) \qquad i = 1,2,3,4 \qquad (9)$$

where pi, qi and ri are the parameters from the output membership function.

Stage 5: The required results are obtained through defuzzification process and it utilizes the following equation:

$$OT = \sum Oi \qquad i = 1,2,3,4 \qquad (10)$$

With the advent of artificial intelligent techniques, these drawbacks can be mitigated. One such technique is the use of fuzzy logic in the design of controller either independently or in hybrid with PI controller. ANFIS replaces the draw-backs of fuzzy logic control and artificial neural network. ANFIS combines the learning power of neural network with knowledge representation of fuzzy logic. ANFIS techniques have emerged from the fusion of Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS) and have become popular for solving the real world problems [9]. Fig. 4 shows the overall structure of Artificial Neural Network and

Inference System model. Fig. 5 shows HVDC System with ANFIS Controller.

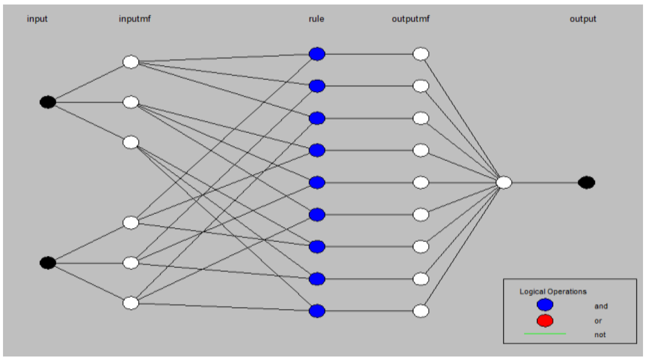

Fig. 3: Basic ANFIS structure.

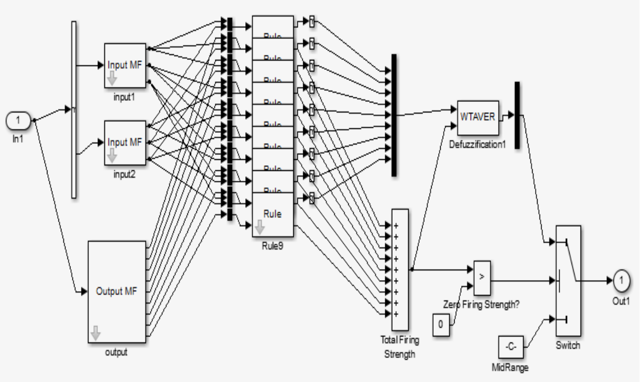

Fig. 4: Artificial Neural Network and Inference System model.

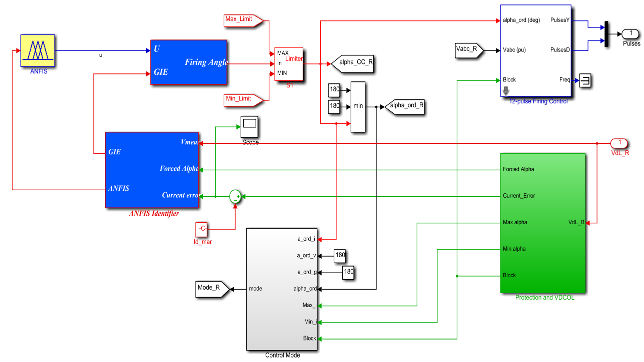

Fig. 5: HVDC system with ANFIS controller.

IV. COMPARISON ON PERFORMANCE ASSESSMENT OF ANFIS CONTROLLER BASED HVDC TRANSMISSION SYSTEM

The rectifier and the inverter are 12-pulse converters using two universal bridge blocks connected in series. The converters are interconnected through a 850 km line and 0.597H smoothing reactors as shown in Fig. 6 the converter transformers (Wye grounded/Wye/Delta) are modeled with three-phase transformer (Three-Winding) blocks.

The HVDC Transmission link uses 12-pulse thyristor converters. Two sets of 6-pulse converters are needed for the implementation stage. The firing-angle control system is configured based on two 6-pulse converters in series, one of which is operated as a modified HVDC bridge. Here, MATLAB/SIMULINK program is used as the simulation tool. Two 6-pulse Graetz bridges are connected in series to form a 12-pulse converter. The two 6-pulse bridges are 345kV, 50 Hz totally identical except there is an in phase shift of 58.4 ° for the AC supply Voltages. Some of the harmonic effects are cancelled out with the presence of 60 ° phase shift. The harmonic reduction can be done with the help of filters. The firing angles are always maintained at almost constant or as low as possible so that the voltage control can be carried out. The control of power can be achieved by two ways i.e., by controlling the current or by controlling the Voltage. It is crucial to maintain the voltage in the DC link constant and only adjust the current to minimize the power loss. The rectifier station is responsible for current control and inverter is used to regulate the DC Voltage. Firing angle at rectifier station and extinction angle at inverter station are varied to examine the system performance and the characteristics of the HVDC System.

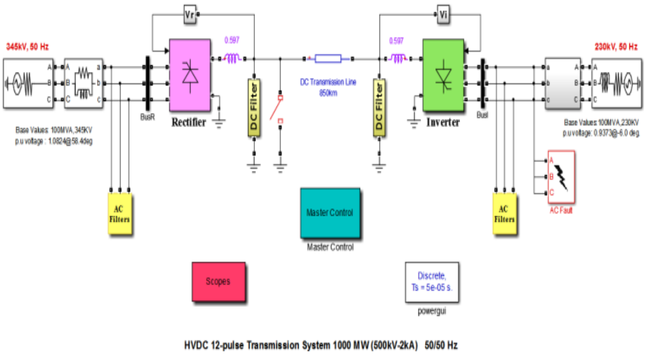

Fig. 6: Simulink diagram of the HVDC Circuit.

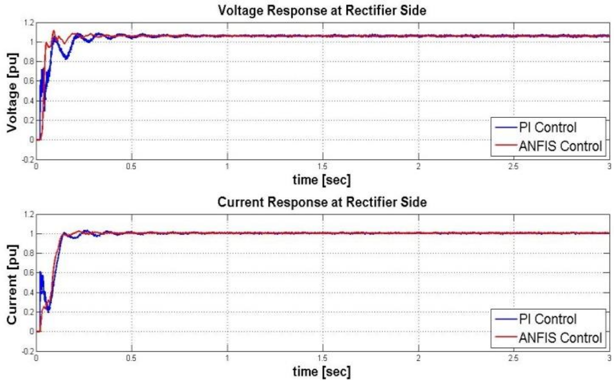

Fig. 7: Voltage and current on the DC side at rectifier (without fault).

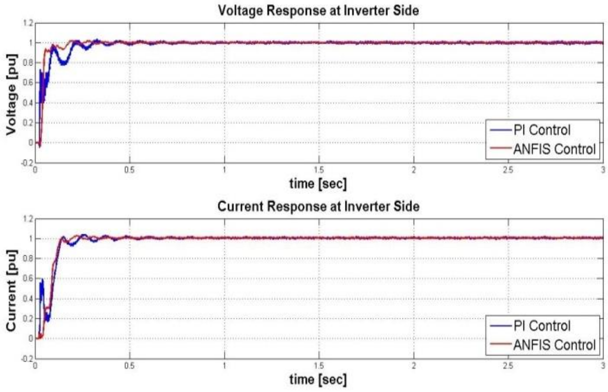

Fig. 8: Voltage and current on the DC side at inverter (without fault).

Fig. 7 and Fig. 8 show the system with no fault in voltage and current waveforms at rectifier and inverter sides using PI and the Artificial Neural Network and Inference System (ANFIS). From the simulation results it is observed that voltage and current reaches the reference value of 1.0Pu at

0.25 second, *i.e.* about 0.1 seconds later after starting HVDC System. It is clear that for no fault, both the controllers perform well but ANFIS gives a better transient performance and quite a low overshoot as compared to the conventional PI controller. The complete HVDC system reaches stable state after 0.25sec.

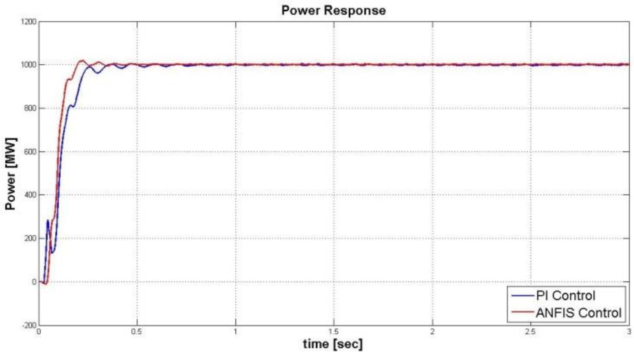

Fig. 9: Active power at rectifier.

Fig.9 shows the change process of the active power of HVDC system without fault with PI controller and the Artificial Neural Network and Inference System (ANFIS). It is clear that for no fault, both the controllers perform well but ANFIS gives a better transient performance and quite a low overshoot as compared to the conventional PI controller.

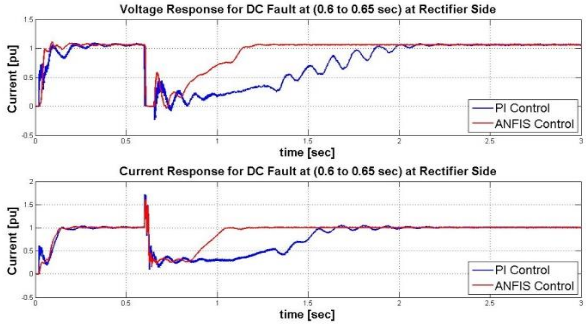

Fig. 10: When DC fault occurs on rectifier

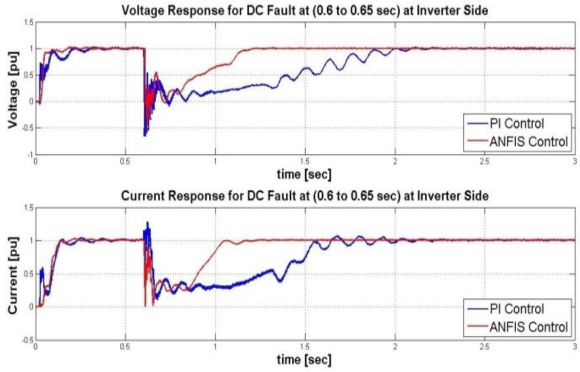

Fig. 11: When DC fault occurs on inverter

In Fig. 10 and Fig. 11, it is observed that DC fault occurs at time 0.6 sec. the fault is created for duration of 0.05 sec. at Rectifier and inverter side of HVDC System. The Artificial Neural Network and Inference System (ANFIS) activates and clears the fault. Fig. 10 and Fig. 11 show the waveforms after 0.6sec. DC fault at the rectifier and inverter. A large number of oscillations have been observed in DC link current and voltage magnitudes in case of a conventional controller. ANFIS reduces the recovery time by 1.2 sec after the disturbance. Once the fault is cleared, at t=1.2 sec the system comes back to its normal operation.

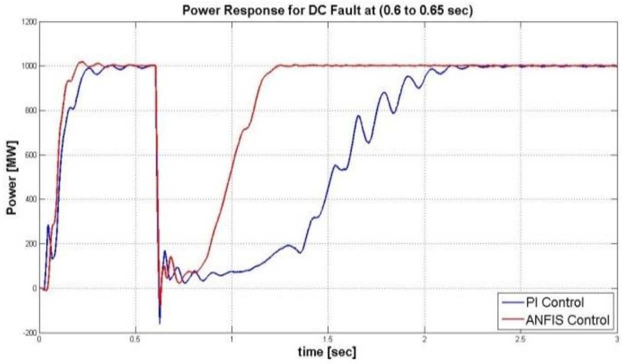

Fig. 12: Active power when DC fault occurs

Fig. 12 shows the change process of the active power of HVDC System after a disturbance of a DC fault with PI controller and Artificial Neural Network and Inference System (ANFIS). It is clear that for DC fault, both the controllers perform well but ANFIS gives a better transient performance and quite a low overshoot as compared to the conventional PI controller.

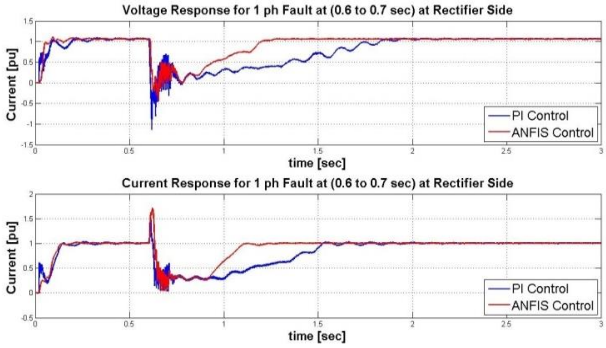

Fig. 13: When a line-to-ground fault occurs on rectifier side

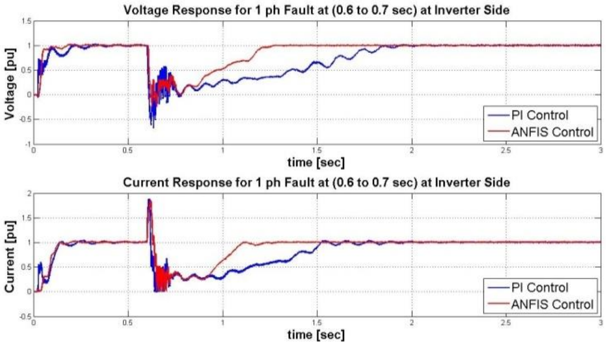

Fig. 14: When a line-to-ground fault occurs on inverter side

In Fig. 13 and Fig. 14, it is observed that a line-to-ground fault occurs at time 0.6 sec. the fault is created for duration of 0.1 sec. on phase A of the rectifier and inverter sides of HVDC System. Artificial Neural Network and Inference System (ANFIS) activates and clears the fault. ANFIS) performs better than the fixed-gain PI controller. The rectifier side DC current suffers from prolonged oscillations and consequently more commutation failures occur in the case of fixed-gain PI controller. The fixed-gain PI controller takes longer time to recover after fault is cleared due to the narrow range of optimum controller gain parameters. ANFIS reduces the recovery time by 1.2

sec after the disturbance. Once the fault is cleared, at t=1.2 sec the system comes back to its normal operation.

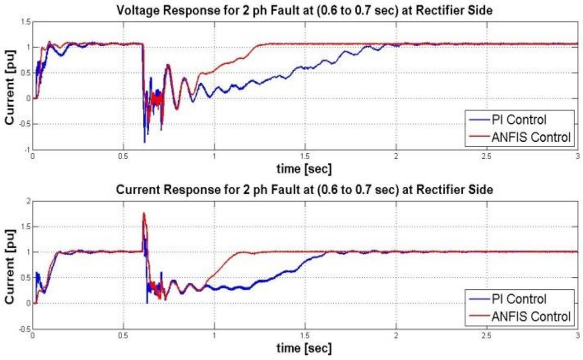

Fig. 15: When a two-phase fault occurs on rectifier side.

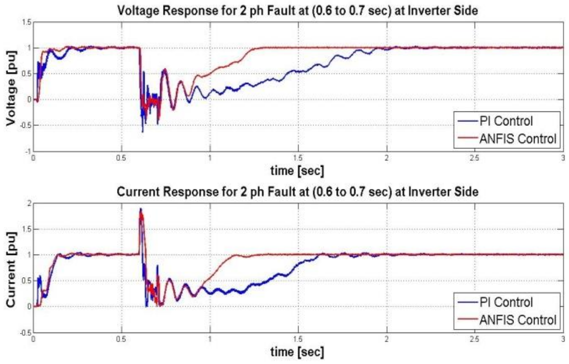

Fig. 16: When a two-phase fault occurs on inverter side.

In Fig. 15 and Fig. 16, it is observed that a two-phase fault occurs at time 0.6 sec. the fault is created for a duration of 0.1 sec. on phase A and phase B of the rectifier and inverter sides of HVDC System. Artificial Neural Network and Inference System (ANFIS) activates and clears the fault. The ANFIS performs better than the fixed-gain PI controller. The rectifier side DC current suffers from prolonged oscillations and consequently more commutation failures occur in the case of fixed-gain PI controller. The fixed-gain PI controller takes longer time to recover after fault is cleared due to the narrow range of optimum controller gain parameters. ANFIS reduces the recovery time by 1.2 sec after the disturbance. Once the fault is cleared, at t=1.2 sec the system comes back to its normal operation.

In Fig. 17 and Fig. 18, it is observed that a three-phase fault occurs at time 0.6 sec. the fault is created for a duration of 0.1 sec. on phase A and phase B of the rectifier and Inverter sides of HVDC System. Artificial Neural Network and Inference System (ANFIS) activates and clears the fault. The ANFIS performs better than the fixed-gain PI controller. The rectifier side DC current suffers from prolonged oscillations and consequently more commutation failures occur in the case of fixed-gain PI controller. The fixed-gain PI controller takes longer time to recover after fault is cleared due to the narrow range of optimum controller gain parameters. ANFIS reduces the recovery time by 1.2 sec after the disturbance. Once the fault is cleared, at t=1.2 sec the system comes back to its normal operation.

Figs.19, 20 and 21 show the change process of the active power of HVDC system after a line-to-ground fault, two-phase fault and three-phase fault are occurred with PI controller and the Artificial Neural Network and Inference System (ANFIS). It is clear that for a line-to-ground fault, two-phase fault and three-phase fault, both the controllers perform well but ANFIS gives a better transient performance and quite a low overshoot as compared to the conventional PI controller.

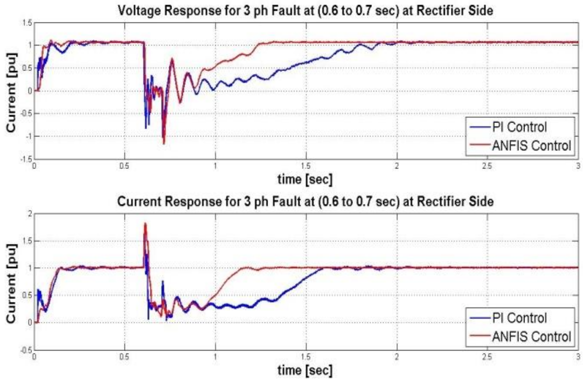

Fig. 17: When a three-phase fault occurs on rectifier side.

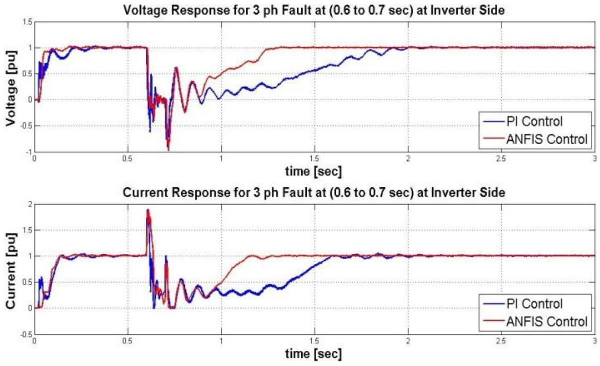

Fig. 18: When a three-phase fault occurs on Inverter side.

Fig. 19: Active power when a line-to-ground fault occurs.

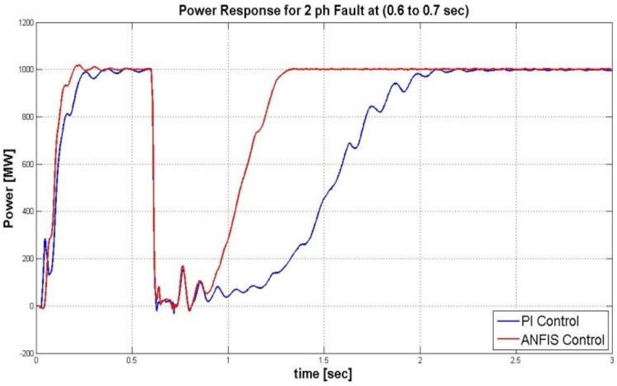

Fig. 20: Active power when a two-phase fault occurs.

Fig. 21: Active power when a three-phase fault occurs.

V. CONCLUSION

In this paper, fuzzy logic and neural networks are combined together to propose ANFIS Controller for a HVDC System. The controller uses feed forward neural network architecture. Simulation results clearly show the successful implementation of the adaptive neuro-fuzzy controller (ANFIS) in MATLAB/SIMULINK program simulation package. Following observations can be made from the results; adaptive neuro-fuzzy controller (ANFIS) efficiently updates the rule base with changing system conditions and uses feed forward neural network architecture which has a better performance than conventional PI controller. This work shows the potential ANFIS controller scheme for a HVDC System. And d it is found that ANFIS provide a more intelligent solution to the control of HVDC systems as compared to the conventional PI controller.

APPENDIX A

Following are the parameters of the HVDC System chosen for the simulation studies:

CIGRE HVDC Benchmark System Data

Parameters	**Rectifier**	**Inverter**
AC voltage base	345kV	230kV
Base MVA	100MVA	100MVA
Transf. tap (HV side)	1.01pu	0.989pu
Voltage source	$1.088\angle 22.18^{o}$	$0.935\angle -23.14^{o}$
Nominal DC voltage	500kV	500kV
Nominal DC current	2kA	2kA

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