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ANFIS-based Controller Application to Regulate Firing Angle of Inverter in Average Value Model-High Voltage Direct Current Transmission System

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Abstract— This research is to regulate firing angle inverter-side of high voltage direct current (HVDC) system using ANFIS-based controller. Average-value model (AVM) is used to implement the HVDC systems because the AVM is needed in level-system simulation of power systems. The AVM neglects switching-device responses and time scale of the AVM is lower than detailed model. Controller based on ANFIS is implemented to control firing angle of inverter-side HVDC because this controller is simple and easy to be implemented. The HVDC system is constructed by using Matlab/Simulink programming. Initializing the variable and parameter of HVDC is loaded to the Matlab workspace using script programme. Some modules for converter, inverter and their controller are developed. Next, the ANFIS controller that consist of 7 inputs and a single output is applied to inverter module. Membership function (MF) that used for input and output are Gaussian MF and constant MF (Sugeno type 0), respectively. The ANFIS scheme control responses are compared to conventional controller responses to validate the ANFIS scheme controller.

Keywords—ANFIS, AVM, controller, firing angle, inverter.

I. INTRODUCTION

Detailed model of power electronic-converters are complex model. This model consist of switch-level electrical system coupled to electronic-converter. Therefore, needed more effort to analysis and linearize in small-signal analysis [1]. To overcome these problems, average value model (AVM) using the first CIGRE HVDC model benchmark system is developed. The AVM is built using Matlab/Simulink (for a state-variable-based simulator) and PSCAD/EMTDC (for a nodal-analysis-based electromagnetic transient program (EMTP)). The 12-pulse converter HVDC system is developed by using a set of nonlinear algebraic functions and these functions are taken out numerically. The AVM results are compared to the detailed model in order to verify AVMs accuracy to predict the large-signal time-domain transients [2]. In time-domain transient studies and small-signal analysis of power-electronic system, it is shown that the AVM is very effective to model the detail model, where the details of switching are

not important and can be neglected [1]. The AVM is used to build the brushless rotating excitation system for synchronous machine. The simulations show that the AVM is able to represent the dynamic of the rotating rectifier accurately and to have effective computational in low-frequency domain [3]. Ref. [4] recommends to build benchmark EMT for HVDC system the emerging included multi-module converter (MMC) grid, the models is being used in different simulation should be harmonized, the model for HVDC for different level of detail could be compared, and to give general guidelines on how to use these models.

The development of control system and its application are expanded from controller based on mathematical model to controller based on artificial intelligent (AI) such as: ANN, fuzzy logic and ANFIS controllers. Moreover, the AI controller has been developed and applied especially in electrical engineering field. Some application the AI-based on the electrical engineering such as: Regulation of firing angle rectifier converter (detailed model) on HVDC transmission by applying controller based on ANFIS [5], The ANFIS power system stabilizer (PSS) is applied to enhance the stability of a single machine in power system [6]. By using ANFIS-based PSS to maintain small-signal dynamic stability of multi machine is done in [7]. Chaos control and voltage collapse suppress are done by applying the ANFIS-based composite controller [8] and based on layered-recurrent neural network PID-SVC [9] in an electric power system. Transient voltage response of a power system is also able to improve by using ANFIS-based composite controller with an additional PID-loop [10]. Based on the some examples application of the AI controller in power system, it is potential ANFIS-based controller applied to regulate the firing angle of average value model-high voltage direct current (AVM-HVDC) transmission line.

The remainder of this paper is organized as follows: Average-value model (AVM) of high voltage direct current (HVDC) transmission system is described in Section II. Next, ANFIS-based control for AVM-HVDC is developed in Section III. Application of ANFIS-based controller to regulate the inverter-converter firing-angle of HVDC system

and its performance of the controller are detailed in Section IV. Finally, the conclusion is given in Section V.

II. AVERAGE-VALUE MODEL OF HVDC

A. Modeling of Inverter by Using Average-Value Model

The effective methodology to represent dynamic value-model is average value model (AVM). In this model the high-frequency switching ripples of the converter are averaged or neglected. Also, the AVM is capable to predict the behavior of slower transient system. The average behavior of the switching cell included the discontinuous switching cells is replacing by continuous blocks within prototypical switching interval. The HVDC system that used in this research provided by [1]. This HVDC system is illustrated in Fig. 1. In order to build the 12-pulse inverter, two 6-pulse line commutated converters are built by serial connected. The HVDC system is equipped by current controller, gamma controller and fault current limiter. The controller for the inverter-side of the HVDC is depicted in Fig. 2.

Parametric AVM approximation is developed for free and not depend upon simulator program platform. On dynamic AVM, AC and DC variables is assumed as the fast dynamic average value on the prototypical switching interval T_{sw} as follows [1][2][11]:

$$\bar{f} = \frac{1}{T_{sw}} \int_{t-T_{sw}}^t f(\tau) dt \quad (1)$$

where $f(\tau)$ is voltage or current. $T_{sw} = (1/12) \times T$, is the period of AC waveform. Formulation for the AC and DC voltages are as follows [11]:

$$\begin{bmatrix} \bar{v}_{qd, is1}^{conv1} \\ \bar{v}_{qd, is2}^{conv2} \end{bmatrix} = \begin{bmatrix} W_{v,1} & \bar{v}_{dc, ir1} \\ W_{v,2} & \bar{v}_{dc, ir2} \end{bmatrix} \quad (2)$$

Formulated to simplify processes of Fig.3(a) and (b) are given in [2].

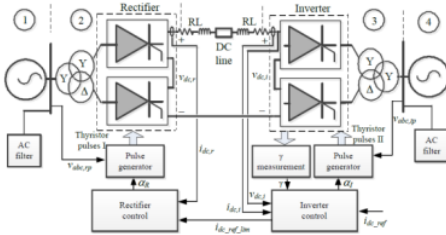


Fig. 1. The HVDC system circuit diagram

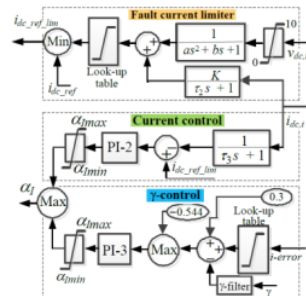


Fig. 2. Diagram block for inverter control sub-system

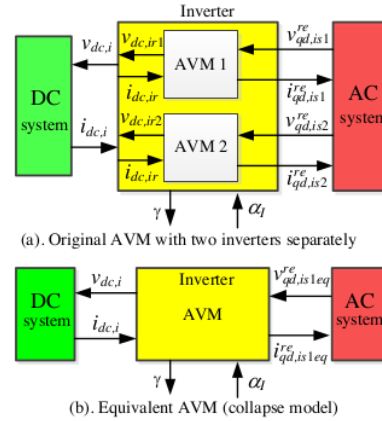


Fig. 3. Diagram block of AVM on inverter-side

B. Principal of Averaging Window

Nowday, conversion forms of AC-to-DC and vice-versa are conducted by switching device on power modern power system and power electronic device. Power conversions are done on DC power level or DC voltage level by using power-electronic [11]. The theories and implementations of dynamic average modeling are represented as a typical power conversion topology as follows. The main component of a power-processing is a switching cell and some additional passive elements, such as: inductor, capacitor or resistor, and input/output filters. Function of the filters are to smooth wave the output of power-processing. Transistor or thyristor is used as a switching module. Where, these switching modules are able to control the input and output power terminal. Special control signal or modulation algorithm are commonly used to trigger ON/OFF the the switch. Fig. 4 shows a basic pulse width modulation DC-DC converter. The DC-DC converter is implemented by using a switched-inductor cell.

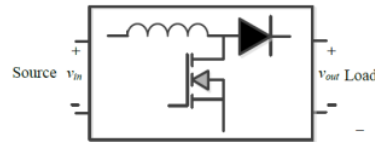


Fig. 4. Circuit of basic switched-inductor cell

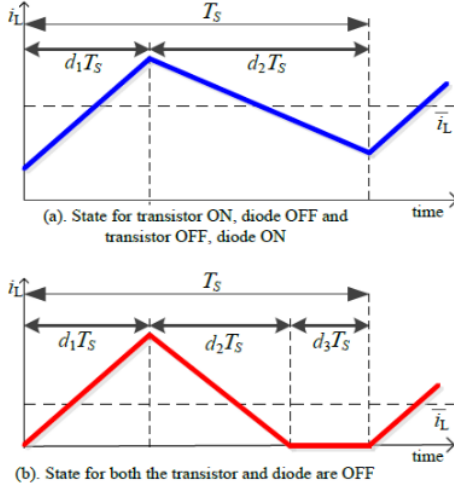


Fig. 5. Current on inductor for state continuous and discontinuous conduction

The state of conducting for active and passive switches obtained by using topology elementary switched-inductor cell is shown in Fig. 4. Elementary switched-inductor is based on an average-value model (AVG) [11]. Fig. 5(a) and 5(b) show the current waveforms of inductor for this switching cell. Each switching interval (T_s) is separated in 2 sub-intervals ($d_1 T_s$ and $d_2 T_s$) for state continuous conduction. The sub-intervals $d_1 T_s$ and $d_2 T_s$ are corresponding to the topological states (transistor ON, diode OFF) and (transistor OFF, diode ON). These sub-intervals are depicted in Fig. 5(a). The variables d_1 and d_2 are named relative duty-cycle, which are defined by $T_s = d_1 T_s + d_2 T_s$.

On the other hand, the switching interval time is also considering the third topology state (transistor OFF, diode OFF) for state discontinuous conduction. In this state, both the switches are at OFF state. In this condition, the current still at zero value for the sub-interval time. These sub-intervals are illustrated in Fig. 5(b). The switching interval is consist of 3 sub-intervals. And, This switching interval are defined as $T_s = d_1 T_s + d_2 T_s + d_3 T_s$.

C. The System under Study

Average value model-high voltage direct current (AVM-HVDC) that studied in this research is given in [14] and is shown in Fig. 6. This HVDC system consist of: Source at Bus 1 (Source Bus), 5000 MVA equivalent, 500 kilo Volt, 60 Hertz, phi angle 80° . Bus 2 is a converter bus that is modeled by average-value model (AVM). Bus 3 (inverter bus) is modeled by the AVM to represent the inverter device also. Bus 4, a 10 GVA source equivalent, 345 kilo Volt, 50 Hertz, phi angle 80° .

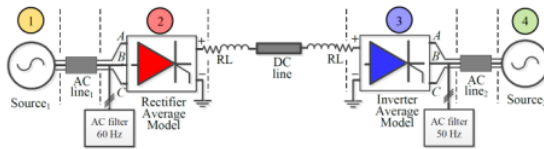


Fig. 6. The HVDC system that under study

```
%Initialize the HVDC
%parameters and variables
%Power;
Vll_nom_r = 500e3;
Vll_nom_i = 345e3;
fnom_r = 60;
fnom_i = 50;
Vdc_nom = 500e3;
idc_nom = 2000;
%Master control
Min_ref =0.1;
SS_ramp=0.3333;
F_up =1.0;
up_slope =5;
T_up=0.4;%
F_down=0;%
down_slope =-5; %
T_down=1.4;%
T_start=0.2 ; %
T_stop=1.6;
```

Fig. 7. Initialize the HVDC on Matlab environment

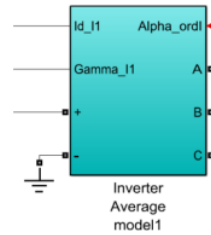


Fig. 8. Initialize the HVDC on Matlab environment

The HVDC system is constructed by using Matlab/Simulink programming. Script programme should be run on Matlab to initiate the variable and parameter of HVDC in first time. This initial script is shown in Fig. 7. Powergui block parameter is loaded from the Simulink source library and this block used to configure the simulation parameter. In powergui, the parameters is setup as follows: discrete mode as simulation, Tustin/backward Euler type as a solver type and sample time taken at 5×10^{-5} s. Next, block diagrams for converter and inverter are constructed. The block diagram for inverter side is shown in Fig. 8. The function of inverter is to convert DC voltage/current become to 50 Hz AC voltage/current. These AC voltage and current are distributed to the consumers through step-down transformer.

D. Inverter and Its Controller

Receiving-end of HVDC system in this research is implemented by inverter device, 3-phase V-I measurement, RLC parallel branch, 3-phase AC source and AC filter as shown in Fig. 9. Average-value model is considered to represent the inverter device. Input of the inverter device is direct current (DC) at plus pole (+) and the minus pole (-) are connected to grounding. The inverter device supplies a 3-phase parallel RLC branch through a measurement device. The voltage and current of the measurement device are treated as control signals. Moreover, these control signals are

used as inputs of inverter controller. The main function of inverter controller is to control the inverter current and voltage by producing the firing angle signal (α_{ϕ}). The firing angle signal of the controller is fed to the input terminal [alpha_ordI] as shown in Fig. 9.

Conventional controller for inverter device is simplified by diagram block as shown in Fig. 10. This controller consists of DC voltage (V_{dL_I}), DC current (I_{d_I}), DC current reference ($I_{d_ref_I}$), DC voltage reference ($V_{d_ref_I}$), Block_I, gamma measurement (γ_{I_I}) and gamma reference (γ_{ref_I}). Outputs of the controller are firing angle (α_{ord_I}), DC current reference limiter ($I_{dref_lim_I}$) and mode operation of inverter (Mode_I).

Meanwhile, function of conventional controller can be replaced by using ANFIS-based controller. Where the ANFIS controller is simplified design of controller because this controller only uses data training to maintain controller parameters in training stage. Complex and hard mathematical formulas are not needed in the ANFIS controller to determine the controller parameters. The ANFIS-based controller block diagram is shown in Fig. 11.

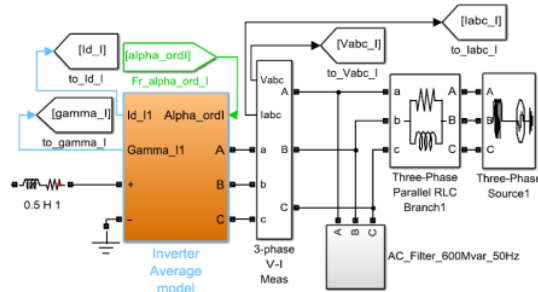


Fig. 9. Diagram block of inverter-side for AVM-HVDC

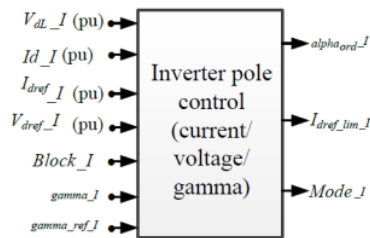


Fig. 10. Conventional controller for inverter AVM-HVDC

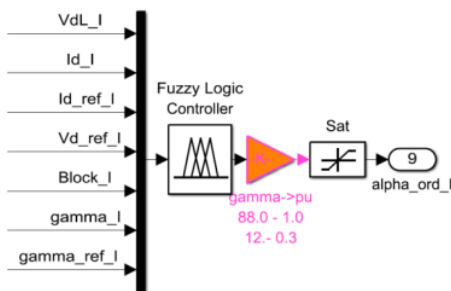


Fig. 11. ANFIS-based controller for inverter AVM-HVDC

III. ANFIS-BASED CONTROLLER DESIGN FOR AVM-HVDC

ANFIS-based controller for AVM-HVDC is design using Neuro-fuzzy designer toolbox [15]. First time, to collect raw-data-set by simulating AVM-HVDC model [14]. In this simulation, input variables of inverter control block (e.g., voltage reference, V_{d_r} and current reference, I_{d_r}) are changed gradually in order to assurance the raw-data-set that get from this simulation are varies. These raw-data-sets consist of 7 inputs such as: DC line voltage (V_{dL}), DC current (I_d), DC current reference (I_{d_r}), DC Voltage reference (V_{d_r}), Block, gamma angle (γ), and gamma reference (γ_r). And, a single output is firing angle (α_{ϕ}) data-set. Next stage is to build an input-output matrix from the raw-data-set using [7. Input + 1. output] $\times 4000 = 8 \times 4000$ data-point. That an input-output matrix is called a training-data-set. By using Program tool Neuro-fuzzy designer (anfisedit), the training-data-set is fed to this tool. Some parameters such as: type membership function (MF) are using Gaussian MF with each inputs are implemented by using 3 Gaussian MF. The input MF are automatically generated by using grid partition. Meanwhile, linear type MF is applied to output membership function. Training of the Neuro-fuzzy designer is done in 30 epochs and this training is conducting repeatedly with varies training-data-set. During the training, fuzzy inference system (FIS) is generated automatically, and FIS parameters are updated and improved.

After the training stage, the FIS is formed and implemented as depicted in Fig. 12. FIS structure of fuzzy Sugeno consist of 7 inputs (V_{dL} , I_d , I_{d_r} , V_{d_r} , Block, γ , γ_r) and a single output (α_{ϕ}), this FIS is named ANFIS_AVM_HVDC. Next stage, this FIS is embedded to fuzzy controller (FL) in Simulink environment to replace the conventional control on the HVDC system.

Figs. 13(a) - 13(c) show examples of input-output surface control for ANFIS (FIS) controller. In Fig. 13 (a), it is shown the relationship of the input (for DC line voltage and DC current) againsts to the output (firing angle). Fig. 13 (b) shows the nonlinear relationship of DC voltage reference and DC current at input-side, and firing angle at output-side. Also, relationship of gamma angle reference and DC voltage reference at input-side, and firing angle at output-side of the controller.

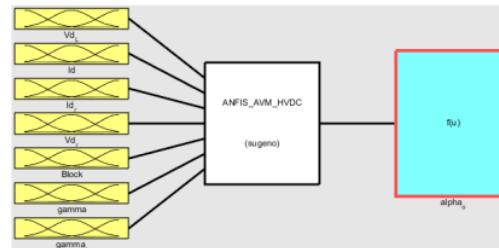


Fig. 12. Structure of ANFIS-control to regulate firing angle AVM-HVDC

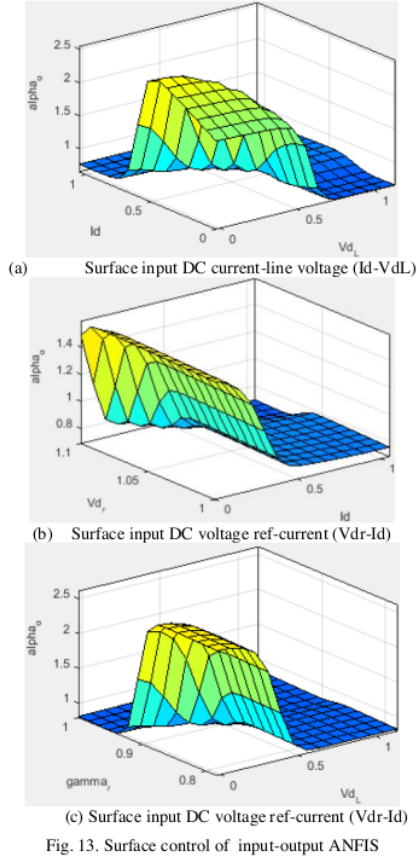


Fig. 13. Surface control of input-output ANFIS

IV. RESULT AND DISCUSSION

The ANFIS-based controller is tested on Matlab/Simulink 7.9.0.529 (R2013b) programme [15] to regulate firing angle of inverter HVDC system at start-up mode. Hardware that applied in this simulation is an Intel Core i5-7400 Processor, 6.0 MB cache, 3.0 GHz, LGA 1151 PC computer. And, windows 7 64-bit (win64) is used as an operating system.

The AVG-HVDC system was started by using DC current reference (I_{d_ref}) as a pilot signal on master controller with parameters as follows: start-ramp-rate and up-ramp-rate at the values of 0.333 and 5.0 pu/s; at times of 0.02 and 0.4 s, respectively. The final value was taken at 1.0 pu. To shutdown (stop operation) of the AVG-HVDC it is needed to determined down-ramp-rate at the value of -5.0 pu/s at time of 1.4 s, and Stop-time at 1.6 s. The simulation results are shown in Figs. 14-17.

Signal output of ANFIS-based controller (ANC) is called firing angle (α_{00}) and this signal is used to regulate the gate thyristor on inverter-side HVDC transmission system. Fig. 14 shows dynamic of firing angle signal from the ANFIS-based controller (ANC). The firing angle signal from the ANC is compared to the signal from the conventional controller (CVC) in order to validate of simulation result. It is shown that both the signals (from ANC and CVC) are similar at start-up time (from 0 to 0.3 s) and steady state time

(from 0.5 to 0.9 s). At transient time, the output of ANC is not able to follow the output of CVC. The firing angle signal of the ANC went to 160° (from 0.3 to 0.5 s). Meanwhile, The firing angle signal of the CVC went to down, from 160° to 142° (0.3 - 0.5 s). This difference occurred may be due to the ANC is not well trained and more training stage should be done.

Fig. 15 shows the voltage output patterns of thyristor device of HVDC system. The output voltage of thyristor device that regulated by using the conventional controller (CVC) is depicted in Fig. 15 (a), as well as regulated by the ANC in Fig. 15 (b). Output current patterns of the thyristor device that regulated by a CVC are shown Fig. 16 (a). It is shows that the 3-phase (phase ABC) currents start at time 0.3 s, then the currents rose moderately to 0.3 pu (from 0.3 to 0.4 s). Next, the 3-phase currents rose from 2.0 to 10.0 pu (from 0.4 to 0.6 s). And, the 3-phase currents achieves steady state at the value of 10.0 pu and time of 0.6 s. Output current pattern of the ANC is depicted in Fig. 16 (b). From the Fig. 16 (a) and (b), there are shown that both the Figs are similar, except the current pattern for the ANC is larger than the CVC from 0.48 to 0.5 s.

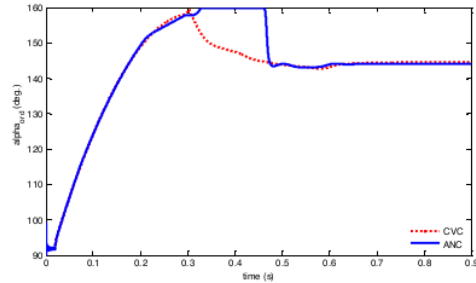


Fig. 14. Firing angle (α_{00}) of thyristor gate at start-up HVDC system

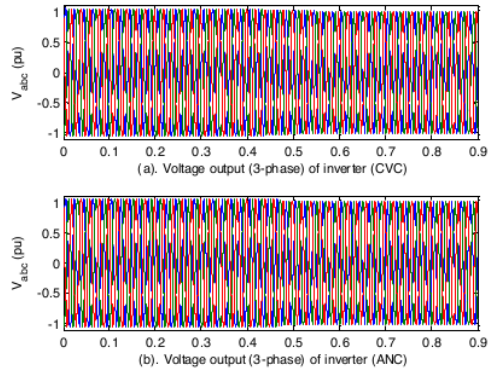


Fig. 15. The output voltage (V_{abc}) at inverter-side HVDC system

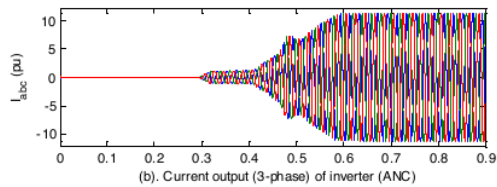
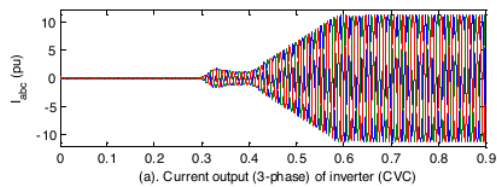


Fig. 16. Output current (I_{abc}) of HVDC system

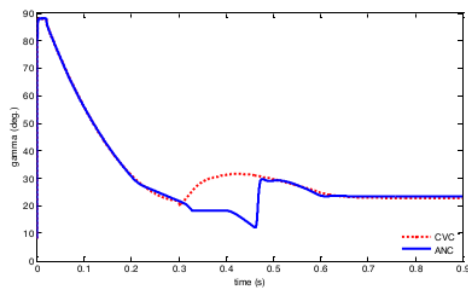


Fig. 17. distinction angle (γ) of thyristor gate HVDC system

Fig. 17 shows the distinction angle of the CVC and the ANC controller. It is shown that the distinction angle ramp down from 88° at start-up time to 25° at steady state time.

V. CONCLUSION

ANFIS-based controller application to average-value model (AVM) high voltage direct current (HVDC) transmission system is the mainly topic in this research. The AVM model is used to implement HVDC model because the (AVM) model is simpler and easier to described the HVDC than detailed model HVDC system. The AVM uses differential equations without including the switching-level of HVDC system and the AVM model is needed to model the HVDC system on the high-level (system-level) in simulation study. Matlab/Simulink modules are implemented to realize the system. Next, ANFIS based controller is constructed by using anfisedit on Matlab environment. After some training processes, the ANFIS based controller is realized to regulate the HVDC line. By using the ANFIS based controller, regulation signal is fed to alpha_ord input of thyristor AVM-HVDC. This controller gives good responses on start-up mode. Responses of the ANFIS based controller are compared to the responses from the conventional controller to validate the simulation.

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