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INTELLIGENT CONTROLLER BASED IMPROVED FAULT RIDE-THROUGH CAPABILITY OF HVDC SYSTEM CONNECTED TO WEAK AC GRID

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ABSTRACT

In the paper, a novel HVDC transmission system operating with weak ac system has been modeled with speed and precision & analyses the control strategy & performance of system, which is controlled using fuzzy. The system can feed a weak or even dead network under fluctuations and big variations of the input power. The fuzzy logic-based control of the system helps to optimize the efficiency of the link under various disturbances. This model provides the basic building blocks found in a typical HVDC system that can be used to build models for individual users own models. The specific contributions, in this paper are that a DQ- type of phase-locked-loop for synchronizing the firing pulses to the HVDC converter has been presented. This gate-firing unit is capable of a providing a clean sinusoidal synchronizing voltage from a polluted and harmonic distorted commutation voltage. The simulations based on PSCAD/EMTDC show that proposed fuzzy logic based HVDC system can operate steadily, has the capability to restore steadily when short circuit fault occurs, and obvious in advantages.

Keywords: *PSCAD/EMTDC, Fuzzy Control, HVDC Transmission, Voltage Dependent Current Order Limit (VDCOL)*

1. INTRODUCTION

Since the first High Voltage Direct Current transmission (HVDC) project was commissioned into commercial operation in 1954, HVDC has been developed so rapidly that it has been widely applied in such fields as large power transmission over long distance, interconnecting two asynchronous systems, power transmission through submarine cables for supplying power to islands. Compared with three-phase AC transmission systems, conventional HVDC is superior in the following aspects [1]. Firstly, HVDC transmission line cost and operating cost are less than those of its AC counterpart. Secondly, it needs not operate synchronously between the two AC systems linked by HVDC. Thirdly, it is easy to control and adjust power flow, etc.

But, there are some disadvantages [2]-[5] caused by its inherent configurations in conventional HVDC as following: (a) Converters produce too much harmonic current and harmonic voltage in both AC system and DC transmission line, (b) It is apt to result in commutation failure when linked with a weak AC system, (c) It is expensive in filter investment because of complicated filter design.

The first CIGRÉ HVDC benchmark system was proposed in [6]. The system is a mono-polar 500-kV, 1000-MW HVDC link with 12-pulse converters on both rectifier and inverter sides, connected to weak ac systems (short circuit ratio of 2.5 at a rated frequency of 50 Hz) that provide a considerable degree of difficulty for dc controls.

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electrical networks. Its graphical user interface enables all aspects of the simulation to be conducted within a single integrated environment including circuit assembly, run-time control, analysis of results, and reporting. Its comprehensive library of models supports most ac and dc of power plant components and controls, in such a way that HVDC, custom power, and FACTS systems can be modeled with speed and precision. It provides a powerful resource for assessing the impact of new power technologies in the power network.

Simplicity of use is one of the outstanding features of PSCAD/EMTDC. It's great many modeling capabilities and highly complex algorithms and methods are transparent to the user, leaving him free to concentrate his efforts on the analysis of results rather than on mathematical modeling. Indeed, the thrust of this paper is to share with the large PSCAD/EMTDC user community our user-defined models for custom power applications, which are not yet available as standard models within PSCAD/EMTDC.

In this respect, one of the aims of the paper is to act as a tutorial in the subject of custom power modeling using PSCAD/EMTDC.

PSCAD/EMTDC, it is recommended that the very useful, generic examples available in [7], [8], [9] be well understood and then the custom power circuits presented in the paper attempted. To show the effectiveness and simplicity of the proposed models, the ac network modeling capabilities of PSCAD/EMTDC are simplified as much as practicable, such that standard features such as bridge rectifier, dc line, rectifier control system, inverter control system, and various types of fault circuits are used in the developed test circuits.

One problem with P-I type control blocks is that in essentially non-linear systems (such as HVDC systems), their performance can only be optimal at one operating point. In order to improve their large-signal performance, several techniques have been used, such as adaptive gains or non-linear weighting of the errors. The fuzzy logic approach used here uses rules based primarily on simple logical reasoning to adaptively select the controller errors, gains and time-constants of a single P-I controller.

Another problem that must be overcome with the control scheme is that of controller saturation. For example, as in the HVDC control system, where two or more control loops compete for the final control action, the P-I controller of the de-selected loop saturates at a limit. This problem has of course been overcome in conventional control schemes [10] -[11], however the approach presented here is simpler, as only one P-I block is used.

The purpose of this paper is to demonstrate how fuzzy logic principles may be applied to the HVDC control problem and to evaluate the performance of the resulting control scheme. It should be noted that a similar performance may be obtainable with other techniques as well. Indeed several proprietary control strategies included in modern HVDC controls [12] do achieve excellent results. However it appears from this study that the fuzzy logic approach is straightforward in its implementation and does improve on the conventional p-I control scheme.

2. DESCRIPTION OF MODELED HVDC SYSTEM

2.1 Power Circuit Modeling

1) Converter Model: The converters (rectifier and inverter) are modeled using *six-pulse Graetz bridge* block, which includes an internal Phase Locked Oscillator (PLO), firing and valve blocking controls, and firing angle (α) and extinction angle (γ) measurements. It also includes built-in RC snubber circuits for each thyristor. Thyristor valves are modeled as ideal devices.

2) Converter Transformer Model: Two transformers on the rectifier side are modeled by three-phase two winding transformer, one with grounded Wye–Wye connection and the other with grounded Wye–Delta connection. The model uses saturation characteristic and taps setting arrangement. The inverter side transformers use a similar model.

3) DC Line Model: The dc line is modeled using an equivalent-T network with smoothing reactors inserted on both sides.

4) Supply Voltage Source: The supply voltages on both rectifier and inverter sides have been represented through three phase ac voltage sources.

5) Filters and Reactive Support: To improve on the power quality of AC system, it is essential to install filters. But the cost of filters is large for conventional HVDC to filter harmonics. It is one of the problems to be settled that how to reduce the cost of filters. In conventional HVDC, the converters can be seen as a harmonic current source so that the filters are designed against the equivalent harmonic current. Currently one to six filters is settled in AC system, which is single tuning filters or damping filters. However, the converter is an equivalent voltage source in developed HVDC system, so a filter is presented which is designed against harmonic voltage as shown in Fig.1.

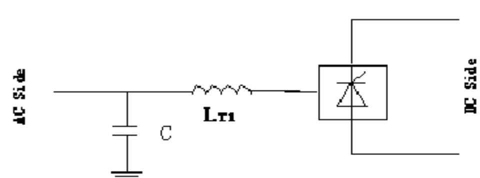

Fig. 1 The structure of the filter

LT1 is the equivalent inductance of commuting transformer, when, $n\omega L_{T1} >> 1/(n\omega C)$, where, n is the harmonic order, ω is the angular frequency of fundamental harmonic, the harmonic voltage generated from the converter are absorbed for the most part by the inductance of the commuting transformer and can not inject the AC side largely. The effect of the designed filter will be shown in Test cases. As can be seen from the configuration, only a capacitor is needed to design the filter. Obviously the simple filter reduces the cost of the whole station.

2.2 Control System Model

The control model mainly consists of α and γ measurements and generation of firing signals for both the rectifier and inverter. The PLO is used to build the firing signals. The output signal of the PLO is a ramp, synchronized to the phase-A commutating bus line-to-ground voltage, which is used to generate the firing signal for Valve 1. The ramps for other valves are generated by adding 60 to the Valve 1 ramp. As a result, an equidistant pulse is realized. The actual firing time is calculated by comparing the order to the value of the ramp and using *interpolation* [13] technique. At the same time, if the valve is pulsed but its voltage is still less than the forward voltage drop, this model has logic to delay firing until the voltage is exactly equal to the forward voltage drop. The firing pulse is maintained across each valve for 120.

The α and γ measurement circuits use zero-crossing information from commutating bus voltages and valve switching times and then convert this time difference to an angle (using measured PLO frequency). The α (in seconds) is the time when valve turns on minus the zero crossing time for valve and γ (in seconds) for valve i is the time at which the commutation bus voltage for valve i crosses zero (negative to positive) minus the time valve i turns off. Following are the controllers used in the control schemes:

• Extinction Angle (γ) Controller;

• dc Current Controller;

• Voltage Dependent Current Order Limiter

1) Rectifier Control: The rectifier control system uses Constant Current Control (CCC) technique [11]. The reference for current limit is obtained from the inverter side. This is done to ensure the protection of the converter in situations when inverter side does not have sufficient dc voltage support (due to a fault) or does not have sufficient load requirement (load rejection). The reference current used in rectifier control depends on the dc voltage available at the inverter side. DC current on the rectifier side is measured using proper transducers and passed through necessary filters before they are compared to produce the error signal. The error signal is then passed through a proportional integral (PI) controller, which produces the necessary firing angle order α. The firing circuit uses this information to generate the equidistant pulses for the valves using the technique described earlier.

2) Inverter Control: The γ control and current control have been implemented on the inverter side [11]. The CCC with VDCOL has been used here through PI controllers. The reference limit for the current control is obtained through a comparison of the external reference (selected by the operator or load requirement) and VDCOL (implemented through lookup table) output. The measured current is then subtracted from the reference limit to produce an error signal that is sent to the PI controller to produce the required angle order. The γ control uses another PI controller to produce gamma angle order for the inverter. The two angle orders are compared, and the minimum of the two is used to calculate the firing instant.

3) DQ-type Gate Firing Unit: Due to weak AC system, harmonics are present in the commutation bus voltage. As converter is connected to this bus, so it requires a GFU to provide gating signals to the converter valves which are synchronized to the commutation voltage. So here, to model HVDC converter system a DQ type GFU is used. The GFU consists of phase locked loop in conjunction with VCO. The block diagram of a DQ type GFU is shown in Fig.2.The three phase commutation voltages V_a, V_b, and V_c are transformed into DQ axis voltages V_{alpha} and V_{beta} using equations (1) and (2) respectively:

$$V_{alpha} = \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c \quad (1)$$

$$V_{beta} = \frac{1}{\sqrt{3}}\left(V_b - V_c\right) \quad (2)$$

$$\text{Error} = -V_{alpha}V_{\sin\theta} + V_{beta}V_{\cos\theta} \quad (3)$$

An error signal is derived using equation (3), which is fed to a PI controller, which generates a reference value for VCO. This reference value can be added to a fixed voltage bias V_{ref} that sets the central frequency 50Hz of VCO.

Transmission of Power

Consider a simple example, the dc voltage of converter is assumed to be order of ± 10V and transmission line resistance is assumed to be 1.0 Ω. If we connect converters together in such a way that current can circulate than we can control the voltage of two converters such that they counter act each other. Assume now, that we control the rectifier voltage to be 10 V. If inverter voltage is now set at 9.0 V, there will be a voltage drop between two converters of 1.0 V. Since the total line resistance is1Ω, current will be 1A. In the example we have arranged a transmission, which transmits 9.0 W to the inverter and 1.0 W is lost on line.

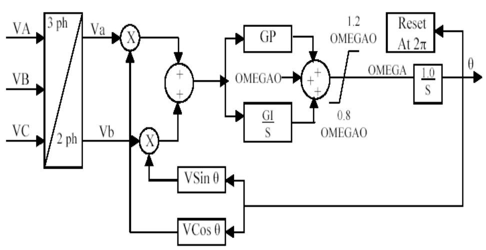

Fig. 2 DQ-type Gate Firing Unit

If voltage at sending end is increased from 10V to 11V, the voltage drop will be 2.0 V between the two converters and current will become 2.0 A. Consecutive the power receive by inverter will increase to 2A × 9V =18W, i.e. it will be double. Similarly if we reduce the rectifier voltage to 9.0 V the current will be reduce to zero. So we see that a change in rectifier voltage of ± 10%, change the current by ± 100%. This voltage change in rectifier can be effectuated in few ms through the control system. It is easy to understand that a DC system offer unique possibility to fast and stable power flow control.

3. FUZZY LOGIC IMPLEMENTATION

The fuzzy logic method [14]-[30] allows for the making of decisions based on the consideration of several different rules. All the rules are considered at once or in "parallel" to arrive at a weighted decision. We demonstrate the application of fuzzy logic by converting the HVDC control system shown in Fig. 3, to the fuzzy control system shown in Fig. 4.

The "plant" in Fig. 3 consists of the converters and the remaining ac/dc network. As the variables on which the control system acts are the dc current and the extinction angle, the plant appears to the controller as a one-input (α_i), two-output (I_{di},γ_{meas}) system. In the conventional method (Fig. 4), the plant is either under CC or CEA control modes and thus one of the two P-I controllers is selected.

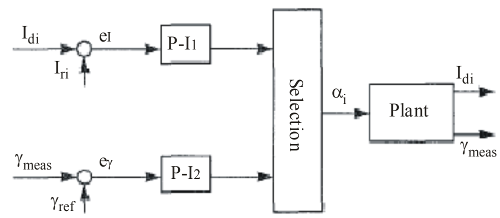

Fig.3 General inverter control system

Note that each P-I controller has its own separate gains and error signal, and that the selection process is carried out at the output end of the two controllers. Thus at the transition from one control mode to another, one controller is abruptly substituted with the other, thus resulting in a sudden change of the gains, time constants and controlling error.

In the proposed fuzzy logic approach, we per form the selection procedure on the input side of the controller by deriving a composite error as shown in Fig. 5. Two new coefficients μ_{cc} and μ_{CEA} are introduced that allow for a gradual transition in the selection process. This can be regarded as a generalization of the conventional process in Fig. 4, where exactly one of μ_{cc} or μ_{CEA} is unity and the other, exactly zero (in CEA mode $\mu_{cc} = 0$, $\mu_{CEA} = 1$ and in CC mode $\mu_{cc} = 1$, $\mu_{CEA} = 0$) . In the fuzzy logic approach these two coefficients are continuous numbers in the interval [0,1] and not necessarily complements. At the nominal operating point, however, the controller is in extinction angle control, with $\mu_{cc} = 0$, $\mu_{CEA} = l$. The two coefficients μ_{CEA} and μ_{cc} are derived from simple rules based on logical reasoning.

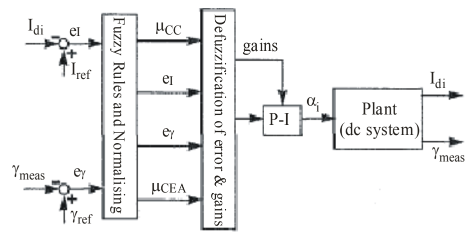

Fig.4 Fuzzy logic control

For example whenever the measured extinction angle is smaller than its set value, the CEA mode of control should be selected in order to bring the extinction angle to its reference in order to provide sufficient commutation margin. The set of rules are explained in next section.

In a similar fashion, the P-I controller gains and limits are also continuously adjusted through a weighting process (depending on the output errors, μ_{CEA} and μ_{cc}) & are continuously loaded into the P-I block as shown schematically in Fig. 5.

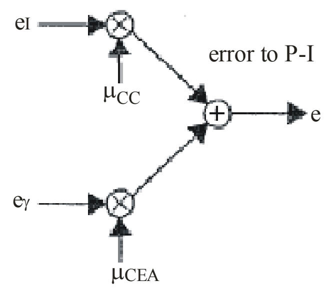

Fig.5 Composite error derivation

Note that as a single P-I block is used, the problem of saturation of the de-selected controller is directly avoided. Also note that at the extreme limits of operation, when the controller is clearly in CC or CEA control, the P-I controller gains are the same as those in the conventional system and the system should show the same small-signal behavior as the conventional system for these operating points. Thus the fuzzy controller can be regarded as a generalization of the conventional controller.

Thus as in Fig. 6, a value of $I_S = l$ implies that the current is "definitely small" whereas $I_S = 0$ means that the current is "definitely not small"; intermediate values between 0 and 1 implying something in between. Similarly $I_L = l$ implies that the current is "definitely large", and so on.

For the two inputs under consideration I_{di} and γ, the following simple linear sets are used (Note: The overlap of the two sets is not necessarily at 50%).

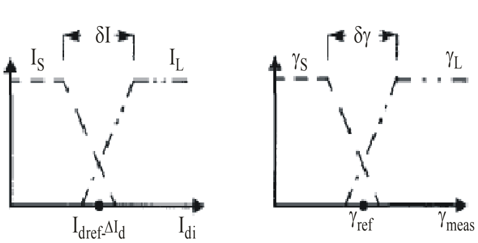

Fig.6 Fuzzy membership functions

I_S and I_L are a measure of small and large dc current respectively. Using the membership values for I_{di} and γ, the following set of rules is used for control.

- *RULE I :* IF I_S AND γ_S THEN μ_{CC}
- *RULE II :* IF I_S AND γ_L THEN μ_{CC}
- *RULE III :* IF I_L AND γ_S THEN μ_{CEA}

- *RULE IV :* IF I_L AND γ_L THEN μ_{CC}

The rules are shorthand expressions for simple real-language statements, which describe our desired operating strategy. For example, rule IV states that *if the current is large and the extinction angle is large, current control should be used.* However, unlike deterministic logic, this rule does not assign a value of 0 or 1 to μ_{CC}, but rather just assigns a contribution. The contributions to kc from rules I, I1 and IV are then used to determine its final value using some de-fuzzification method. Shown below is the procedure for using the above rules in a quantitative manner. For any typical measured I_{di} and γ_{meas}, the quantities I_L, I_S, γ_L and γ_S assume values between 0 and 1. For example suppose that for some I_{di} and γ_{meas} we get $I_S = 0.35$, $I_L = 0.7$, $\gamma_S = 0.77$ and $\gamma_L = 0.13$. Using correlation-product inference the above rules yield the following:

- *From rule I:* $\mu_{CC} = 0.3 * 0.75 = 0.225$
- *From rule II:* $\mu_{CC} = 0.35 * 0.1 = 0.035$
- *From rule III:* $\mu_{CEA} = 0.6 * 0.75 = 0.45$
- *From rule IV:* $\mu_{CC} = 0.7 * 0.1 = 0.07$

Selecting the *"Maximum Membership De-fuzzification"* method to obtain the values for the two multipliers. In this method, we simply use the largest values generated by the rules, i.e., $\mu_{CEA} = 0.46$ and $\mu_{CC} = 0.235$.

4. TEST CASES

The developed model of HVDC is based on HVDC benchmark model proposed by CIGRE. The converters are 12 pulses. Large capacitor is paralleled in the dc side of rectifier. Filters for harmonic voltage source are connected in the AC system. The main parameter of system are as following: Rated power capacity S=1000MW, V_{DR}=500kV, V_R = 345 kV, V_I =230kV, rated commuting transformation ratio of each transformer in the sending side 345 kV/213.456 kV, 603.73MVA, rated commuting transformation ratio of each transformer in the receiving side 209.2288 kV/230 kV, 591.79 MVA, the paralleled capacitor in the DC side of the rectifier C = 100μF, in AC filter, Cfilter = 18μF. The main HVDC system variables measured during the simulations are listed and described in Table I.

Case 1: steady state operation.

When the system is in steady state, rectifier DC voltage, rectifier DC current, converter-firing angle for the inverter γ, converter firing angle for the rectifier α, active power on rectifier side Prec and AC line to line rectifier & inverter voltage are shown in Fig. 7 and Fig. 8. It can be seen from Fig.7and Fig.8 that the HVDC system can operate steadily; the variables measured during the simulations are in the range of constraint, the AC voltage and current is ideal due to the HVDC characteristics and the pertinent filter designed.

TABLE I

MEASURED HVDC SYSTEM VARIABLES

Variables	Description
Rectifier DC Voltage (V_{DR})	DC voltage measured on the dc side of the rectifier terminal
Inverter DC Voltage (V_{DI})	DC voltage measured on the dc side of the inverter terminal
Rectifier DC Current (I_{DR})	DC current measured on the dc side of the rectifier terminal
Inverter DC Current (I_{DI})	DC current measured on the dc side of the inverter terminal
Rectifier AC Voltage (V_R)	AC voltage measured on the ac side of the rectifier terminal
Inverter AC Voltage (V_I)	AC voltage measured on the ac side of the inverter terminal
Prec	Active power on rectifier side
Gamma (γ)	Converter firing angle for inverter
Alpha (α)	firing angle

Case 2: DC fault

This fault has been located at the midpoint of the dc line. Suppose the fault start at the moment of 1.5s and lasts for 0.02s. Fig. 9 and Fig. 10 illustrate different output parameters of the system. During the fault, the dc voltage has gone down to zero (the small oscillation is due to the energy stored in the capacitor), and a momentary transient dc current has been observed. However, control response forces rectifier α and inverter γ to reach maximum and inverter α to reach minimum, thereby reducing the current flow. VDCOL forces the current to stay minimum until the dc voltage situation is improved. Once the fault is cleared, the dc voltage is recovered, and the control system brings the system back to normal operation. We can see that the developed HVDC system can recover the initial state after the DC fault is eliminated.

Case 3: AC line-to-ground fault of the receiving side

A line-to-ground fault occurs on phase A of the inverter side AC system. Suppose the fault start at the moment of 1.5s and lasts for 0.02s. The simulation curves are shown in Fig.11 and Fig. 12. During fault, the dc voltage has gone down to zero (neglecting oscillation due to capacitor energy storage), the dc current faces a momentary overshoot, and then goes to minimum limit with some oscillation present (due to the oscillation of dc voltage). Rectifier α, inverter α, and inverter γ reach to maximum value, thereby blocking the system for the fault duration. Once the fault is cleared, the system comes back to its normal operation. During an ac fault, commutation failures happen, resulting in a momentary drop-down of dc voltage. This causes the VDCOL to limit the dc current to a minimum, and ac voltages also get disturbed (not shown in the figure). As can been seen form Fig.7 to Fig.12 that the developed HVDC system can recovery the initial state independently and the stability is good.

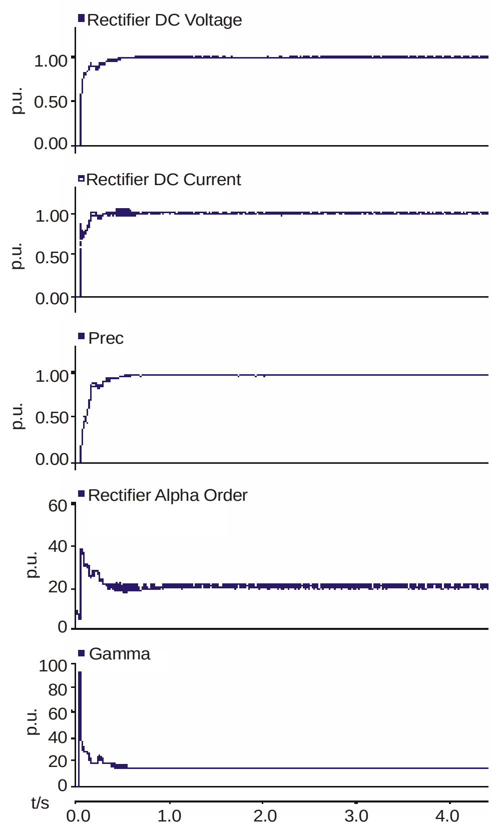

Fig.7 Simulation results for steady state operation on rectifier

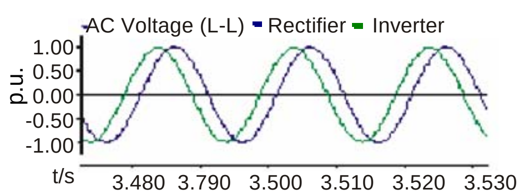

Fig.8 Simulation results for steady state operation on AC voltage

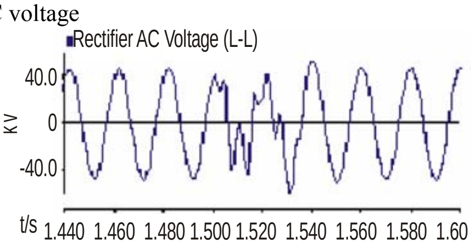

Fig.9 Simulation results when DC line-to-ground fault occurs on AC voltage

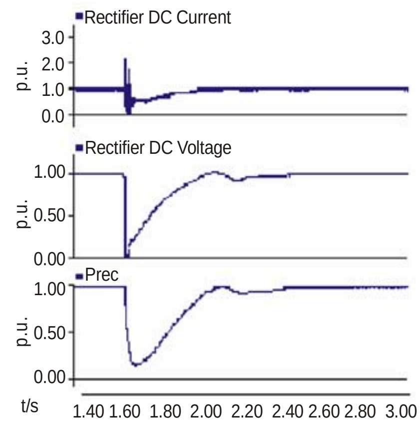

Fig.10 Simulation results when DC line-to-ground fault occurs on rectifier

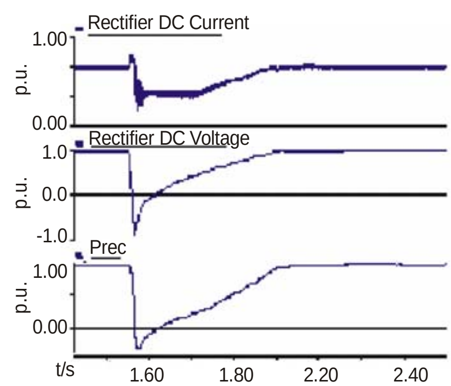

Fig.11 Simulation results when a line-to-ground fault occurs on phase A of the rectifier side

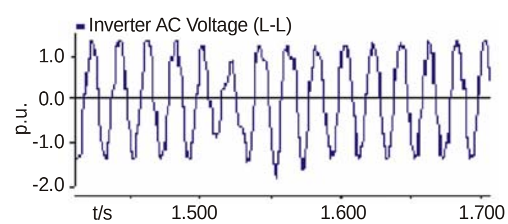

Fig.12 Simulation results when a line-to-ground fault occurs on phase A of the inverter-side AC system

5. CONCLUSION

An Intelligent controller for HVDC system operating with weak AC system has been developed using PSCAD/EMTDC to enhance the fault ride through capability of system. With this controller, system can feed a weak or even dead network under fluctuations and big variations of the input power. It provides the basic building block found in a typical HVDC system, which can be used to build models for individual users own models. A VCDOL unit is developed which provides the reference to the current controller. The dynamic behavior of the typical HVDC system has been demonstrated using various short time short circuit faults and typical results have been presented. These tests demonstrate the ability of the DC system, the fuzzy control and the protection system to recover from such faults easily.

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