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A NEW SELF-TUNING ROBUST PI CONTROLER FOR HVDC SYSTEMS

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ABSTRACT

The design and implementation of a new self-tuning fuzzy-based robust controller for basic dc controls in an HVDC system is presented. The fuzzy logic approach uses rules based primarily on simple logical reasoning to adaptively adjust the controller gains, and time constants of a single PI controller. Also, a fuzzy control-mode changer is implemented and applied for smooth transition from one control mode to another. Error signals and their derivative are input to the fuzzy system to give optimum system performance under various normal and abnormal conditions. Simulation results verify improved performance of proposed controller compared to the conventional PI controller under various operating conditions.

Key Words: Fuzzy System, HVDC, Constant Current Control, Constant Extinction Angle Control

INTRODUCTION

High Voltage Direct Current (HVDC) technology finds application in the transmission of power over long distances or by means of underwater cable, and in the interconnection of independent AC power systems or AC systems concentrated around widely separated hubs. HVDC technology continues to be deployed as the cost and performance of the power electronics involved improves. The converter bridge controller used in HVDC transmission terminals is designed to maintain specific power transmission characteristic.

For an AC/DC power system, the fast acting converter controller offers the feature of hierarchical control of the system following a disturbance. Despite advances in modern and nonlinear control theory, classical proportional-integral (PI) or proportional-integral-derivative (PID) controllers are still widely used in industry due to their relatively simple structure and ease of implementation. Conventional HVDC-converter controllers are based on PI-type controllers. Typically, such controllers make use of a fixed gain structure that is optimized for rated conditions of operation. However, for much of the operating range controller performance is often less satisfactory, and a method of adjusting the PI controller settings as operating conditions vary has been investigated to try and resolve this. The tuning of the HVDC converter controls is a compromise between the speed of response and stability after 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 requires careful selection of control constants to accommodate the full range of operating conditions.

The interaction between AC and DC systems becomes more sensitive to disturbance as the effective short-circuit ratio (ESCR) of the AC-system interface reduces [1], and hence the tuning of the controls for low and very low ESCR is more critical. To circumvent the above problems, extensive research has been carried out in the area of HVDC control. But much of the published work on adaptive HVDC control does not show clear evidence of success when applied in practical applications because there is often little assessment of performance with large disturbances, where the adaptive control may not only be ineffective but may actually degrade performance [2,3].

A gain scheduling adaptive control strategy is attempted in [4] where the effect of large disturbances is taken into account. In [5], the advantages of continuous automatic fine-tuning are combined with predetermined gain scheduling in order to achieve robustness during large disturbances. A robust coordinated control scheme for parallel-connected AC and DC systems is proposed in [6]. In this, the derivation and validation of a coordinated controller is described, which makes use of on-line identification of the AC/DC system. Most of the above controllers, although superior to the conventional PI type, need either an accurate plant model or a reliable instrumentation scheme. The noise rejection property of these controllers is rather limited.

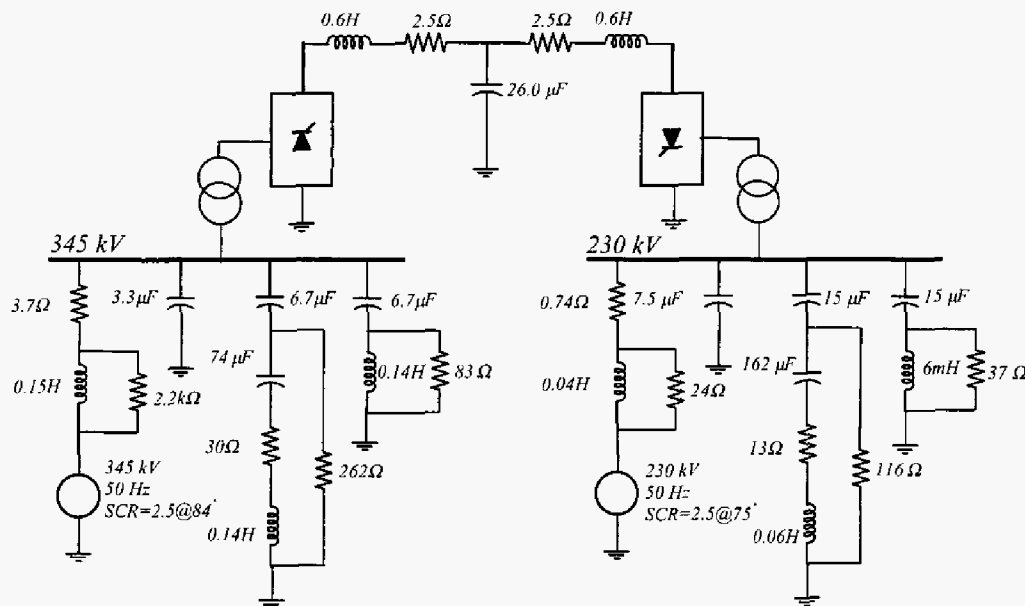


Fig. 1 Cigré Benchmark model (approximate values shown for simplicity).

Recent, research on fuzzy-logic control has demonstrated its suitability for application in large nonlinear systems. To date, such controllers have proved successful in controlling small nonlinear plant [7]. It is therefore proposed that the adjustment, or adaptation, of PID controller constants are performed by a scheme based on fuzzy logic. In order to account for sensor noise, model uncertainties, and change in operating point, the linguistic characteristics of fuzzy control provide a very good approach to solving the uncertainty problem [8]. Fuzzy-logic control proves to be highly effective in controlling variable, nonlinear plant, for which detailed and accurate mathematical descriptions are not available. Furthermore, the derivation of fuzzy rules, in principle, relies on the experience of a human expert; which sometimes limits the fuzzy-logic controller to lower order systems [8].

The purpose of this paper is to demonstrate how fuzzy-logic principles may be applied to HVDC control and to evaluate the performance of the resulting control scheme. The controller error signal and its derivative are used as the principle signals to adjust the proportional and integral gains of the converter controllers.

DESCRIPTION OF THE STUDY SYSTEM

To date, a wide variety of HVDC converter control strategies have been tested and optimized with the help of various digital programs. Finally, great interest in HVDC-system simulation has led to the idea of establishing an HVDC benchmark model [9], [10]. The Cigré benchmark model is used here as a test system [10].

The single-line diagram of the test system is shown in Fig. 1. The selected short-circuit ratio (SCR) and the effective short-circuit ratio (ESCR) for the Cigré benchmark model characterize a weak system. The combination of the weak inverter system, the DC-side resonance approaching fundamental frequency, and the AC-side resonance near the second harmonic make this system particularly onerous for DC control operation.

The standard HVDC control system is defined and described in IEC 60633. It should be considered as indicative or typical of what is required. The main control levels in this standard control system hierarchy are master and pole controls. The pole control provides independent control at pole level and incorporates the minimum functionality required to allow power transfer via the pole. Sophisticated control algorithms are used to produce firing pulses that instruct the thyristor valve when to fire. The Pole Control imposes DC voltage or DC current characteristics on the principal control loops of the converters. Separate characteristics are implemented for rectifier operation and inverter operation. The single crossing point of the two converter characteristics defines the working point for the scheme for different operating conditions. The actual static characteristics will be defined for each scheme during system studies. The control characteristic for the benchmark model in this study has the principal components shown in Fig. 2.

The DC link current is maintained constant by subjecting the rectifier converter with constant current (CC) control (pole control), segment AE, Fig. 2. The inverter converter is in constant extinction angle (CEA) control, segment AC, Fig. 2. A pole controller in inverter converter, i.e.,

constant-current controller, has also been provided for rectifier operation under transient and power reversal conditions, segment BF, Fig. 2. However, in steady-state normal operating conditions, it operates with CEA control. Normally the operating point is the intersection of the rectifier CC and inverter CEA characteristics (point A, Fig. 2), which results in the minimum reactive power demand [12], without an excessive risk of commutation failure.

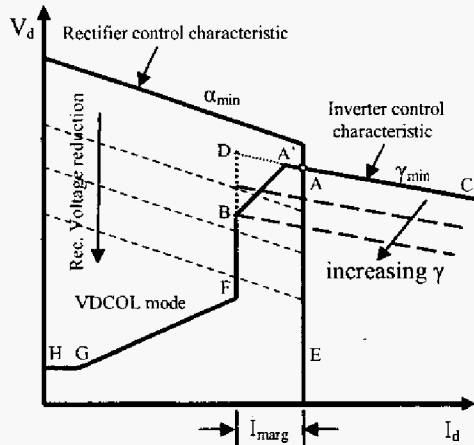


Fig. 2 HVDC control characteristic

It is important that the control system should be designed to ensure that under all operating conditions there is one, and only one, intersection between the two characteristics and hence only one operating point. If this is not achieved it would be uncertain which operating point would be achieved, and, in practice, operation may oscillate between various points.

In order to prevent sudden change in the operating point, the sharp knee is broken with a positive resistance slope from the γ -control characteristic to current control characteristic of the inverter (A'B instead of A'D and DB, Fig. 2). This droop characteristic is usually called the current error (CE) control system [13].

Direct voltage is controlled at the rectifier terminals by the inverter. The inverter target voltage is based on a direct voltage measurement at the inverter terminals and a correction factor based on the voltage drop across the link. The correction factor is adjusted during normal operation based on the actual voltage measured at the rectifier, which is communicated to the inverter.

The conventional inverter control system is depicted schematically in Fig. 3. There are two control paths. The upper one (CC) compares the current order $I_{dref} - I_{marg}$ with the measured current I_{di} , and produces the firing angle order. The firing angle is controlled in a direction that would reduce the current error. Similarly, the lower path (CEA) generates the firing-angle order in an attempt to

make the measured extinction angle γ_{meas} to equal the set point value of γ_{min} . The actual firing-angle order passed to the HVDC converter is the smaller of the two firing-angle orders. This ensures that only one of the paths is in control, with the other path being de-selected.

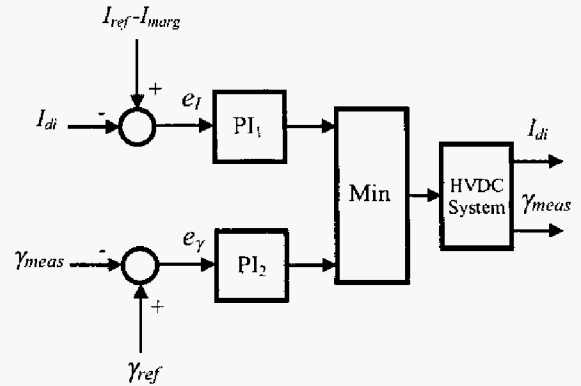


Fig. 3 Conventional inverter control system.

FUZZY SELF-TUNING CONTROLLERS

The rectifier current-controller has been replaced by a fuzzy self-tuning controller as shown in Fig. 4. The fuzzy-logic method allows decisions to be made based on the consideration of several different rules. All the rules are considered at once to arrive at a weighted decision.

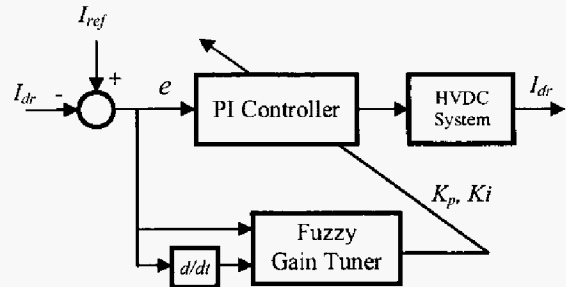


Fig. 4: Rectifier fuzzy current controller.

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 current controller. These inputs are fuzzified into five sets, i.e., PB , PS , ZO , NS and NB . The membership grades (Fig. 5) are taken as triangular and symmetrical. The output membership grades for different fuzzy sets are derived by Zadeh's AND, OR rules from the rule table (Table I). The controller's gains are normalized using Eqs. 1 and 2 [14].

$$K_p = \frac{K_{p_{max}} - K_{p_{min}}}{K_{i_{max}} - K_{i_{min}}} \quad (1)$$

$$K_i = \frac{K_i - K_{i_{min}}}{K_{i_{max}} - K_{i_{min}}} \quad (2)$$

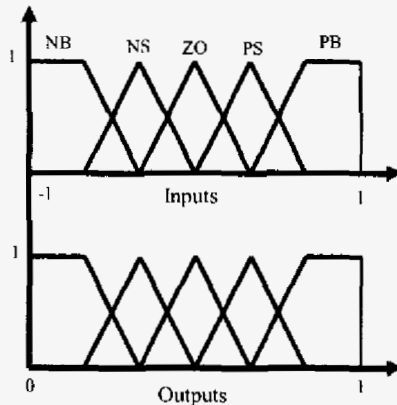


Fig. 5 Membership grades of inputs (error and its derivative) and output (change in gain)

K_p		Error				
		NB	NS	ZO	PS	PB
Error Rate	PB	PS	PB	PB	PB	PB
	PS	ZO	PS	PB	PB	PB
	ZO	NS	ZO	PS	PB	PB
	NS	NB	NS	ZO	PS	PB
	NB	NB	NB	NS	ZO	PS
K_i		Error				
		NB	NS	ZO	PS	PB
Error Rate	PB	ZO	NS	NB	NB	NB
	PS	PS	ZO	NS	NB	NB
	ZO	PB	PS	ZO	NS	NB
	NS	PB	PB	PB	PS	NS
	NB	PB	PB	PB	PS	ZO

Table 1: The fuzzy rule base table, P-Positive, N-negative, ZO-Zero, B-Big, S-Small

In the conventional controller, the system is either under CC or CEA control modes and therefore one of the two PI controllers is selected. Hence, 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 inverter fuzzy-controller (Fig. 6), this problem is solved by introducing a fuzzy mode changer that works based on a composite error concept [15].

$$e = e_i \mu_{cc} + e_r \mu_{CEA} \quad (3)$$

Two coefficients μ_{cc} and μ_{CEA} are introduced that allow for a gradual transition in the selection process. In the fuzzy logic approach these two coefficients are continuous numbers in the interval [0, 1] and not necessarily complement [15]. At the normal operating point, $\mu_{cc}=0$ and $\mu_{CEA}=1$. In a similar manner (as in the rectifier fuzzy controller), the PI controller gains are also continuously adjusted through a fuzzy gain tuner.

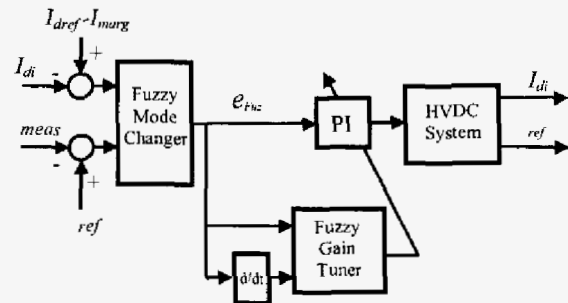


Fig. 6 Proposed inverter control system, γ_{meas} : measured extinction angle, γ_{ref} : reference extinction angle, I_{di} : inverter direct current, I_{dref} : reference direct current.

APPLICATION OF PROPOSED CONTROLLER

The proposed fuzzy controller and the conventional controller were simulated and the results were compared. In order to produce a noticeable test perturbation, the current setting of the rectifier is given a step reduction of 30%. The resulting DC power recovery is shown in Fig. 7. The performance comparison shows that for small disturbance, the proposed controller may not be much better than conventional one. The behavior of the study system is tested during severe faults under different control strategies (see Fig. 8 and Fig. 9).

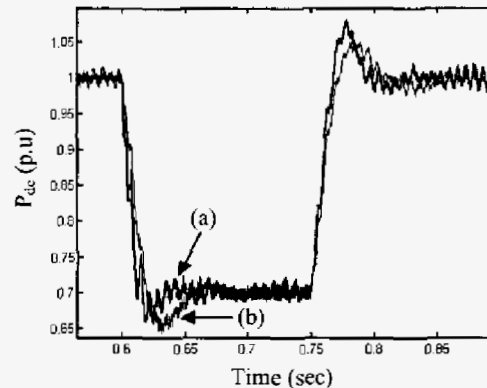


Fig. 7 Current order change, a) fuzzy b) conventional controller

A pole to ground fault is applied in the DC line near the rectifier station (between the smoothing reactor and DC line) and then the fault is cleared after 5 cycles by a force retard action of the rectifier in which the firing angle is increased into the inverter region (160°). For comparison, the response with a conventional control is shown in Fig. 8. The results show fast recovery of DC power, when the proposed fuzzy controllers are used at both side of HVDC link [rectifier and inverter side, Fig. 8 (a)]. Also, the conventional controller appears to suffer a higher magnitude of the DC current at the beginning of the fault. Fig. 9 shows the results of a three phase AC fault on the inverter AC bus for 5 cycles. Recovery to the pre-fault power level is shown to be fast as compared with the conventional controller.

CONCLUSION

The paper presents a fuzzy logic-based approach for the on-line tuning of the PI controller gains in an HVDC system. For small disturbances, the proposed fuzzy controller may not be much better than the conventional one, but for severe disturbances like 3-ph AC fault, the proposed controller makes the system recover much faster than the conventional PI controller does. Certainly, for an HVDC link, it is more convenient to improve the PI control strategy rather than to work out complicated dynamic models, which require sophisticated control strategies. The fuzzy logic approach allows for the incorporation of simple rules into a control system.

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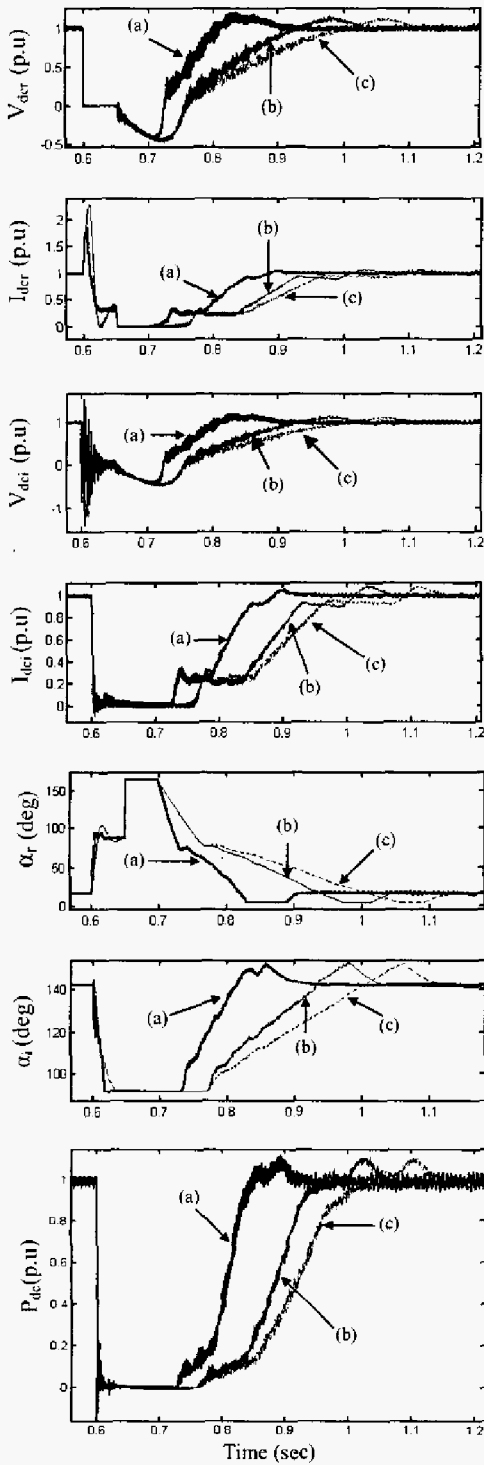


Fig. 8 Performance comparison, DC line fault and recovery, a) fuzzy controller at two side b) only inverter fuzzy controller c) conventional controller

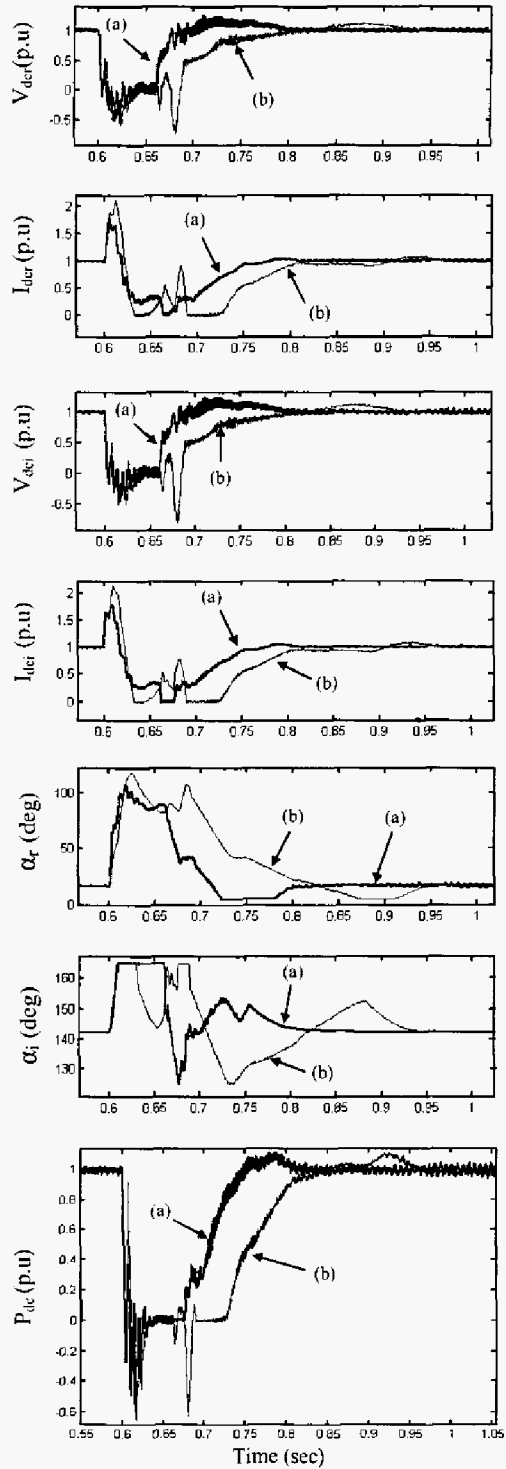


Fig. 9 Performance comparison, 3-ph ac fault at inverter, a) proposed fuzzy controller, b) conventional controller