A Novel Fuzzy Logic Based PI Control Strategy for VSC- HVDC Transmission

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***Abstract*— This paper presents a Fuzzy Logic Based PI Controller for a Voltage Source Converter Based HVDC transmission system. The proposed Fuzzy Logic Control strategy involves a Direct Current control strategy and a subsequent dual closed loop structure which is designed in a d-q reference frame. Independent control of active and reactive power is adhered to. Several simulations on the test system were carried out in Matlab/Simulink environment. The results show that the closed loop system demonstrates better performance characteristics and a faster power flow adjustment than the conventional PI controller.**

Index Terms*— *VSC- HVDC, Fuzzy Logic Control, Membership Function, Direct Current Control

I. INTRODUCTION

CLIMATE change activism as well as a limited access of primary conventional fuels is setting the platform for a subtle shift to a carbon-di-oxide-neutral, multi-layered energy system. In this transformation renewable energies will play a leading role followed by the formation of energy corridors for transport of the clean energy. As an emerging technology, HVDC systems technology provides a highly efficient and a flexible transmission system. The HVDC transmission system will provide the required flexibility to integrate renewable energy sources such as wind and solar energy in the grid. It will support the increase in the number of the connections and power flow between energy The HVDC system provides the platform to interconnect two AC power systems that are not synchronized as well as transfer of electric power between two distant nodal points through overhead transmission or submarine cables.

The converter stations form the backbone of an efficient HVDC transmission system. The two kinds of converter technologies currently used are: Line Commutated Current Source Converters (CSC's) and Self commutated voltage source converters (VSC's). HVDC systems based on the principle of conventional CSC's require a substantially large generation source with a very high level of short circuit ratio in order to operate satisfactorily. In other words there is a ne for the transference of reactive power from the AC system at the point of contacts to the converter so accomplish the conversion process which amounts to nearly about 50 percent of the total active power through the converter. Moreover based on the CSC technology principle, power flow direction can be reversed only by reversing the Direct Current DC voltage polarity. This characteristic needs a highly complicated switching technique in case the CSC system is used for building a Multi Terminal Direct Current System (MTDC).

On the contrary, VSCs utilizing the Insulated Gate bipolar transistor (IGBT) valves as well as Pulse Width Modulation (PWM) techniques can lead to the production of a near sinusoidal AC voltage which is fully controllable with respect to magnitude and phase of the AC wave. Unlike the CSC systems, VSCs have no reactive power demand and can also exchange the reactive power with the AC grid.

VSCs can rapidly control the active power exchange by controlling the phase angle of the produced voltage as well as control the reactive power at each terminal by controlling the magnitude of VSC voltage independent of the Direct current power transmission. Due to this property VSCs can be installed anywhere in the AC grid irrespective of the short circuit current capacity. Moreover to change the direction of the power flow in its DC link, VSC does not need to reverse the voltage polarity. This power reversal is observed by changing the direction of the current. Many attempts have already been made to conceptualize the formation of the meshed grids using classic HVDC or CSC technology. However due to the high amount of complexity involved the projects was thereby limited to a maximum of 3 nodes **[1].** On the other hand the VSC-HVDC provides the most suitable conditions for a multi terminal system which is the basis for the modeling of a super grid because the number of nodes and the kind of grid topology utilized does not have any limit in the case of VSC-HVDC.

Power Control strategies for VSC- HVDC systems have been widely implemented in literature. [2-5] gives a lucid description of PID based control strategy implemented in the dq reference frame. However the adequate mathematical modeling and thus obtaining the transfer function for the

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conventional controller design such as the PID controller is difficult for HVDC systems as it consists of non linear power electronics devices. Several other modern control techniques such as the Fuzzy Control Strategy and $H-\infty$ based robust control strategy have been applied for this particular problem. The Fuzzy Logic Control strategy has been shown to provide significant improvement over the closed loop response of the VSC-HVDC systems [6-7]. Although an improvement is obtained, the performance is precariously affected because of the dependence on Fuzzy Logic membership function that are applied to tune the PI parameters. In this paper a novel Fuzzy Logic Control strategy is employed for VSC-HVDC to reduce the effect of the accuracy of the Fuzzy Logic membership functions.

II. MODELLING OF VSC HVDC

The need to understand the underlying structure of the VSC station model arises because of the presence of several VSC stations in the VSC based MTDC systems. Figure 1 shows the elements constituting a VSC station. The model consists of AC buses, series reactance, AC filters, coupling transformers and converter blocks on the AC side, and the DC bus, the DC filter and the DC line on the DC side. A single line represents the DC side of the model.

The point of common connection acts as a medium from where the VSC station is connected to the AC grid. The PCC is connected to the AC side of the VSC through a converter transformer, shunt filter and a phase reactor while as on the other side the DC bus, at which a shunt DC capacitor is connected to the ground, is connected to the DC line on one side and the VSC on the other side.

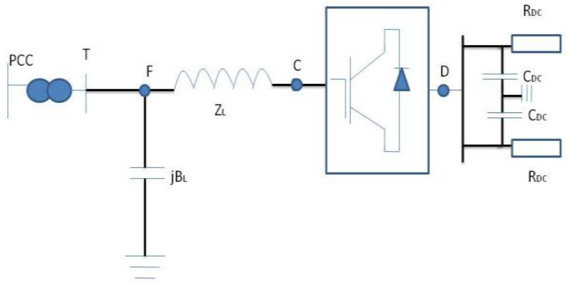


Fig. 1: Schematic of a Two Terminal VSC-HVDC

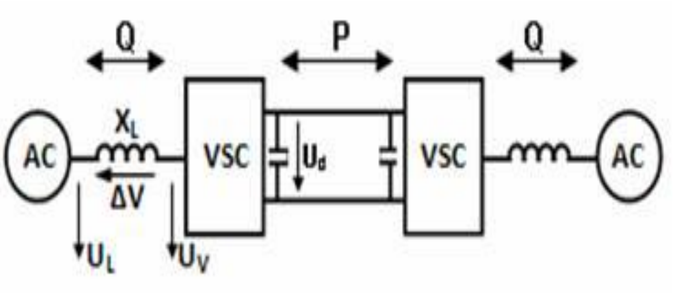


Fig. 2: VSC HVDC station modeling

Two interconnected stations in a VSC-HVDC have symmetry and thus either converter can be used for modeling. In the d-q frame the AC-DC converter can be modeled from Figure 2 as:

$$L\frac{di_d}{dx} = -Ri_d + wLi_q + us_d - u_{cd} \tag{1}$$

$$L\frac{di_q}{dx} = -Ri_q + wLi_d + us_q - u_{cq} \tag{2}$$

$$C\frac{du_{dc}}{dx} = i_{dl} - i_{dc} \tag{3}$$

Where, $.i_{d,q}$ and $u_{sd,q}$ are the dq- axis components of current and voltage of the AC source respectively, and $u_{cd,q}$ are the dq-axis components of AC voltage injected into the converter, R and L are the equivalent resistance and inductance, w is the source frequency, u_{dc} is the DC bus voltage, C being the capacitance of the DC capacitor, and i_{dc} is the DC bus current.

Using Parks transformation or the Clarkes transformation the dq-axis is aligned so that the d-axis is in phase with the AC source voltage, i.e., $u_{sd}=u_s$, $u_{sq}=0$. The power exchanges from the AC source to the DC link assuming the losses of the converter and the transformer to be zero is given by:

$$Q = -3u_{sd}i_q/2 \tag{4}$$

$$P = 3u_{sd}i_d/2 \tag{5}$$

According to the equations, if u_{sd} is maintained constant, then P is only proportional to i_d and Q is proportional to i_q. Thus by controlling of i_d and i_q technically termed as a direct current control method active and reactive power can be adjusted and a good dynamic response is possible.

III. CONTROL STRATEGY

A novel fuzzy- PI control strategy for VSC-HVDC has been proposed in this paper through which significant improvement in the performance has been obtained. The proposed controller as in Figure 3 consists of an outer loop fuzzy controller, the phase locked loop (PLL) and an inner loop fuzzy controller. Intelligent control of the constant DC voltage control and the Active/ Reactive power control is achieved by using the outer loop fuzzy controller while as the direct current control is achieved by using the Inner loop current controller. PLL is used to ensure the synchronism of the rotating dq-reference plane with the three phase abc system. The q component of the AC source voltage becomes zero in this case.

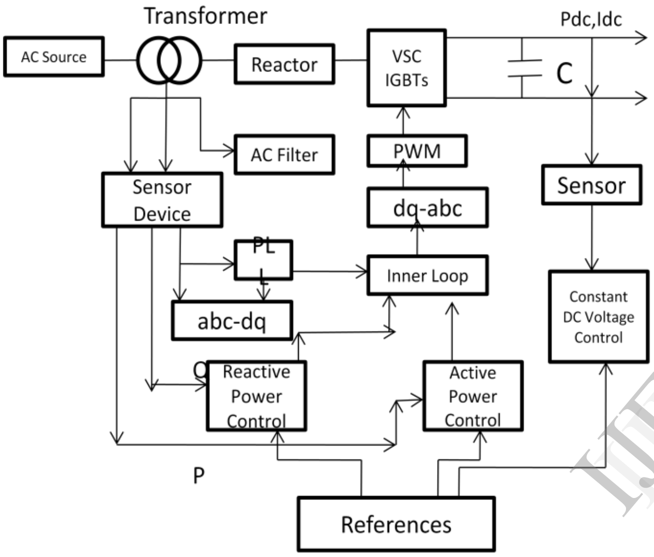


Fig. 3: VSC-HVDC control structure

A. Outer Loop Control

1) Constant DC Bus Voltage Control

According to (1),

$$Cu_{dc}\frac{du_{dc}}{dx} = u_{dc}i_{dl} - u_{dc}i_{dc} = p - u_{dc}i_{dc} \qquad (6)$$

In Steady state however, i_{dc} is constant and therefore the differential of u_{dc} is zero, so

$$u_{dc} = 3u_{sd}i_d/2i_{dc} \qquad (7)$$

When voltage and reactive power references $u_{dc}*$ and Q* are given, i_d* and i_q* can easily be obtained through the novel fuzzy PI regulators. The schematic of the control structure is given in Figure 4 where K_{dc} has to be defined and is the scale factor, $K_{dc} = 2U_{dc}*/3U_{sd}$, and the main function of the limiters is to restrict the amplitude of the current to avoid electronic equipment damage.

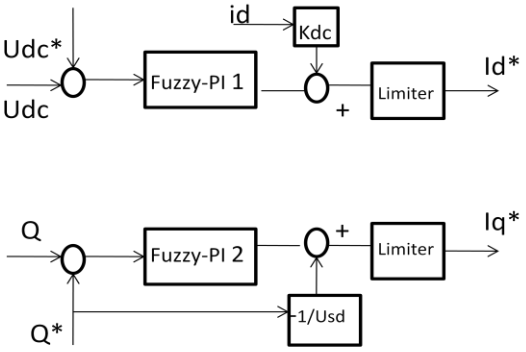


Fig. 4: Schematic of the DC line voltage control

2) Power Control

The schematic diagram for the power control is shown in Figure 6. As mentioned above when references P* and Q* are provided, then i_d* and i_d* can be obtained using the fuzzy logic PI controller.

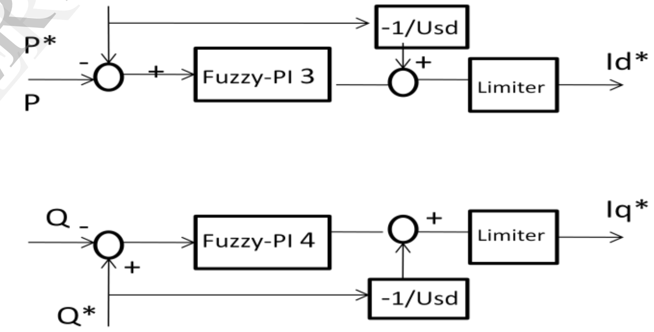


Fig. 5: Power Control

B. Inner Loop Control

Equation 1 can be modified as,

$$u_{cd} = u_{sd} - v_d + wLi_q \qquad (8)$$

$$u_{cq} = u_{sq} - v_q + wLi_d \qquad (9)$$

where, $$\begin{cases} v_d = Li_d/dt + Ri_d \\ v_q = Li_q/dt + Ri_q \end{cases} \qquad (10)$$

In order to decouple v_d and v_q PI regulators are used. Thus,

$$\begin{cases} v_d = K_{p1}(i_d * - i_d) + K_{i1}\int(i_d * - i_d)d \\ v_q = K_{p2}(i_q * - i_q) + K_{i2}\int(i_q * - i_q)d \end{cases} \quad (11)$$

Where K_p and K_i are the PI controller coefficients.

IV. ROBUST FUZZY PI-CONTROLLER

A combined novel Fuzzy-PI control strategy has been proposed to solve the problem of parameter uncertainty and non linearity in the VSC-HVDC. Figure 6 shows the schematic of the novel Fuzzy-PI control. The control strategy consists of the Fuzzy control in the large error range which provides robust control capability because of its insensitive nature to parameter variations while as the PI control is used to reduce the steady state error in the small error range.

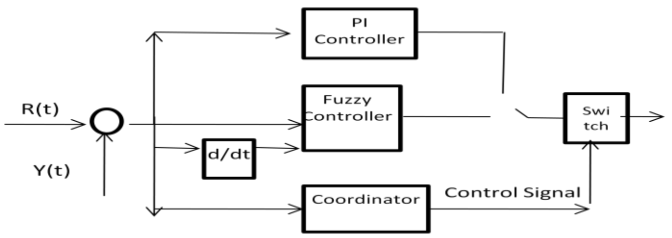


Fig. 6: Robust Fuzzy-PI Controller.

A coordinator is used for mode conversion. A threshold value of the error is assumed depending on the working conditions and if the error |e| exceeds the threshold ϵ the fuzzy control is activated; otherwise the conventional PI controller continues to work. Mode Shifting Algorithm is given by:

$$f(m) = \begin{cases} |e| > \epsilon \ \ (Fuzzy\ Control) \\ |e| < \epsilon \ \ (PI\ Control) \end{cases}$$

For the Fuzzy controller design the absolute value of the error between the actual value and the reference value, e and the error derivative ec are used as the input variables. Control signal u is the output variable. The value of the fuzzy variables can be either positive or negative or zero. The following 7 fuzzy sets are a direct consequence of the argument.

NS: Negative Small; NM: Negative Medium; NB: Negative Big; PB: Positive Big; PM: Positive Medium; PS: Positive Small; ZE: Zero.

Figure 7 is the input and output variable membership function.

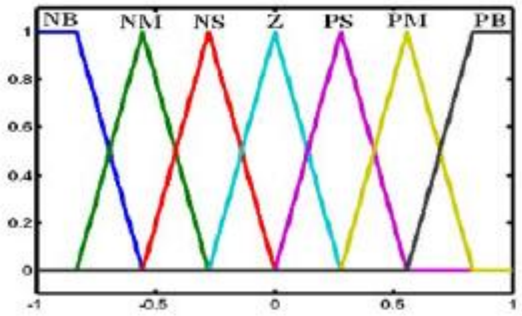


Fig. 7: Input Variable Membership Function

Fuzzy rules simply provide a mechanism in linguistic terms for the quantitative relationship between variables. For the current problem the rules are structured as:

$$r_i: IF\ e_N\ is\ A_i\ and\ ec_N\ is\ B_j\ THEN\ u\ is\ C_{ij}$$

Table 1 provides the set of control rules. Centre of gravity method is used for the process of defuzzification.

Table 1
The Fuzzy Control Rules

u		***e***						
		NB	NM	NS	Z	PS	PM	PB
ec	NB	PB	PB	PM	PM	PS	Z	Z
	NM	PB	PB	PM	PS	PS	Z	Z
	NS	PM	PM	PM	PS	Z	NS	NS
	Z	PM	PM	PS	Z	NS	NM	NM
	PS	PS	PS	Z	NS	NS	NM	NM
	PM	Z	Z	NS	NM	NM	NM	NB
	PB	Z	Z	NM	NM	NM	NB	NB

V. SIMULATION RESULTS AND ANALYSIS

MATLAB/ SIMULINK platform is used for the simulation of the two terminal VSC HVDC as shown is Figure 2 for the testing of the proposed control system. VSC1 is a constant active power control employing converter while as VSC2 is a DC voltage control employing inverter. Both the terminal of the system are active networks. The various parameters are: Per phased voltage magnitude Em=110 kV; Line resistance R = .075ohms; Line reactance L= 12mH; C= 50microF; L_{DC}=1mH; R_{DC}=.1 ohm; Power reference=100MW; Voltage reference= 50kV at AC side and 100 kV at DC side.

Figure 8 gives the various waveforms for the active power reference of VSC1 P* stepping from 1 to -1pu. The system responds ore robustly to the tidal current reverse. The conventional PI controller took more than 1 second to reach the steady state while as the Novel Fuzzy-PI controller to only .3 seconds (from 1.5s to 1.8s) thus reaffirming the capability of the proposed controller.

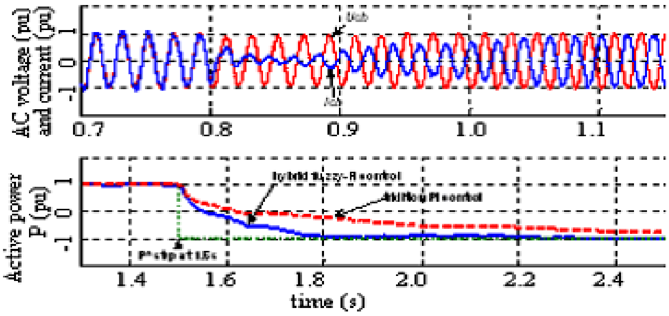
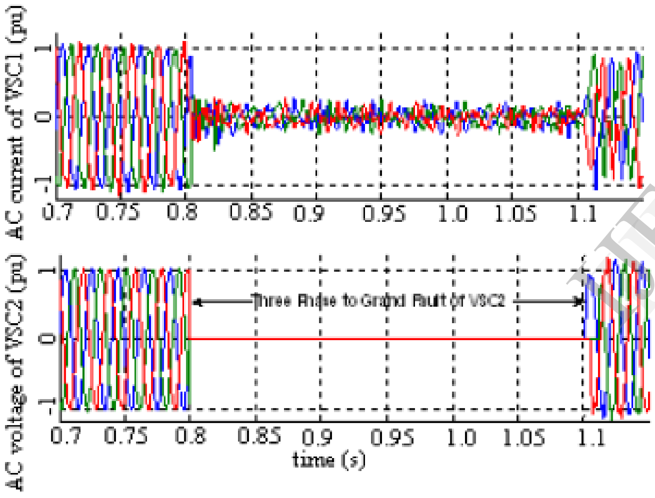


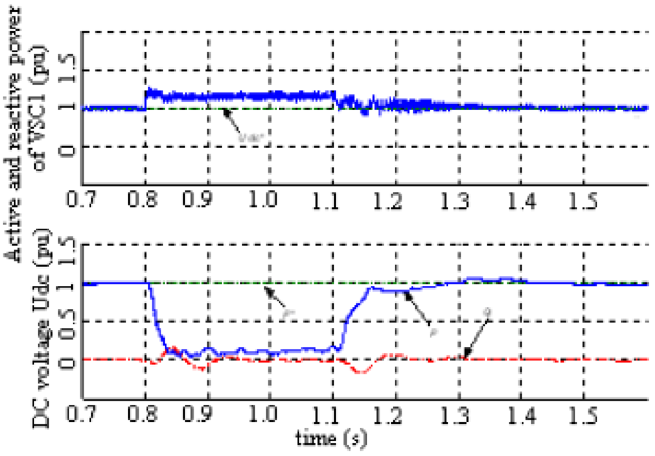
Figure 9 consists of the waveforms for a three phase to ground fault at VSC 2 from .8s to 1.1s. The transmitted DC power is almost stopped while as the DC voltage is increasing during the fault because of the excessive charging of the DC side capacitor during the fault. System is recovered in both the cases, however using the Novel Fuzzy-PI controller the system is recovered faster than the conventional PI controller.

The proposed controller for the VSC HVDC system has better transient and steady state characteristics than the classical PI controller.

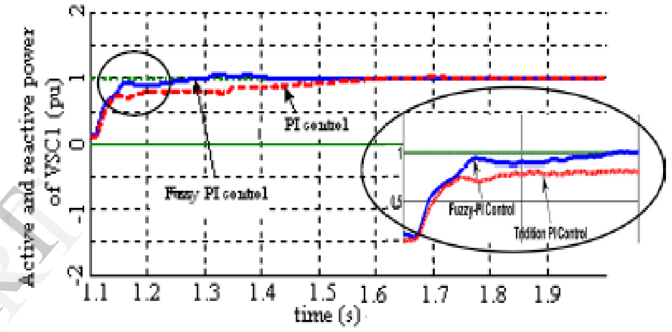


(a) AC current of VSC1 and AC voltage of VSC2.

Fig. 8: Simulation results under reference stepping



(b) DC line voltage and active/reactive power of VSC1.



(c) Performance comparison between fuzzy-PI and tradition PI.

Fig. 9: Simulation Results of three-phase to ground fault

VI. RESULTS AND DISCUSSIONS

The proposed combined Fuzzy-PI controller for the VSC-HVDC system combines the robust capability of the fuzzy logic controller and the global asymptotic stability of the PID controller. Better performances in the transient response and the steady state response are obtained in normal and abnormal conditions.

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