PERFORMANCE ANALYSIS OF SVPWM BASED FUZZY CONTROLLED HVDC LIGHT SYSTEMS

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Abstract: *In this paper, modeling of converter is described, and space vector pulse width modulation (SVPWM) scheme is utilized to control the HVDC Light system in order to achieve better DC bus utilization, harmonic reduction, and for reduced power fluctuations. Fuzzy logic PI controller is also implemented for controlling both the converters of the HVDC Light transmission systems. The simulations are carried out in the MATLAB/SIMULINK environment and the results are provided for steady state and dynamic conditions. Finally, the performance of SVPWM based fuzzy PI controlled HVDC Light transmission system is compared with the conventional PI controlled HVDC Light system for different perturbations.*

Key words: *VSC HVDC, HVDC Light, Space vector PWM, Fuzzy logic controller.*

1. Introduction

The conventional Line-commutated Current source Converter based HVDC (LCC-HVDC) transmission system is a power electronics technology used in power systems which can transmit large amount of power over long distances [1] - [2]. Due to advancement of power electronic technology, HVDC technology utilizes voltage source converters (VSC) with self-commutating IGBT converter valves and this technology is named as HVDC Light system [3] - [5]. The breakthrough was made when the world's first IGBT technology based HVDC Light system was installed in March 1997 (Hellsjon project, Sweden, 3MW, ±10kV, 10km distance) [3]. Since then many HVDC Light systems have been installed worldwide [5].

The HVDC Light system is different from the Conventional HVDC system in many aspects. Specifically, Pulse Width Modulation (PWM) technique is used in the HVDC Light system to create any desired voltage waveform, any phase angle and magnitude of the fundamental frequency component. The HVDC Light transmission system has several benefits [6] - [7].

- Since, IGBT can turn-off a current at any time, the HVDC Light system offers rapid and independent control of active and reactive power generated or consumed by the converters.
- The HVDC Light system provides a convenient and cost-effective way for connecting non-polluting and renewable energy sources to the main grid, with strong environmental benefits.
- The HVDC Light system allows the two converters to either generate or consume reactive power, to the AC side, and thus work as independent static VAR compensators on the AC sides.
- By eliminating the commutation failure problem, the HVDC Light system reduces the voltage dip and waveform distortions on the AC network.
- In the HVDC Light transmission system, without changing the polarity of the DC voltage, reversal of power flow can achieve by simply reversing the direction of DC current.
- By employing multi-level converter topologies, HVDC Light system inherently reduces the harmonics in the AC currents and voltages, and hence the size of the filters required is also small.
- With an excellent feature of the HVDC Light system so called “Black-start capability”, it can start up against a dead network.

Traditionally, both of the converters in the HVDC Light system are controlled by the pulses generated by Sinusoidal PWM (SPWM) scheme [8]. But the conventional SPWM has the limitations of incomplete utilization of dc bus voltage, high THD, and difficult to implement advanced vector control algorithms.

The main goal of this paper is to develop a control scheme of an HVDC Light transmission system by incorporating a fuzzy logic based PI controller in order to overcome aforementioned drawbacks and to suppress the power oscillations; thereby it improves the stability and overall system performance. Fuzzy logic controllers are superior over the conventional PI controllers, particularly for nonlinear systems such as HVDC Light systems. It doesn't depend on the detailed system modeling and is robust to different operating conditions [9].

2. Principle of HVDC Light system

A typical HVDC Light transmission system is shown in Fig.1. It consists of two identical neutral point clamped (NPC) VSC stations, which are linked with a DC cable. The main function of a transformer is to transform AC voltage into secondary voltage adapted to the DC link in the converter. Reactors are placed to secure the power exchanges between VSC and AC system. Filters are also introduced to absorb high frequency harmonics. Finally, the purpose of DC capacitors on the DC side on each converter is to provide voltage support and harmonic attenuation.

In Fig.1 AC side and VSC side having the line-to-line AC bus voltage V_s and converter AC voltage V_c respectively, are interconnected by a DC cable withthe reactance X. In steady state ignoring the harmonic components and resistance, the active power P, and reactive power Q absorbed by the VSC are given by the following relations:

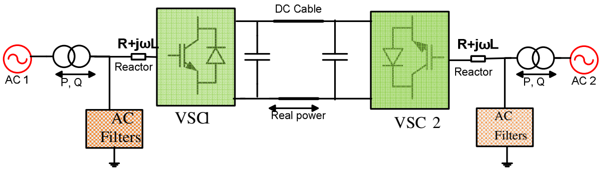


Fig 1. Typical HVDC Light transmission system

$$P = \frac{V_s V_c}{X} \sin \delta \tag{1}$$

$$Q = \frac{V_s (V_s - V_c \cos \delta)}{X} \tag{2}$$

Where δ is the phase angle of the fundamental component of PWM. Thus, it is possible to control P and Q independently by δ and V_c, respectively. When VSC operates as a rectifier, the converter output AC voltage lags AC bus voltage by an angle δ; when VSC operates as an inverter, the converter output AC voltage leads by an angle δ.

3. Mathematical Modeling and Control

A plethora of excellent publications exists in the literature associated with the HVDC Light system, in the area of modeling and control. Each station in the HVDC Light system is coupled with AC network via line resistor R, phase reactor L and a DC capacitor C is in parallel to the DC bus of the station shown in Fig. 1. The following equations are obtained in the d-q synchronous frame [10].

$$V_{sd} - V_{cd} = L\frac{di_d}{dt} + Ri_d + \omega L i_q \tag{3}$$

$$V_{sq} - V_{cq} = L\frac{di_q}{dt} + Ri_q - \omega L i_d \tag{4}$$

Where V_{sd} and V_{sq} are source voltages, i_d and i_q are line currents, V_{cd} and V_{cq} are converter input voltages.

Based on the instantaneous reactive theory, neglecting the losses of the converter and the transformer, the active and reactive power exchanges from the AC end of the DC link are:

$$P_{ac} = \frac{3}{2}(V_{sd} i_d + V_{sq} i_q) \tag{5}$$

$$Q_{ac} = \frac{3}{2}(V_{sd} i_q - V_{sq} i_d) \tag{6}$$

Set the direction of the source voltage vector as d-axis, $V_{sq} = 0$. So (5) and (6) can be written as:

$$P_{ac} = \frac{3}{2} V_{sd} i_d \tag{7}$$

$$Q_{ac} = \frac{3}{2} V_{sd} i_q \tag{8}$$

Since V_{sd} is constant, from (7) and (8) it is clear that the active power will be controlled by i_d, whole the reactive power will be controlled by i_q.

On the DC side of the converter, DC current and DC power are;

$$i_{dc} = C\frac{dv_{dc}}{dt} + i_c \tag{9}$$

$$P_{dc} = V_{dc} i_{dc} \tag{10}$$

Where i_{dc} is the DC current to be followed by the capacitor, v_{dc} is the DC link voltage and i_c is the current on the DC cable. Neglecting the loss of converter, power of AC side equals to the DC side.

$$P_{ac} = P_{dc} \tag{11}$$

$$\frac{3}{2} V_{sd} i_d = V_{dc} i_{dc} \tag{12}$$

The AC voltage of VSC can be described as,

$$V_c = \frac{m}{\sqrt{2}} V_{dc} \tag{13}$$

Where V_c is the converter ac voltage and, m is the modulation ratio. In general the converters are controlled through Sinusoidal PWM (SPWM), where the modulating signal is a sinusoidal one and the carrier signal is a triangular signal and the ratio between the two peak values is known as modulation ratio (m). But in the space vector PWM, modulation ratio 'm' is given by:

$$m = \sqrt{3} \frac{V_{ref}}{V_{dc}} \tag{14}$$

The value of m can be :

$$0 \leq m \leq 1$$

Fig.2 shows an overall control structure of the NPC converter station and its interface with the main circuit. The station1 and station 2 controller designs are identical. In the present case, controlled parameters are :

- Active power (P) and reactive power(Q) in station 1
- DC voltage (V_{dc}) and reactive power(Q) in station 2.

The phase locked loop (PLL) block measures the system frequency and calculates the phase angle (θ) for the dq transformation block. The active/ reactive power and voltage loop block in Fig.2 contains the outer loop regulators that calculate the reference value of the converter current vector (I_{ref_dq}), which is the input to the inner current loop.

Inner current loop block contains two PI regulators that will calculate the reference value of the converter voltage vector (V_{ref_dq}). By using clarke's transformation V_{ref_dq} is transformed into V_{ref_abc} , which is the input to the space vector pulse width modulation (SVPWM). Due to inherent unbalance in the circuit components impedance, there may be some deviations in the DC side pole voltages. DC voltage balance control block is to maintain the dc side of the three level bridge balanced.

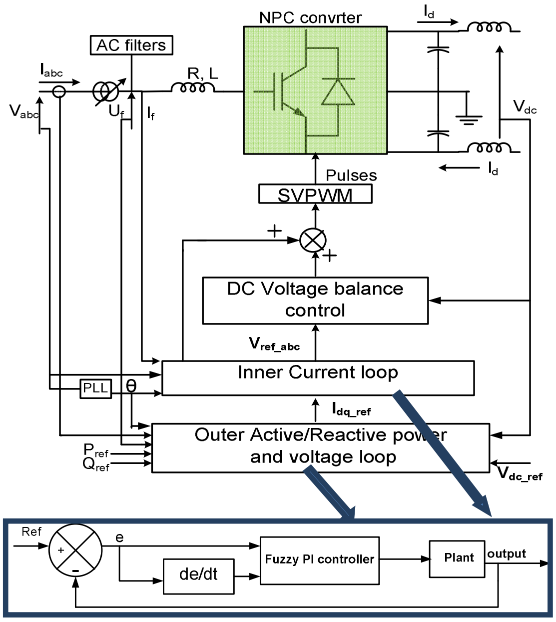


Fig 2. Overall control structure of converter

4. Space Vector PWM for three-level Converters

A three phase three level neutral point clamped (NPC) converter is shown in Fig 3. It consists of 12 IGBT's (4 on each leg) and also supplied with two capacitors to split the DC voltage into two, for providing the neutral point. Space vector pulse width modulation (SVPWM) scheme is a new concept for HVDC Light applications. It is based on the space vector representation of the voltages on the two phase coordinates [11]. Initially, using park's transformation, three phase quantities are transformed into their equivalent two phase quantities either in the stationary or synchronously rotating frame, where the total power and impedances, are remains same. The resultant of these two components gives the V_{ref} vector magnitude, which will decide the converter output.

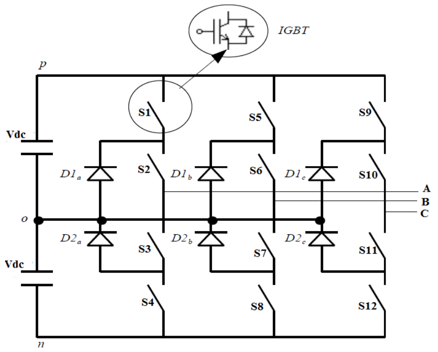


Fig 3. A three phase three-level NPC converter

5. Step by Step Algorithm for realization of SVPWM

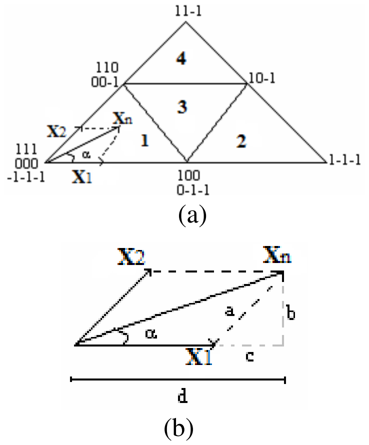
Step 1: Calculate V_d, V_q, V_{ref} and the angle (α) by using park's transformation.

Step 2: After Calculating α, determine the sector depending on the position of V_{ref} as shown in table 2.

Table 2. Sector calculation based on v_{ref} location

Range of α (degree)	Location of V_{ref}
$0 \le \alpha < 60$	Sector I
$60 \le \alpha < 120$	Sector II
$120 \le \alpha < 180$	Sector III
$180 \le \alpha < 240$	Sector IV
$240 \le \alpha < 300$	Sector V
$300 \le \alpha < 360$	Sector VI

Step 3: Determine the region in the corresponding sector. To estimate the region in sector I, space vector diagram for X_1 and X_2 is shown in Fig 4. and corresponding switching logic is given in table 3.



(a)

(b)

Fig 4. Space vector diagram for X_1 and X_2 in Sector I.

$$a = X_2 = \frac{b}{\sin(\pi/3)} = \frac{2}{\sqrt{3}} b = \frac{2}{\sqrt{3}} X_n \sin\alpha \qquad (15)$$

$$X_1 = X_n \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right) \qquad (16)$$

Step 4: Determine the switching time of each switch in all the regions. Following equations gives the switching time in region 1:

$$T_a = 2mT_s \sin\left(\frac{\pi}{3} - \alpha\right) \qquad (17)$$

$$T_b = \frac{T_s}{2}\left(1 - \left(2mT_s \sin\left(\frac{\pi}{3} + \alpha\right)\right)\right) \qquad (18)$$

$$T_c = 2mT_s \sin(\alpha) \qquad (19)$$

Where ‘m’ is the modulation index and $0 \leq \alpha \leq \pi/3$.

Table 3. Logic used to find the region in which v_{ref} is located

X_1 and X_2	Position of V_{ref}
X_1, X_2 and $(X_1 + X_2) < 0.5$	Region 1
$X_2 > 0.5$	Region 2
$X_1 > 0.5$	Region 3
X_1 and $X_2 < 0.5$ and $(X_1 + X_2) > 0.5$	Region 4

6. Fuzzy Logic Controller

In HVDC Light transmission systems, active and reactive power is controlled by using different types of controllers. In general, conventional PI controllers are used for this application. The gain values used in conventional PI controlled system are:

$K_P = 3$; $K_I = 20$ (For P and Q control modes at station 1)

$K_P = 2$; $K_I = 40$ (For DC voltage control mode at station 2)

$K_P = 3$; $K_I = 25$ (For Q control mode at station 2)

But, these controllers are designed to work at a particular operating point; any disturbance may cause deterioration of the controller performance. To avoid such a situation, fuzzy PI controllers are introduced to control above parameters in the HVDC Light transmission systems. Fig. 2 shows the overall structure of the proposed controller.

In this research work, four PI controllers are used to get faster response and smaller overshoot. Fig.3 shows the inner structure of the fuzzy PI controller. The basic fuzzy logic controller is composed of four function blocks as depicted in Fig.5. These are fuzzifier block, knowledge base, inference engine and defuzzifier block. There are two inputs for each of the fuzzy logic controller, namely, error (e), change of error (de) and the output known as gain(K_p and K_i) [12].

Here, the data of two inputs i.e. error and change of error are transformed into linguistic variables by fuzzifier. Then, the linguistic variables are processed by the fuzzy rules in the rule base in the form of “If – Then” through fuzzy implication. To fuzzify both input data and output, triangular membership function set is used in this paper with five linguistic variables viz, Negative large (NL), Negative small(NS), zero (Z), positive small (PS) and positive large (PL). The membership functions used for the input and output variables in the fuzzy logic tool box are shown in Fig.6. The knowledge base unit has two components, the data base and the rule base. The rule base is shown in the table .4, which is dependent on the system. The inference engine executes the inference operations on the rules.

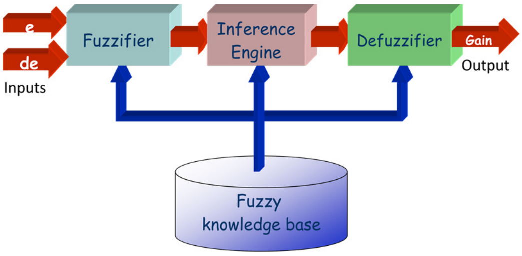
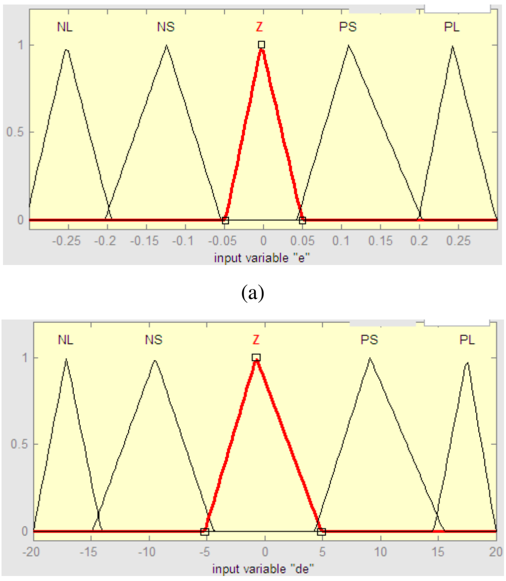


Fig.5. Inner structure of fuzzy logic controller

The proposed system will have a total number of 25 fuzzy rules, each one of which is formulated in the “*IF –THEN*” form like,

IF error (e) is NL and change of error (de) is NS, *THEN* output gain is Z.



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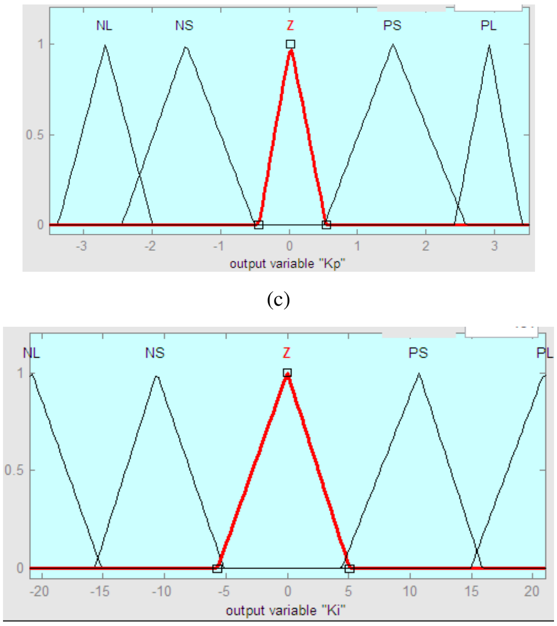

(c)

(d)

Fig. 6. (a) Error (b) change of error (c) K_p (d) K_i membership functions

TABLE.4. Rule base for fuzzy PI controller

e / de	NL	NS	Z	PS	PL
NL	NL	NL	NS	Z	PS
NS	NL	NS	NS	NL	PS
Z	NS	NS	Z	PS	PS
PS	Z	NL	PS	PS	PL
PL	PS	PS	PS	PL	PL

Here, the controlled output is estimated by the center average method, which can be written as:

$$\mu^{crisp} = \frac{\sum_{i}^{n} b_i \mu_i}{\sum_{i}^{n} \mu_i} \tag{20}$$

Where, μ_i = output label for value contributed by the i th membership function.

b_i= Center of i th membership function

n= Number of contributions from the rules.

7. Simulation

System data:

AC systems1&2:100kV, 50 Hz, Smoothing reactor: 8mH; Grid-filter: 0.75Ω, 0.2H;
DC line: ±100kV, 100km; DC link capacitor:70μF; Switching frequency :1350 Hz;

The operation of this control strategy in the HVDC Light transmission system was verified in a MATLAB/SIMULINK environment for a steady state, single phase to earth fault and three phase fault at t = 1.0 s.

8. Result analysis

In this paper, conventional PI and fuzzy logic PI controlled SVPWM based HVDC Light transmission systems were simulated for single phase to ground fault, three phase short circuit fault and the results were shown in Figs. 7 to 10. Here, the limiting values of the gains for all the controllers are the same as in the conventional PI controlled system. The dynamic performance of the test system has been studied for different perturbations on an inverter AC bus.

Fig.7 and Fig.9 shows the rectifier side active and reactive power responses of an HVDC Light transmission system for a single phase and three phase short circuit fault between 1s~1.1s at the inverter side AC bus. Similarly, active and reactive powers on the inverter side for the same fault condition are depicted in Fig. 8 and 10. After clearing the fault, proposed system was smoothly recovered to its pre-fault condition with smaller peak overshoot.

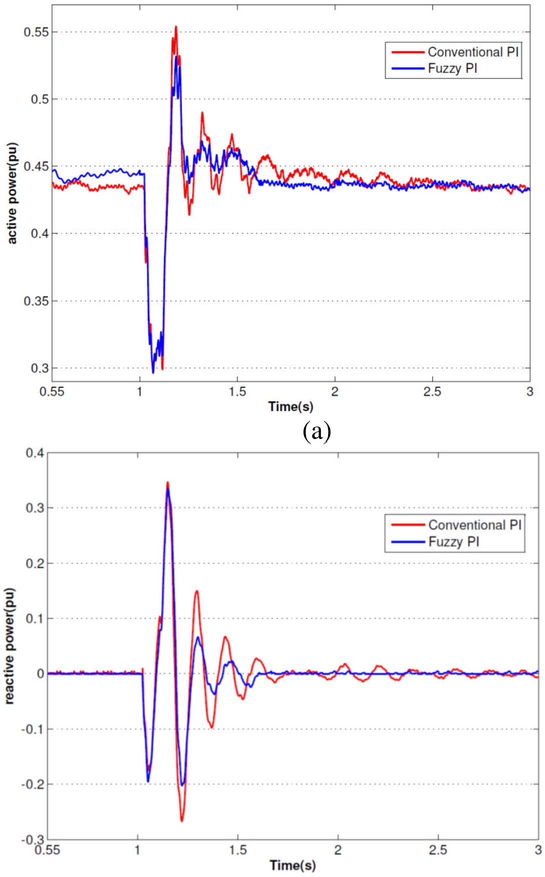

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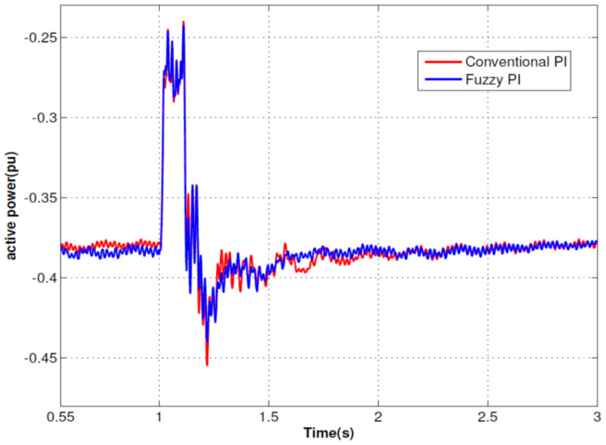
Fig.7. (a) Active power (b) reactive power at the rectifier AC bus for a 5 cycle single phase to ground fault on the inverter side AC bus



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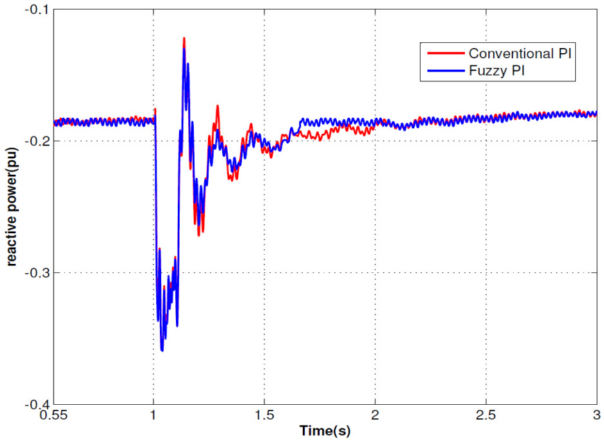

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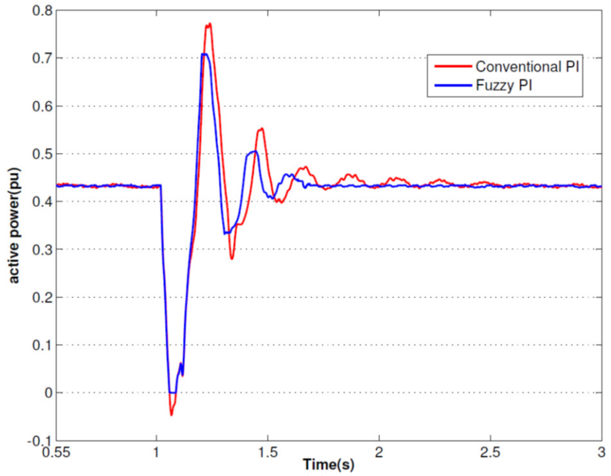
Fig.8. (a) Active power (b) reactive power at inverter AC bus for a 5 cycle single phase to ground fault on the inverter side AC bus



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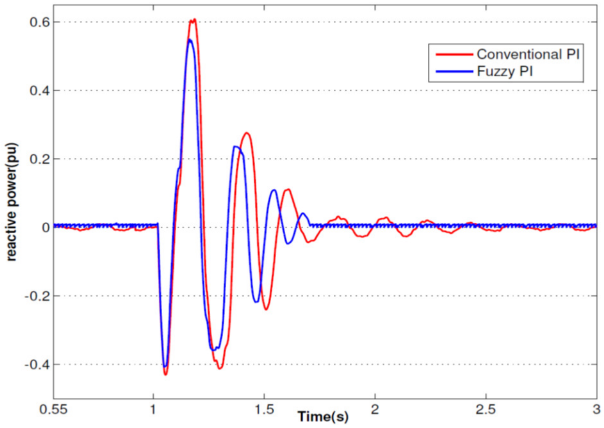

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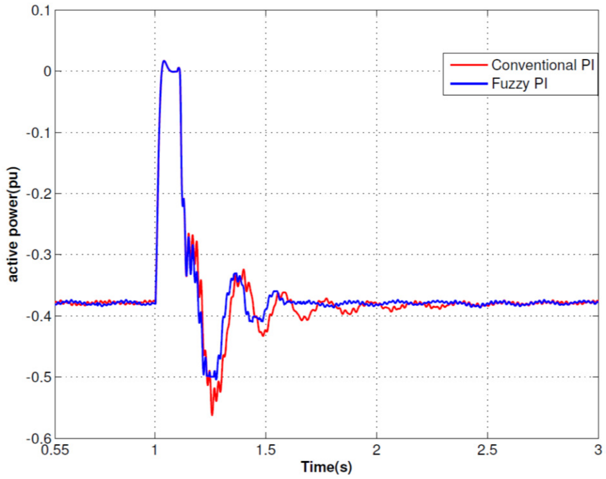
Fig.9. (a) Active power (b) reactive power at rectifier AC bus for a 5 cycle three phase fault on inverter side AC bus



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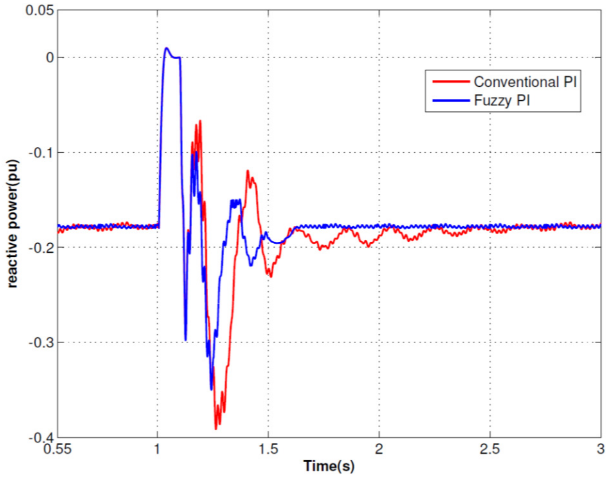

(b)

Fig.10. (a) Active power (b) reactive power at inverter AC bus for a 5 cycle three phase fault on inverter side AC bus

9. Conclusion

In this paper, the stability improvement of two AC systems connected through a SVPWM controlled HVDC Light transmission system using an intelligent controller has been validated. A fuzzy logic PI controller has been designed to improve the dynamic performance of the studied system and simulation study has been carried out to compare the effectiveness of the proposed controller. It is clear from the simulation results that, the dynamic performance of the test power system is better for the fuzzy logic PI controller compared to the conventional PI controller for the AC faults at the inverter end. Hence, it can be concluded that the proposed controller in the HVDC Light system will offer better solutions in the future in order to meet the grid code requirements.

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