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THE IMPACT OF A FUZZY SELF-TUNING PI CONTROLLER SUPPORTED BY STATCOM ON LCC-HVDC SYSTEM CONNECTED TO WEAK AC GRID IN BOTH SIDE

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Abstract

The AC/DC interaction between an HVDC system and the adjacent weak AC system is very sensitive to disturbances. For this reason, this paper presents an effective control system integrated in HVDC system, based on the use of different values of proportional and integral gains varied online by fuzzy self-tuning PI controller (FSTPIC) according to necessity, supported by a static synchronous compensator (STATCOM) to compensate the reactive power and achieve improved performance of the HVDC system. The fuzzy logic device has self-adaptive input gains to ensure normalization between -1 and +1 of the input signals. To evaluate the effectiveness of the proposed a control strategy, a comparison is made on four cases of CIGRÉ HVDC benchmark model, the first is conventional system (PI controller only), the second HVDC system with fuzzy Self-Tuning PI Controller, the third is HVDC system with the STATCOM only and finally HVDC system with fuzzy self-tuning PI controller and the STATCOM. This comparison is done for different types of defaults like the single-phase short circuit to ground and three-phase short circuit to ground inverter side of LCC-HVDC transmission link system.

Keywords: LCC-HVDC system, Fuzzy self-tuning PI controller, STATCOM, CIGRÉ HVDC benchmark model, Commutation failure.

1.Introduction

The production and distribution of electrical energy is carried out in the form of AC because of the ease of production, the possibility of changing the voltage value and the ease of switching-off. However, control of AC power transportation poses extra challengers difficult to solve.

Nomenclatures

I_d	The direct current, A
I_{dmes}	The measured direct current, A
I_{dref}	The reference direct current, A
P	The active power, W
P_{dc}	The continuous power, MW
Q	The reactive power, var
S_{SC}	The short-circuit power, MVA
X_{sh}	Equivalent reactance between transformer and filters, Ω

Greek Symbols

α	Firing angle of converters, deg
α_{min}	Minimum value of firing angle, deg
γ	Extinction angle, deg
γ_{mes}	Extinction angle measured, deg
γ_{ref}	Extinction angle of reference, deg
ω_i	The membership grade of the output membership function
δ	The angle of busbar voltage V_r with respect to STATCOM voltage V_{sh}, deg

Abbreviations

AC	Alternative Current
DC	Direct Current
FSTPIC	Fuzzy Self-Tuning PI Controller
HVDC	High Voltage Direct Current
LCC	Line-Commutated Converter
MFs	The Membership Functions
PI	Proportional Integral
SCR	The Short Circuit Ratios
STATCOM	Static Synchronous Compensator
VSC	Voltage-Sourced Converter

There are situations in which the transmission of DC power is more advantageous than AC power, especially when reactive power compensation and stability become difficult to guarantee. In cases when it is vital to develop innovative solutions to improve stability and prevent congestion, the HVDC links may prove to be a good reliability of control. On another hand, it is the most cost-effective solution as they can minimize and even eliminate the need for additional transmission lines [1].

Generally, the HVDC systems are used for long distance transmission, due to less electrical losses than the alternating current. Sometimes, HVDC for shorter distances is necessary despite the higher costs because of other benefits achieved, such as improving system stability and interconnection between asynchronous AC systems.

HVDC is actually a part of the electric grid in different places of the power transmission system. Therefore, the interaction with AC system imposes itself. Especially in the case of weaker adjacent AC systems, the AC/DC interaction becomes more sensitive to disturbances which lead to the need of research for improved solutions. The nature of HVDC converters based on power electronics, which related to non-linear behaviour, results in undesirable increase of current harmonics, high reactive power consumption, low power factor and overall weakness of performance. In addition, the highly non-linear nature of the control loops requires a wide parameter control that takes into account a range of operating conditions and propose appropriate solutions if necessary [1-3].

The controllability of an HVDC link can be used to enhance the stability of its associated AC systems. This feature can be achieved by modulating the DC power. Thus, there is a need for supplementary HVDC controls to improve system dynamic performance [1].

The general objective is the construction of a valid and appropriate strategy of control, for the different operating conditions, so the equilibrium between speed response and stability must be respected, in case of small disturbances on the one hand, and on the other hand, the system have to support disturbances due to both faults and switching.

Recently, the intelligent control systems such as fuzzy logic controllers do not need an accurate mathematical model; they can continue with imprecise inputs and are able to work well in non-linear conditions. The fuzzy controllers are applied to HVDC systems to dampen the dynamic oscillations. Actually, these controllers provide good control performance when the systems are complex and cannot be analysed [3-5].

LCC-HVDC converters inherently consume large amounts of reactive power. There are special disadvantage when connecting to weak AC systems such as high temporary over voltages, low frequency resonances, risk of voltage instability, harmonic instability, long fault recovery times and increased risk of commutation failure. Many of these disadvantages are closely related to the AC voltage regulation at the converter bus. One of the possible means of voltage regulation is the use of STATCOM which is developed as a reliable method to compensate the reactive power [6].

It is clear that an HVDC system supported by a fuzzy self-tuning PI controller and STATCOM can work well. Accordingly, it is possible to test the proposed strategy in order to find a better solution.

The strategy of control is based on the tuning of PI controllers gains on-line by the fuzzy logic using the error and the error rate as inputs of the FSTPIC. The output gains of the controller leads the signal to follow the reference. On the other hand, the STATCOM is integrated to compensate the reactive power [6-8].

Different cases of study of CIGRÉ HVDC system are performed to validate the performance of proposed devise. Results show a promising response with FSTPIC and STATCOM witch improved stability of the HVDC system as compared with conventional control schemes. The rest of the paper is organized as follows: Section 2 describes the HVDC system model. The Interaction between DC and AC system is explained in Section 3. Section 4 Show the principles of HVDC control. Proposed controller for HVDC system is presented in section 5. Results are presented and discussed in Section 6. Section 7 concludes the results of this research work.

2. HVDC System Model

The system model is the first CIGRÉ HVDC benchmark system supported by (FSTPIC) and STATCOM illustrated in Fig. 1. The simulation of this system is realized in Matlab/Simulink.

The HVDC model system is mono-polar 500kV, 1000 MW HVDC link with a twelve pulse converters on each sides (rectifier and inverter). Each converter station has a 12-pulse thyristor based Line-Commutated Converter (LCC) which is formed by two six pulse Graetz converter bridges.

- Rectifier: 2.5∠84° at 50 Hz.
- Inverter: 2.5∠75° at 50 Hz.

The data system and a detailed model for HVDC system can be found in [2, 7-9].

3. Interaction with DC and AC System

The study of interaction between high voltage power systems (HVDC) and AC systems is necessary to improve the performance of HVDC power system. The degree of AC/DC interaction depends on the capacity of the adjacent AC network of the HVDC link compared to the transmitted DC power.

In order to determine the degree of interactions and influences, the strength of an AC/DC conversion system must be characterized. The strength AC/DC system is defined by the relative term Short Circuit Ratio (SCR). The SCR can usually be expressed as the ratio of the short-circuit power S_{SC} at the connection point from the station with AC systems to the continuous power P_{dc} of converters, it means that:

$$SCR = \frac{S_{SC}}{P_{dc}} \tag{1}$$

where:

$$S_{SC} = \frac{U^2}{Z_S} \tag{2}$$

Both side of HVDC are connected to the weak AC system, which is a good choice for the test in HVDC control studies [7].The Short Circuit Ratios (SCRs) for the CIGRÉ HVDC model are:

- Where: S_{SC}, U and Z_S are short-circuit power of the alternative network, the AC voltage between phases and the impedance of the AC network at the fundamental frequency respectively.
- The classification of the AC/DC system depends on the use of the short-circuit ratio (SCR). This classification is as follow: very weak systems have an SCR less than two, weak systems have a value between two and three while in strong systems, SCR is greater than three [10-11].

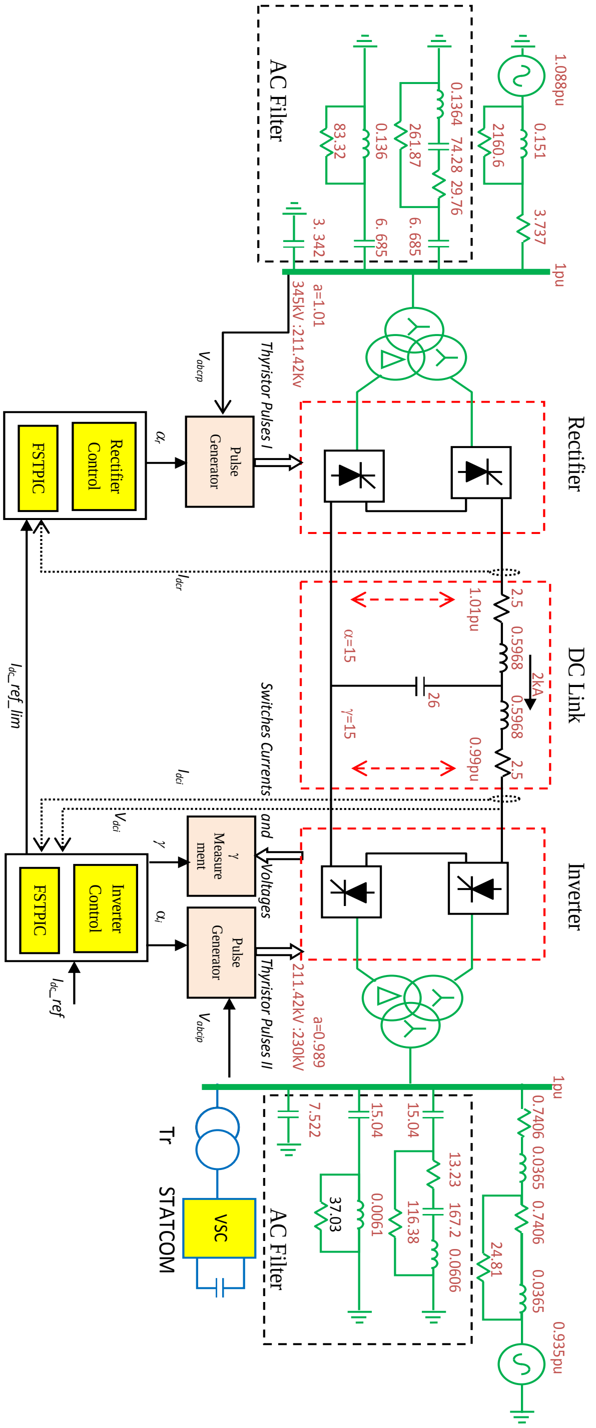

Fig. 1. Schematic diagram of HVDC system model.

- The interaction between the LCC-HVDC system and the weaker adjacent AC system occurs in many manifestations such as overvoltage, low frequency resonances, long recovery time after fault, large amounts of reactive power consumption and the occurrence of commutation failure. Thus, the objective is to reduce the AC/DC interaction and bring back the weak HVDC system to a similar behavior of a strong system [3-4].

4. Principles of HVDC Control

The essential role of control systems is to distribute a sequence synchronous pulse to the valves AC/DC of converter station network that puts them in conduction. The sequence should be very regular to reduce operating disequilibrium, eliminate harmonics and to allow the controllability of the voltage.

The power flow adjustment is based on the setting of the voltage on the rectifier or inverter. This setting is made with a quick adjustment on the angles of fire of the valves. Figure 2 shows the equivalent circuit of a single-pole HVDC link.

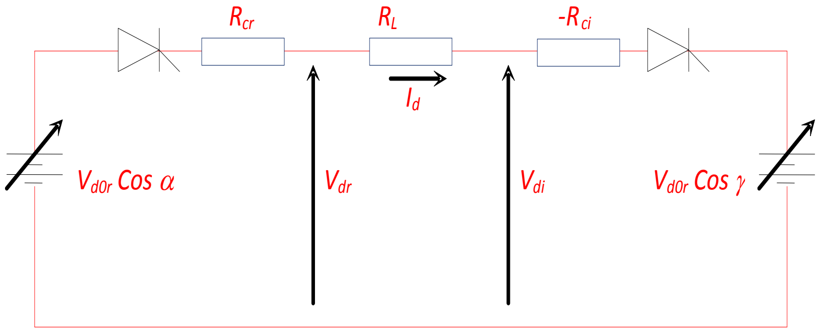

Fig. 2. The equivalent circuit of a single-pole HVDC link.

The direct current I_d, flowing from the rectifier to the inverter is [12]:

$$I_d = \frac{(V_{d0r}\,Cos\alpha - V_{d0i}\,Cos\gamma)}{R_{cr} + R_L - R_{ci}} \tag{3}$$

where: V_{d0r}, V_{d0i}, R_L, R_{cr} and R_{ci} are an open circuit rectifier DC voltage, an open circuit inverter DC voltage, resistance of DC line, equivalent resistances of the rectifier switching and equivalent resistances of inverter switching, respectively.

According to Eq. (3), a small variation of V_{d0r} or V_{d0i} voltages can cause a very large change of the direct current I_d because the resistance of the DC line and the other resistors of the converters are relatively low. It is essential to design a control system to solve this problem of instability.

There are several basic objectives of an HVDC system control, such as the transmitted power with good accuracy and sufficient velocity, provision of eligible commutation voltage to avoid commutation failure (specially in inverter side), low losses, low reactive power consumption in the converter and ensuring proper operation with fast and stable recoveries during AC system faults, or disturbance.

The conventional HVDC system uses the PI controller to control these converters. In case of strong AC system, the system performance is acceptable and all control settings are adequate for a given power flow. But the control performance of HVDC is very difficult to assure if the SCR of AC system is low. It is possible that a large change in power can be made when there are relatively small changes in the angle of firing. This leads to the conclusion that we can regulate the power of HVDC link by acting on the firing angles.

The control functions, which allow adjustment of the converter, will ensure at the level of the converters. In the rectifier, in order to avoid commutation failure, a minimum value of the firing angle α_{min} must be ensured in order to ensure sufficient voltage across the valves before these gates get the firing order**.**

Another mode in rectifier control by using a control loop that ensures an increase of the firing angle α in case when the measured current (I_{dmes}) is greater than the value of the reference current (I_{dref}) and decrease in the contrary. For the inverter, the setting mode is made to determine its firing angle, which allows obtaining an extinction angle γ desired by the control loop that compares the angles prior extinctions (γ_{mes}) to a reference set (γ_{ref}) and make it in the good sense.

Sometimes, an AC voltage controller mode is applied at the inverter end, when PI controller is used to generate inverter firing angle. Where, alpha order is selected by the minimum value in output of three PI controllers; voltage, gamma and current controller. This allows the use of new techniques for the development of controller, such as the application of artificial intelligence which provides good efficiency, particularly in complex systems where a simple mathematical model is not available. As an example, the fuzzy logic permits the use of linguistic rules and human experiences to facilitate control and access to satisfactory results compared to traditional PI controller [12-15].

5. Proposed Controller for HVDC System with STATCOM

5.1. The fuzzy self-tuning PI controller

The fuzzy self-tuning PI controller based on fuzzy logic is combined with conventional PI controller in both sides of converters, for updating online the values of the classical PI gains (K_p and K_i) of current and voltage regulators of rectifier and inverter respectively. The errors for the regulators and their derivatives are used as inputs to the fuzzy self-tuning PI controller. Figure 3 shows the principle of its integration in HVDC system. Let:

$$E = g_{ref} - g_{meas} \tag{4}$$

$$R = \frac{(E - E_{prev})}{T_s} \tag{5}$$

where: E, E_{prev}, R, g_{ref}, g_{meas} and T_s are the error between reference greatness and measured greatness, previous value of error, the error rate, the reference greatness, the measured greatness and the sampling time, respectively.

The inputs (E and R) and the outputs (ΔK_p and ΔK_i) from the fuzzy schemes are fuzzified by seven sets, namely, PB: Positive Big, PM: Positive Medium, PS: Positive Small, Z: zero, NS: Negative Small, NM: Negative Medium, NB: Negative Big. The membership functions are considered as triangular for (PM, PS, Z, NS and NM), and trapezoid for (PB and NB) as shown in Fig. 4.

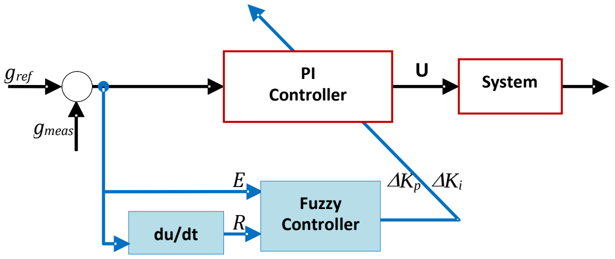

Fig. 3. Block diagram of fuzzy-PI controller.

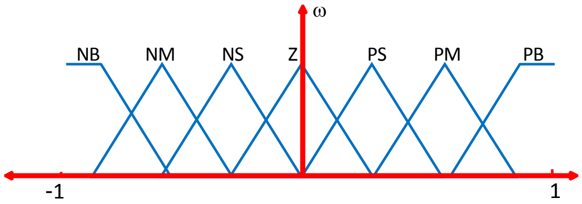

Fig. 4. Membership function of inputs.

The initial values of the proportional and integral gains (K_{p0} and K_{i0}) of the conventional PI controller are found using trial and error (tuned to best performance). The error and rate of change of this error are taken as inputs to the fuzzy logic controller. These inputs are normalized and then fuzzified using MFs. Then, these fuzzified inputs are applied to the rule base for finding the output from the fuzzy logic controller *Delta* K_p and *Delta* K_i in Fig. 5, where these outputs can be scaled using the scaling factors k_p and k_i (can be obtained by Genetic Algorithms) to obtain the best possible performance.

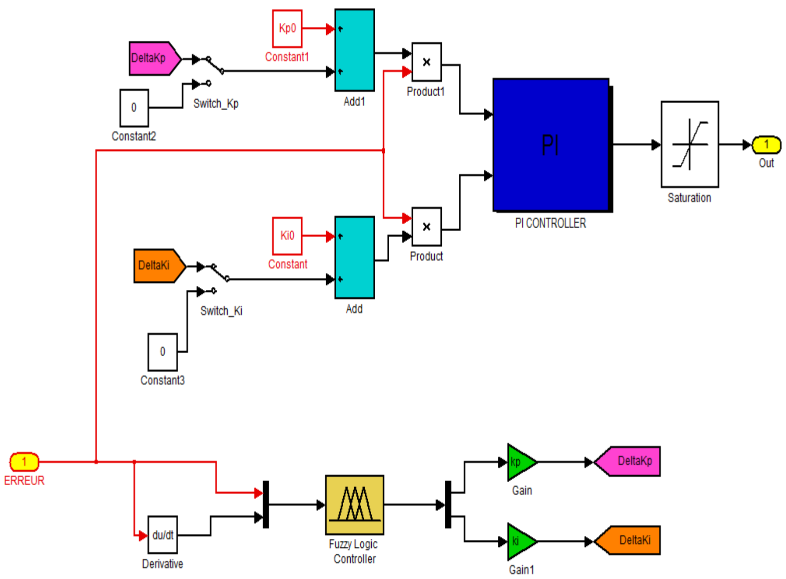

Fig. 5. Fuzzy self-tuning PI controller in MATLAB/SIMULINK.

The rules base of outputs is summarized in Table 1 and Table 2 respectively.

Table 1. K_p control rules.

"ERR"	"ERR RATE"						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NB	NM	NS
NM	NB	NB	NM	NM	NM	NS	Z
NS	NB	NM	NS	NS	NS	Z	Z
Z	Z	Z	Z	Z	Z	Z	Z
PS	Z	Z	PS	PS	PS	PM	PB
PM	Z	PS	PM	PM	PM	PB	PB
PB	PS	PM	PB	PB	PB	PB	PB

Table 2. K_i control rules.

"ERR"	"ERR RATE"						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NS	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NS	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PS	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

Defuzzification is carried out using the centroid defuzzification method to obtain crisp values of ΔK_p and ΔK_i, where the center of gravity is used as final output. The output is:

$$\Delta K = \frac{\sum \omega_i * z_i}{\sum \omega_i} \tag{6}$$

where: ω_i and z_i are the membership grade of the output membership function and the output variable, respectively.

The output of the fuzzy logic controller is used to solve the problem of fixed proportional and integral gains of a conventional PI controller (Fig. 6). The gains K_p and K_i of PI controller are updated online using the fuzzy logic controller according to the following equations:

$$K_p = K_{p0} + k_p * \Delta K_p \tag{7}$$

$$K_i = K_{i0} + k_i * \Delta K_i \tag{8}$$

where: K_{p0}, K_{i0}, ΔK_p, ΔK_i, k_p, k_i initial proportional gain, initial integral gain, output of proportional gain, output of integral gain, scaling factor from output of proportional gain and scaling factor from output of integral gain, respectively [3, 8, 10, 15-18].

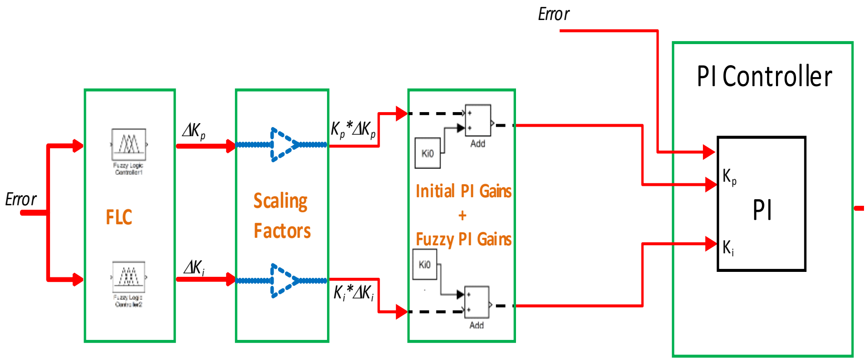

Fig. 6. Integration of FSTPIC in conventional PI controller of HVDC system.

5.2. Operation principle and insertion of STATCOM in HVDC systems

The STATCOM is a shunt device, which uses force-commutated power electronics to control power flow and improve transient stability on electrical power grids. The STATCOM based on a Voltage-Sourced Converter (VSC) is connected to the grid using a coupling transformer at the inverter side of the HVDC link and has a rating of ±100 MVA. It consists of a three-level 48-pulse inverter and two series-connected 3000 μF capacitors which act as a variable DC voltage source.

The role of STATCOM is to exchange reactive power with the network through a three-phase inductor, the latter being in general the leakage inductance of the coupling transformer. The reactive energy exchange is done by controlling the voltage of the inverter V_{sh}, which is in phase with the bus-bar voltage V_r where the STATCOM is connected [6, 19].

The flow of active power P and reactive power Q between these two voltage sources is given by:

$$P = \frac{V_r V_{sh} \sin\delta}{X_{sh}} \tag{9}$$

$$Q = \frac{V_r (V_r - V_{sh} \cos\delta)}{X_{sh}} \tag{10}$$

From the Eq. (9) and (10), it can be seen that when the two voltages are in phase (δ = 0), there is only a reactive power flows, the value of the power exchanged depending only on the amplitude of the two voltages V_r and V_{sh}.

Three possible cases can be considered ($\delta = 0$) [11]:

- If $V_{sh} < V_r$, the current in the inductance is shifted by $+\pi/2$ with to the voltage V_r and the current is capacitive.
- If $V_{sh} > V_r$, the current in the inductance is shifted by $-\pi/2$ with to the voltage Vr and the current is inductive.
- If $V_{sh} = V_r$, the current in the inductance is zero, there is no exchange of energy.

6. Simulation Results and Discussion

In order to study the performance of the HVDC system, two cases of fault are studied at inverter side which are the single and three phase-to-ground fault, many figures of simulations are presented in Figs. 7 to 14 according to cases of Table 3.

Table 3. Different cases of simulation for each fault.

Case	conventional PI	FSTPIC	STATCOM
1	×		
2		×	
3	×		×
4		×	×

6.1. Single phase-to-ground fault at inverter side

For a single phase to ground fault of 5 cycles, with breaker resistance equal 40 Ω, the HVDC system with (FSTPIC) controller and STATCOM gives good transient performance in terms of lower peaks (1.282 p.u. in Fig. 10) and a better shape when compared with the other cases. The settling time is very low in the last case (Table 4).

In cases where the STATCOM is applied, it is noted that an undershoot current does not exceed 0.7 p.u.

Table 4. Performance comparison of single phase to ground fault case in inverter side.

Devices With HVDC system	Overshoot Peak (p.u.)	Rise Time (s)	Settling Time (s)	Recovery Time (s)
Conventional PI	1.905	0.180	0.692	0.507
FSTPIC	1.804	0.164	0.142	0.100
STATCOM	1.332	0.182	0.159	0.119
FSTPIC+STATCOM	1.282	0.162	0.137	0.110

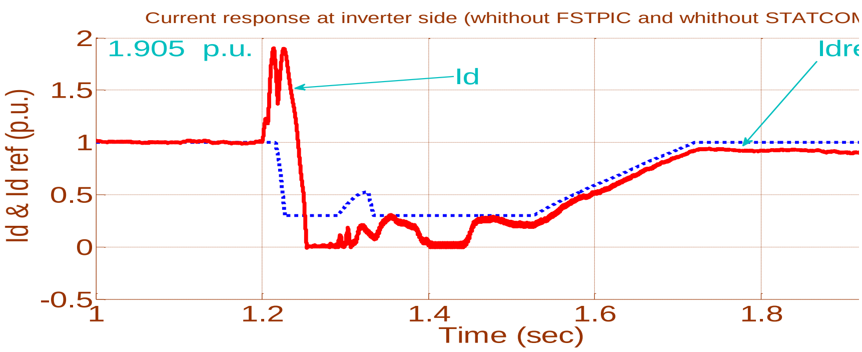

Fig. 7. Single phase-to-ground fault at inverter side (conventional PI).

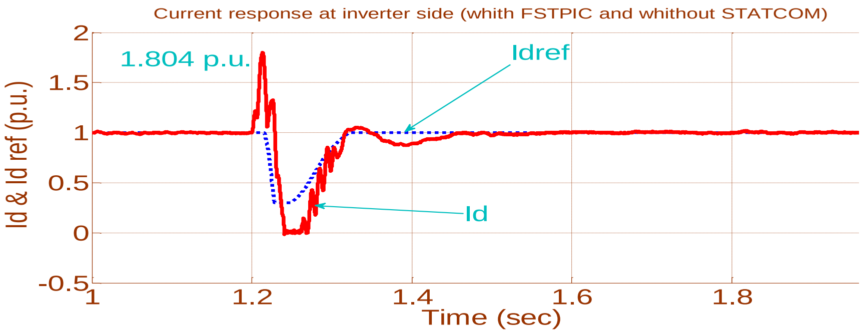

Fig. 8. Single phase-to-ground fault at inverter side (with FSTPIC).

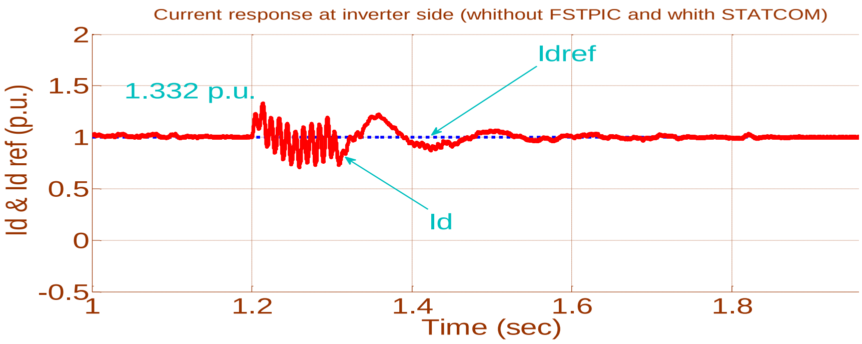

Fig. 9. Single phase-to-ground fault at inverter side (with STATCOM).

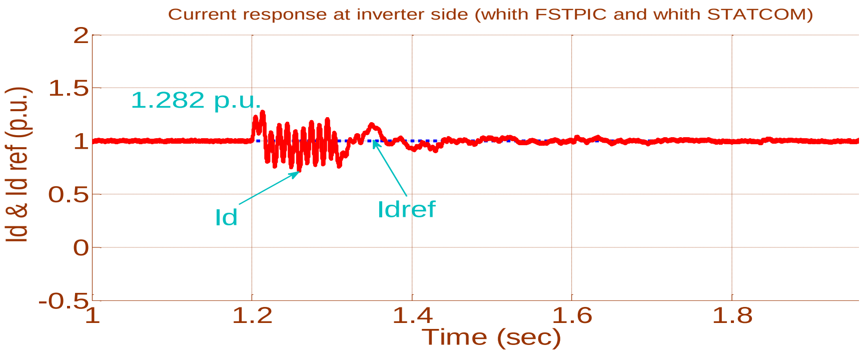

Fig. 10. Single phase-to-ground fault at inverter side (with FSTPIC and STATCOM).

6.2. Three phase-to-ground fault in inverter side

For a three phase-to-ground fault of 5 cycles, between t = 1.2 s and t = 1.3 s with breaker resistance equal 47 Ω, the HVDC system with (FSTPIC) and STATCOM gives good transient performance in terms of lower peaks (1.515 p.u. in Fig. 14) and a better shape.

At the beginning of the response of current I_d, it is noted that the FSTPIC influences the performance of the system which appear in the good form and low rise time (Table 4).

The FSTPIC can better withstand the oscillations of the current and leads to a rapid response, which restore the system more quickly to stability. The settling time after fault is very low in the cases when the FSTPIC is applied. The current undershoot does not exceed 0.35 p.u. in cases where the STATCOM is applied.

After connecting STATCOM, the HVDC system gives a good waveform and mitigates the current. In this case the value of amplitude (in Fig. 13 equal to 1.536 p.u.) is less than the case where the STATCOM is not connected (in Fig. 11 the peak is 2.587 p.u.). This is explained as a more stable performance. The low value of the settling time is in the latter case (Table 5).

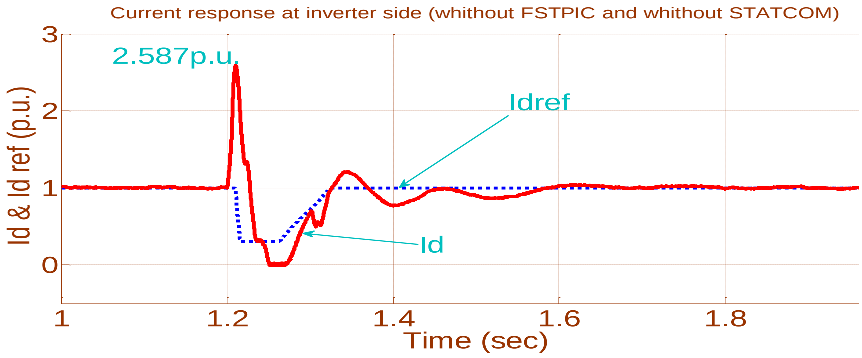

Fig. 11. Three phase-to-ground fault at inverter side (conventional PI).

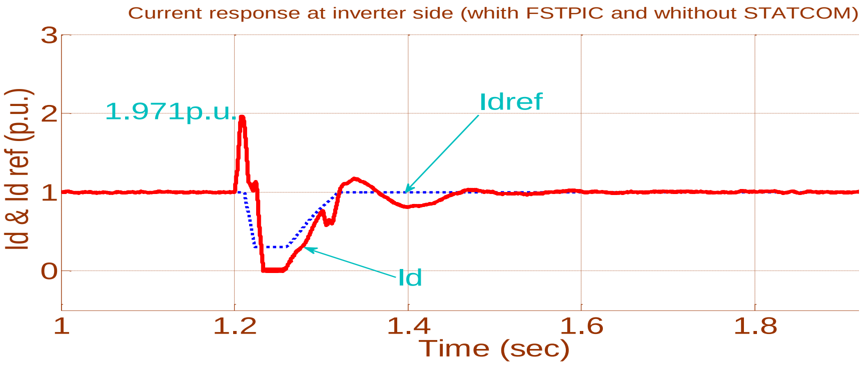

Fig. 12. Three phase-to-ground fault at inverter side (with FSTPIC).

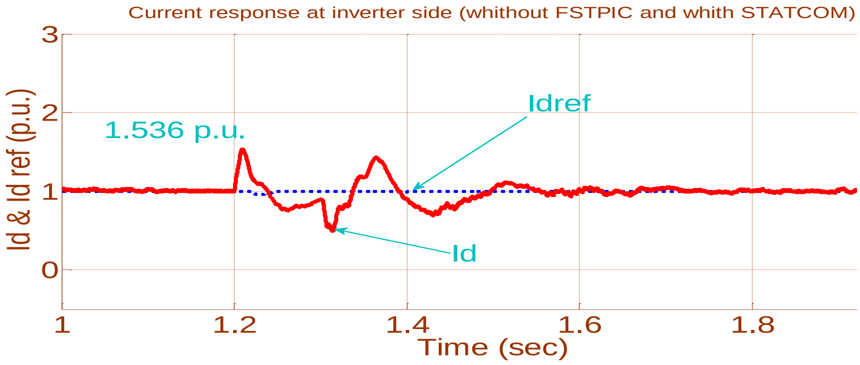

Fig. 13. Three phase-to-ground fault at inverter side (with STATCOM).

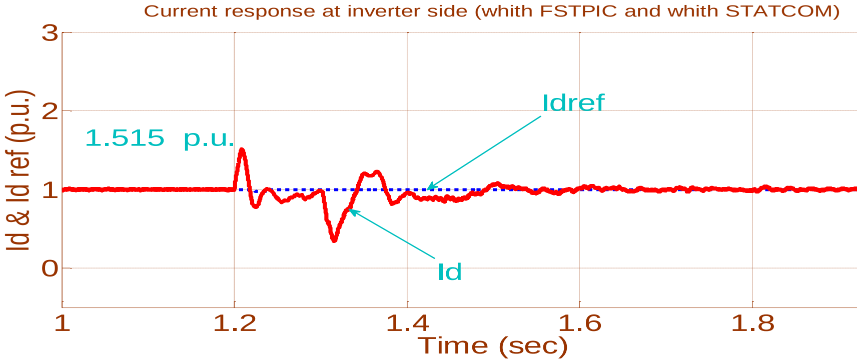

Fig. 14. Three phase-to-ground fault at inverter side (with FSTPIC and STATCOM).

Table 5. Performance comparison of three phase to ground fault case in inverter side.

Devices with HVDC system	Overshoot Peak (p.u.)	Rise Time (s)	Settling Time (s)	Recovery Time (s)
Conventional PI	2.587	0.180	0.270	0.119
FSTPIC	1.971	0.164	0.147	0.109
STATCOM	1.536	0.182	0.360	0.141
FSTPIC+STATCOM	1.515	0.162	0.187	0.133

7. Conclusion

In this paper, a method of combining FSTPIC with a STATCOM was integrated in the HVDC system. The comparison between four systems including different controls showed the robustness and the adaptation of the proposed controller.

When the AC system is weak, the HVDC system suffers with the conventional controller, while the proposed controller has a satisfactory performance and operates consistently under all conditions, i.e. short recovery time after default, low peak and no commutation failure, in cases where the breaking resistance is greater than or equal to the applied values.

The deffuzification method for the controller FSTPIC in this work based on the method of Mamdani only. In practice, there are several methods of deffuzification. A comparison between them after their integration in the FSTPIC controller can be a work of perspective for researchers who want to continue in the same direction and it is hoped that this work will be useful to them.

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