Improvement of the VSC-HVDC System Performances based on the Intelligent Controller

A. Hameyrlaine[1*], H. Sayah[2], M. Boudiaf[3]
1- Intelligent Control and Electrical Power System Laboratory, Djillali Liabes University of Sidi Bel-Abbes, Algeria.
Email: elhadi06@gmail.com (Corresponding author)
2- Intelligent Control and Electrical Power System Laboratory, Djillali Liabes University of Sidi Bel-Abbes, Algeria.
Email: housayah @yahoo.fr
3- Department of Electrical Engineering, University of Djelfa, Algeria.
Email: boudhiaf_mohamed@yahoo.fr

Received: January 2019 Revised: June 2019 Accepted: August 2019

ABSTRACT:
Voltage Source Converter based High Voltage Direct Current (VSC-HVDC) has been an area of growing interest during the recent years. Indeed, VSC-HVDC has the capability of controlling the active power and the reactive power; rapidly, independently, and simultaneously. The main focus of this research is on VSC-HVDC system modeling; in which, two different controllers, such as the PI controller and the fuzzy logic controller, have been implanted in the system. Furthermore, these two controllers have been analyzed and compared to each other. Whereas, the main objective of the work presented in this paper is finding the more suitable controller which could allow improving the robustness of the whole control system and its impact on the dynamic performance of the VSC-HVDC during parameter uncertainties, such as load change, parametric variation, and faults occurrence. The obtained results have shown that using the fuzzy controller could lead to a better performance of the studied system, compared to the other controller.

KEYWORDS: VSC-HVDC, PI Controller, Modeling, Fuzzy Logic Controller, Robustness, Faults**.**

1. INTRODUCTION

The important development on power electronics devices has led to the appearance of several and improved converters topologies. Among these devices the IGBT with higher rated capabilities [3] which has allowed to the VSC-HVDC transmission to be included as a very feasible solution and used as a keystone for power system grid expansion. Indeed, the VSC-HVDC transmission has become a major factor in the planning of the power transmission and has attracted much interest and attention due to a number of factors, such as its modularity, the possibility to control the active and the reactive power independently [8], and the power transmission reversal. Accordingly, the globalization process based on VSC-HVDC transmission systems has been emerged and the numbers of these systems have been increased rapidly all over the world [4]. In this paper, a dynamic model of the VSC-HVDC is developed and mathematical model of the control system based on the relationships between voltage and current is described. Furthermore, the vector control strategy is studied and the control system is developed combining the inner current loop controller and the outer controllers. In order to fully utilize the capability of the VSC-HVDC, two control strategies (PI controller and, fuzzy logic) are presented; where the corresponding dynamic performance is studied under step changes and parameter uncertainties (different types of faults, change load) are investigated. The presence of large nonlinearities in VSC-HVDC system dynamics makes the linearized model inadequate for controller design. Furthermore, traditional PI controllers often works only within a limited operating range [13] which motivates the use of nonlinear control techniques in order to overcome the undesired problems that may be caused by using conventional tuned PI controllers under operating conditions variations and to guarantee system stability. Therefore, in this paper robust control design and adaptive control structures based on fuzzy logic have been proposed. Finally, the dynamic performance of the VSC-HVDC system through various simulation scenarios is tested for the validation of the proposed controller performances.

2. VOLTAGE SOURCE CONVERTER (VSC) HVDC SYSTEM

The fundamental operation of VSC-HVDC system can be explained by considering a (VSC) voltage source converter connected to two AC networks as shown in Fig. 1 [10], [11].

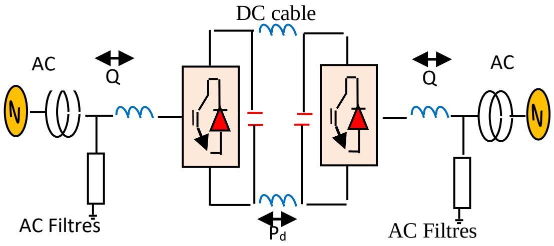


Fig. 1. Basic configuration of VSC-HVDC.

3. MODELING OF VSC-HVDC SYSTEM

The first step to apply any control strategy of VSC-HVDC system is the mathematical model as shown in Fig. 2. [1.2].

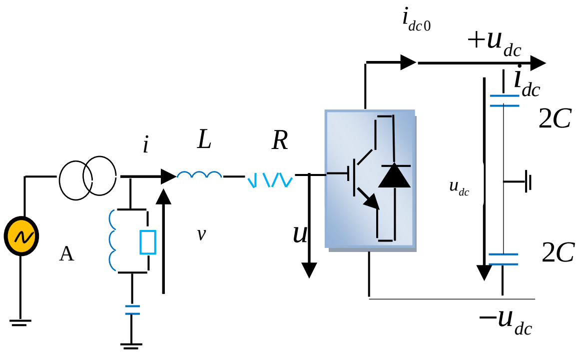


Fig. 2. Single line diagram of VSC-HVDC system.

The main purpose of the modeling is to represent the non linear HVDC system with a linear time system and apply a proportional integral (PI) controller to achieve the desired response from the system [10]. The difficulties of a control system design increases with the system order. Especially, in adaptive control design, a higher order system needs to be simplified to apply adaptive control and parameter estimation. Indeed VSC-HVDC system has advantage of independent control of active and reactive power [6]. It is obvious that the direction of active power flow can be changed without changing the DC voltage polarity. The reactive power can be controlled independently at either converter station by controlling converter AC output voltage. The control of a VSC-HVDC system is basically the control of the transfer of energy between the two sides of the VSC-HVDC system [9]. Therefore, the aim of the control in VSC based HVDC transmission is thus the accurate control of transmitted active and reactive power. Moreover, the VSC controls are often used to provide ancillary services, such as the improvement of the AC grids dynamics. Different control strategies of the VSC-HVDC system can be found in literature[4.5], such as direct control and vector control methods which are based on voltage controlled VSC and current controlled VSC [1] schemes respectively are the most widely used methods. Direct control method is not used in practical applications, it is useful in comparative studies of operation and performance of VSC-HVDC. The vector control strategy can be derived from the mathematical modeling of the system shown in Fig. 2, by the AC dynamics in stationary coordinates, seen from the filter bus voltage towards the converter are given by the dynamics of the phase reactors, based on Clark transformation matrix, which allows the transformation of the three-phases system variables in ABC-frame to bi-phase variables in (alpha-béta) frame [7.12], the AC dynamics can be presented in (alpha-béta) frame as follows:

$$L\frac{di_{\alpha\beta}}{dt} = v_{\alpha\beta} - u_{\alpha\beta} - Ri_{\alpha\beta} \qquad (1)$$

By using the transformation angle θ derived from a phase-locked loop (PLL), the above equation can further be transferred to the synchronous rotating dq reference frame, as follows:

$$L\frac{di_{dq}}{dt} = v_{dq} - u_{dq} - (\mathrm{R}+\mathrm{j}\omega L)i_{dq} \qquad (2)$$

The term ($j\omega Li_{dq}$) represents the time derivative of the synchronous rotation of the dq reference frame, the equation (2) can be rewritten as:

$$\begin{cases} L\dfrac{di_d}{dt} = v_d - u_d - Ri_d + \omega \mathrm{L} i_q \\ L\dfrac{di_q}{dt} = v_q - u_q - Ri_q - \omega \mathrm{L} i_d \end{cases} \qquad (3)$$

During steady state operation, the dq-components of voltages are constant at the rated values. Therefore,

$$v_q = 0 \text{ and } v_d = v \qquad (4)$$

Considering the above assumptions, the active and reactive powers are expressed as follows:

$$\begin{cases} P_{ref} = v_d i_{d\_ref} \\ Q_{ref} = -v_d i_{q\_ref} \end{cases} \qquad (5)$$

This equation shows the independent control of the active and the reactive power.

The dynamics models of the DC link are given by:

$$\begin{cases} C\dfrac{du_{dc}}{dt} = i_{dc0} - i_{dc} \\ p_{dc} = u_{dc} i_{dc0} \end{cases} \tag{6}$$

4. CONTROL STRATEGIES BASED ON PI-CONTROLLER

Equation (3) shows that the model of the VSC in the synchronous reference frame is a multiple-input multiple output, strongly coupled nonlinear system. Thus, it will be difficult to realize the exact decoupled control system with conventional linear control strategies. The transformed voltage equations of each axis have speed/frequency induced term ($\omega \mathrm{Li}_d$ and $\omega \mathrm{Li}_q$) that give a cross-coupling between the two axes. For each axis, the cross-coupling term can be considered as disturbance from a control point of view. Thus, a close-loop direct current controller with decoupled current compensation and voltage feed-forward compensation is required to obtain a good control performance.

Equation (3) can be rearranged as follows:

$$\begin{cases} u_d = L\dfrac{di_d}{dt} + Ri_d \\ u_q = L\dfrac{di_q}{dt} + Ri_q \end{cases} \tag{7}$$

This equation shows that the cross coupling terms are cancelled out and independent control in *d* and *q* axis is achieved. Moreover, the equations in *d* and *q* axis show the same form. Thus, analysis of the d -axis controller is enough. Using Laplace transformation for this equation, the system transfer function can be obtained as follows:

$$T(s) = \frac{1}{R}\frac{1}{1+\tau s} \tag{8}$$

Where, the time constant, τ is defined as: $\tau = L/R$.

Equation (8) shows that the resulting system is composed of two independent first order systems, thus it is sufficient to use a PI controller as a controller. Finally the transfer function H(s) can be expressed as:

$$H(s) = K_p + \frac{K_i}{s} \tag{9}$$

Based on the basic relationship of the system model, the inner current control loop can be implemented in the *dq* frame as in Fig. 3.

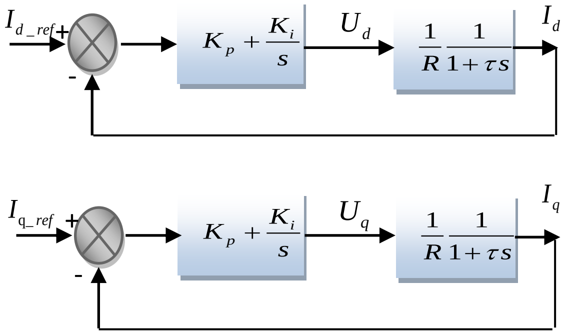


Fig. 3. Schematic diagram of current control loops.

4.1. Block Diagram of Control Scheme of VSC-HVDC

Based on precedent equations obtunds in modeling system, the block diagram of VSC-HVDC system is shown in Fig. 4.

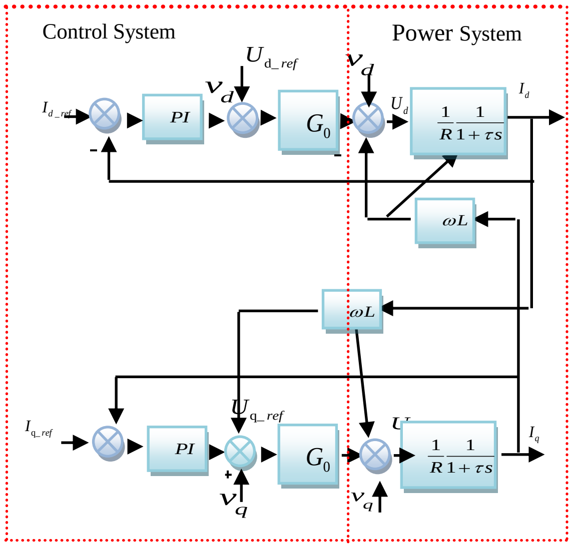


Fig. 4. Vector control scheme of VSC-HVDC.

4.2. Direct Voltage Control

The main objective of the DC voltage controller is to ensure the DC-link voltage regulation following the reference value. As it is shown in Fig.2, the active and reactive powers in dq-reference frame at the AC side of the VSC are expressed as follows:

$$\begin{cases} P_{ref} = v_d i_{d\_ref} \\ Q_{ref} = -v_d i_{q\_ref} \end{cases} \tag{10}$$

From equations (6) and (7), the reference current i_{d_ref} is derived as follows:

$$i_{d\_ref} = \frac{i_{dc0} u_{dc}}{v_d} \tag{11}$$

This current *d*-component gives the reference current for the inner current controller of the DC voltage control. The block diagram of the DC voltage controller is shown in Fig. 5.

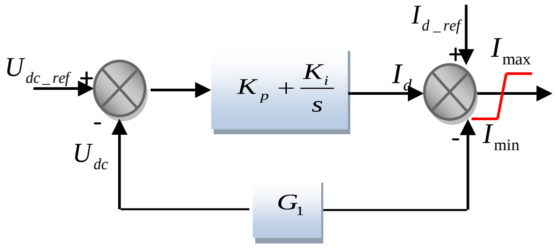


Fig. 5. Block diagram of the DC voltage controller.

5. CONTROL STRATEGIES BASED ON FUZZY LOGIC

Application of fuzzy logic controller in VSC-HVDC transmission systems have been carried out for the last one decade [6]. Adaptive controllers have the ability to adjust gain parameters based on system operating conditions. An adaptive controller based on fuzzy logic does not need any prior knowledge of the system.

Fuzzy Logic is a new control approach with a great potential for real-time applications [14]. It is a rule based controller where a set of rules represent the control decision mechanism [15]. The presence of large nonlinearities in VSC-HVDC system dynamics causes the design of appropriate controllers. To overcome these problems, a controller with the capability of changing gain parameters depending on system dynamics or a controller with wide operating range of gain would be a good solution. The proposed control strategy for VSC-HVDC is PI fuzzy logic controller as shown in Fig. 6.

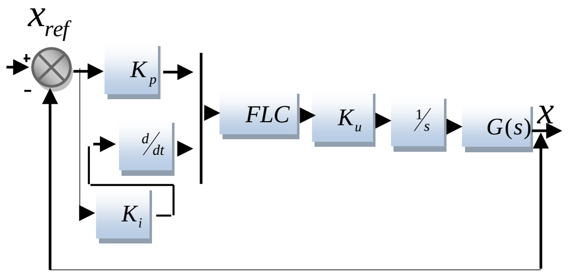


Fig. 6. Fuzzy PI controller.

The fuzzy logic rules for tuning the PI controller gain are shown in Table 1; they are based on the following factors:

In the Fuzzification of the PI fuzzy logic controller [7], the error (**e)** and its derivative (Δ **e)** are used as the principal signals controller inputs. The inputs **e** and Δ **e** are fuzzified into three sets, namely P, Z, and N (positive, zero and negative respectively).The output membership functions are shown in Fig. 7.

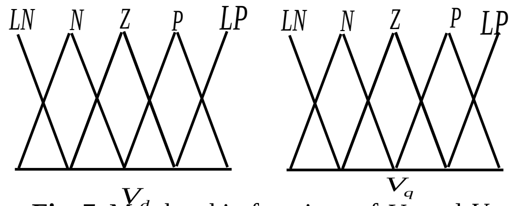


Fig. 7. Membership functions of V_d and V_q .

The five linguistic variables used for error and variations are: LN-large negative, N-negative, Z-zero, P-positive, LP-large positive.

Table 1. Fuzzy rules implementation.

Δe e	N	Z	P
N	LP	P	Z
Z	P	Z	N
P	Z	N	LN

To convert the fuzzy sets to the real numbers, the centroiddefuzzifier is used to calculate the output change V_s of fuzzy PI controller.

The output is expressed as:

$$V_s = \frac{\sum_{i=1}^{n} h_i u_i}{\sum_{i=1}^{n} u_i} \qquad (12)$$

Fig. 8 shows the fuzzy logic decoupling of VSC-HVDC.

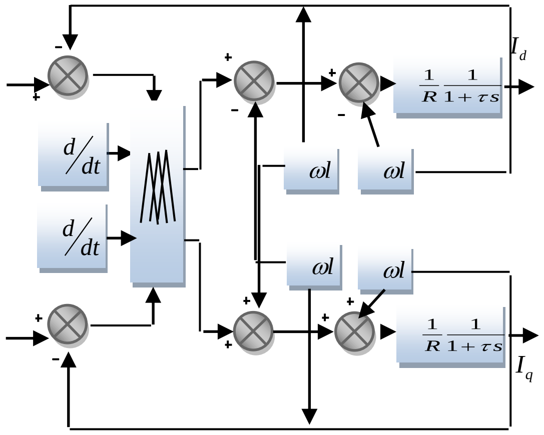


Fig. 8. fuzzy logic decoupling of VSC-HVDC.

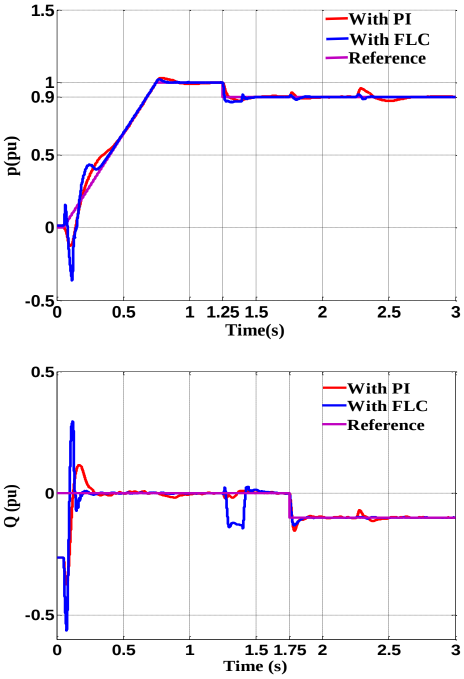
6. SIMULATION RESULTS

Simulation results are presented in this paper, in order to evaluate the system behavior of the VSC-

HVDC at steady state and dynamic state conditions. Therefore, an advanced control scheme fuzzy logic controller is compared to a conventional PI controller strategy to improve and enhance system performance. The dynamic performance of the transmission system is verified by simulating and observing dynamic response to step changes applied to the principal regulator references and dynamic performance during load changes, parameters variations and AC side, DC side faults. Model parameters are provided in appendix.

6.1. Step Changes Applied to the Principal Regulator

In this case, step changes in active power, reactive power and DC voltage are implemented in all VSC-HVDC controllers. As shown in Fig. 9, a negative step of 10% is applied at 1.25s in active power controller at VSC1. First, the transition is observed to be well controlled with little overshoot. Second, it can be seen that the change in active power does not affect the reactive powers on either side of the AC systems though there are some transients observed when the step is applied. A noticeable effect in the DC voltage is observable and the size of the DC capacitor employed will have an impact on this. Next, a negative step of 10% is applied at 1.75s in the reactive power controller at VSC1. First, the transition is observed to be well controlled with little overshoot. Second, it can be seen that the change in reactive power affects neither the active power on same side nor the reactive power on other side of the AC system. This clearly demonstrates the independence of the P and Q controllers at the VSC1 end.



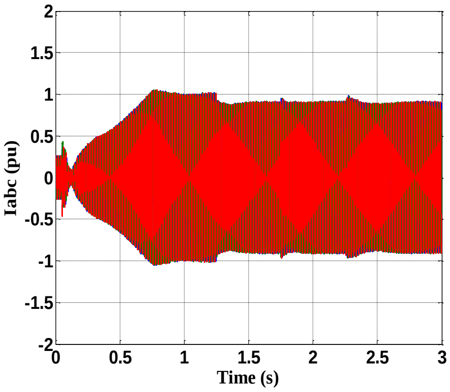
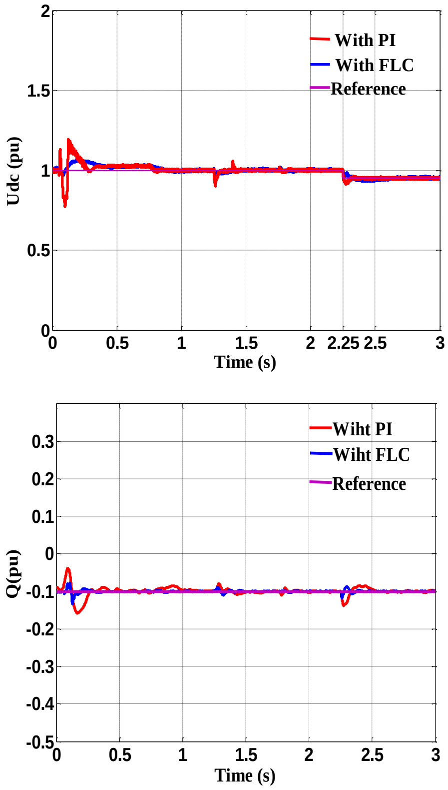


Fig. 9. Step changes in the active power, reactive power at VSC1.

In Fig. 10, initially the DC voltage is maintained constant at 1pu which is followed by a negative step of 10% applied at 2.25s in DC voltage controller at VSC2. First, the transition is observed to be rapid, well controlled with overshoot. Second, it can be seen that the change in DC voltage does affect the reactive powers on either side of the AC systems. Naturally, the size of DC capacitor will be a significant element in controlling this effect.



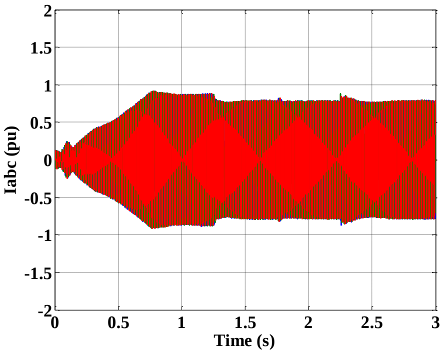


Fig. 10. Step changes in the DC voltage at VSC2.

Based on the simulation results, both the controllers perform well but the fuzzy logic controller gives a better transient performance and quite a low overshoot as compared to the conventional PI controller.

6.2. Parameter Variations

In this case, a performance comparison between fuzzy logic and conventional PI controller has been made. This is done by putting the VSC- HVDC system under parameter variations considering a decrease DC and AC side parameters from the nominal value to 25%. Figures 11, 12, 13 and 14 illustrate the simulation results. It is seen that in this conditions, Fig. 11 demonstrates the active power and reactive power dynamic behavior following the change in parameter. After the variation, slow PI control renders acceptable overshoot and settling time.

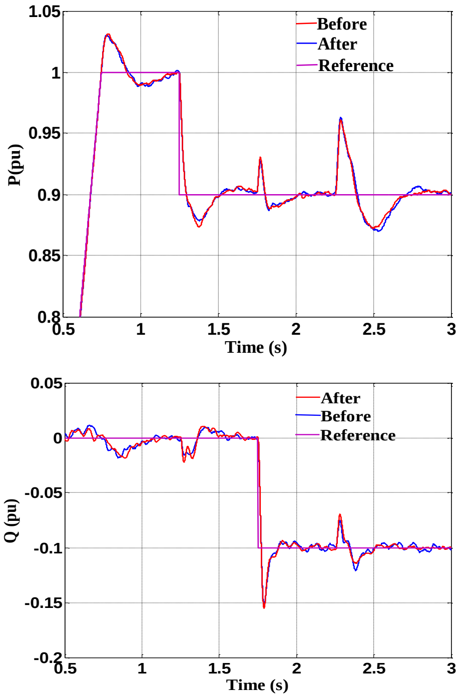


Fig. 11. Response of PI controller to parameter variations at VSC1.

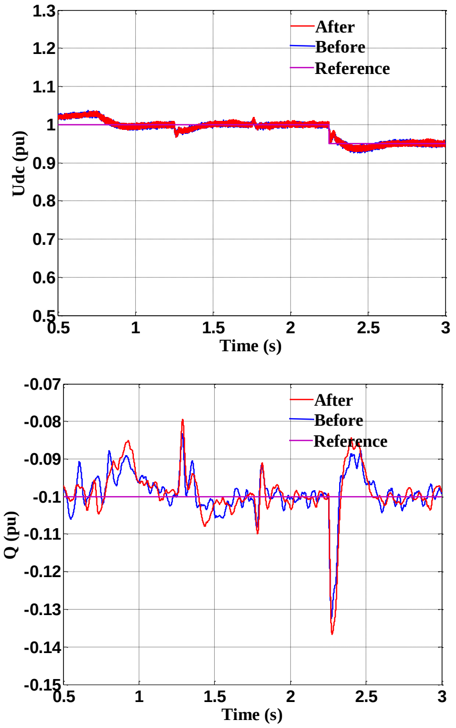


Fig. 12. Response of PI controller to parameter variations at VSC2.

Fig. 13 shows that the active power dynamic behavior remains stable even in presence of parameter variation in favor of fuzzy logic controllers.

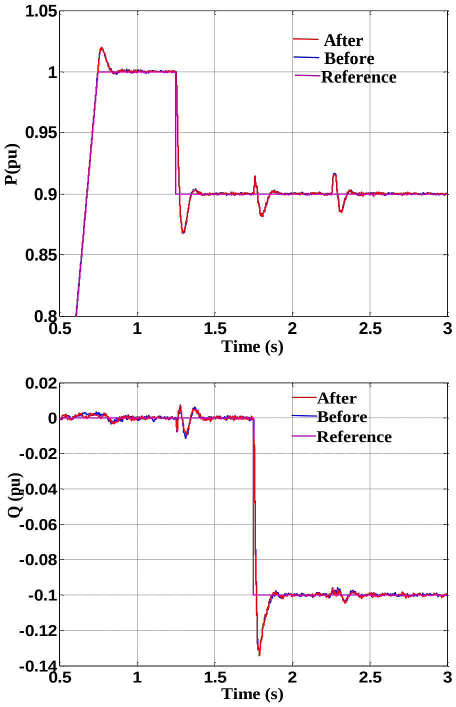


Fig. 13. Response of fuzzy logic controller to parameter variations at VSC1.

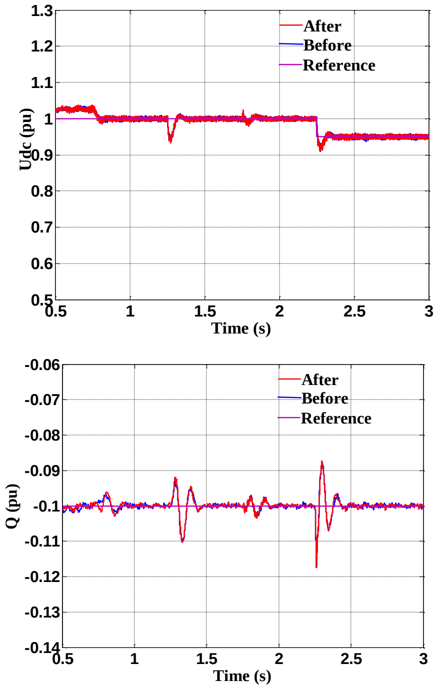
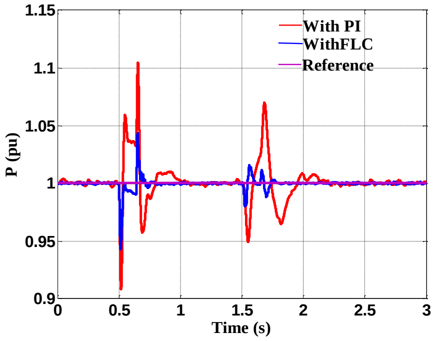


Fig. 14. Response of fuzzy logic controller to parameter variations at VSC2.

Results have shown the robustness of the fuzzy logic controller; the flexibility of the implemented controller could improve the system dynamic behavior and increase its stability better than conventional PI controller.

6.3. Change Load

In this case, a change in the load of the both AC sides, decreasing 20% of the nominal values, is applied. One of these changes is applied at the converter VSC1, which controls the active power and reactive power, and the other one is applied at the VSC2, which controls the DC voltage and reactive power. From the simulated results in Figs. 15 and 16, it is clear that for a load change, both the controllers perform well but the fuzzy logic controller gives a better transient performance and quite a low overshoot as compared to the conventional PI controller.



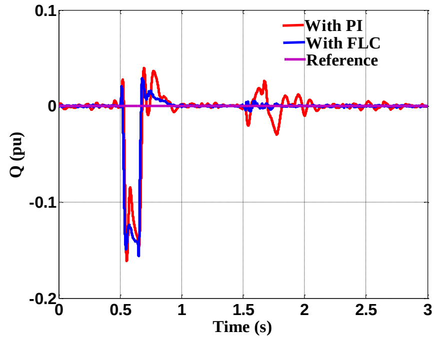


Fig. 15. Response of PI controller and fuzzy logic controller to load change of 20% at VSC1.

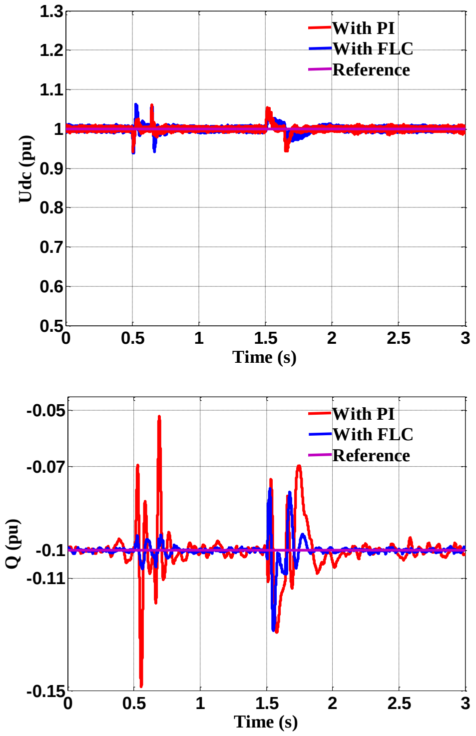


Fig. 16. Response of PI controller and fuzzy logic controller to load change of 20% at VSC2.

For a large disturbance change in load, conventional PI controller suffers and does not recover well as in Fig. 12; the reason for the inadequate of PI controller may be attributed to the gains fixed. On the other hand, fuzzy logic controller is able to recover quite well, which shows the potential of the proposed controller.

6.4. Three-phase Fault at VSC2

At the simulation time point of 0.5s, a three-phase fault is applied for 100ms at VSC2 active and reactive powers, at VSC1, DC voltage and reactive power at VSC2 are shown in Figs. 17 and 18.

When the fault is removed at 0.6s, the DC voltage at VSC2 shows the variation from 0.3pu with fuzzy controller and 0.65pu with PI controller. After the fault clearing a slowly recover of the active power but fuzzy controller should have a very short response time then PI conventional controller.

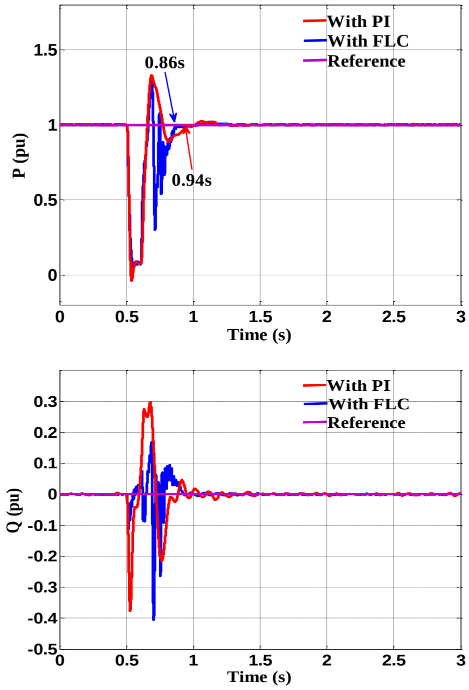


Fig. 17. Response to three-phase fault at VSC1.

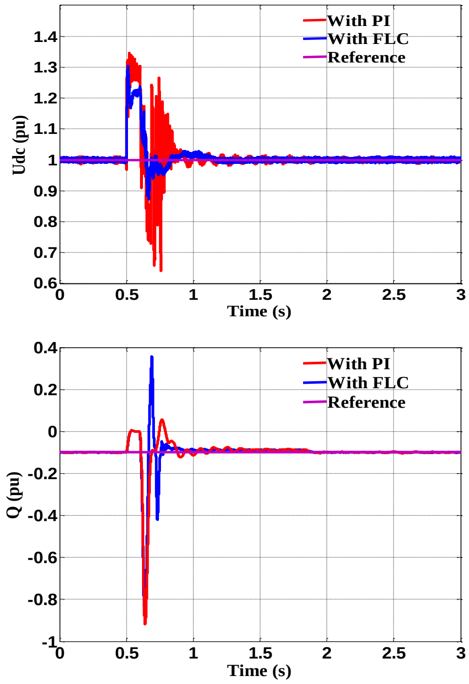


Fig. 18. Response to three-phase fault at VSC2.

6.5. DC pole-to-pole Fault

A DC pole-to-pole fault is applied at 0.5s for duration of 100ms. The active power at VSC1 is shown in Fig. 19. It can be observed that the fault active power is limited to 0.4pu during the fault in DC transmission system, the DC voltage at VSC2 (fig.20) reduces due to continuous flow of the DC fault current. Since DC breakers are not available to interrupt this fault current, so the AC breakers on both the AC systems must be opened to remove this fault. An implemented protection system must supplement to the control system in order to mitigate the DC faults that can occur on VSC- HVDC system.

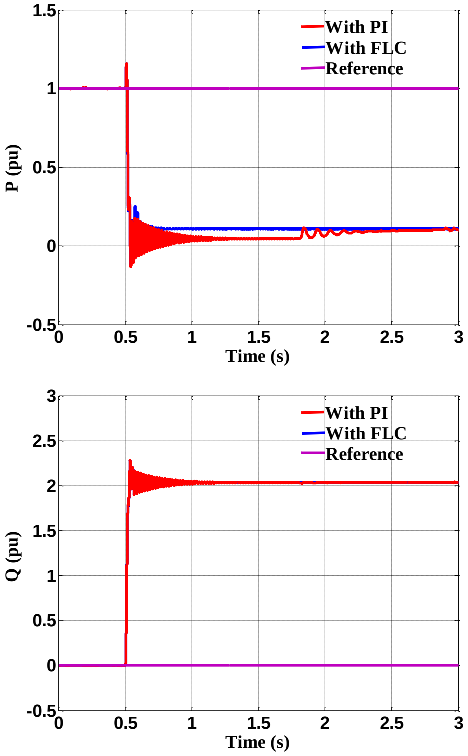
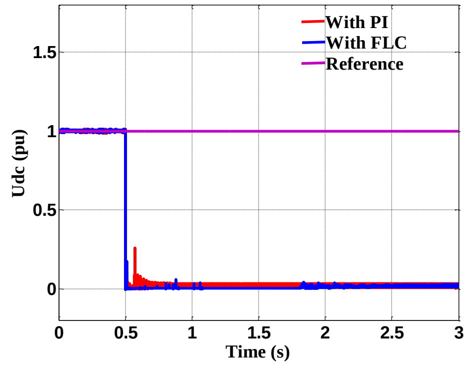


Fig. 19. Response to DC pole-to-pole fault at VSC1.



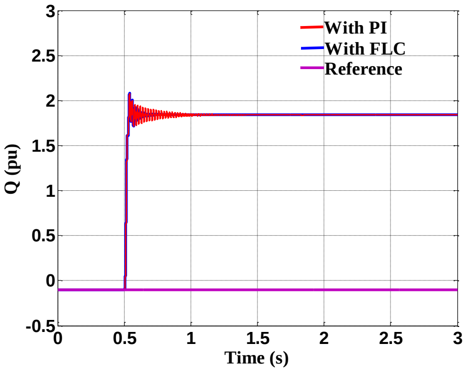


Fig. 20. Response to DC pole-to-pole fault at VSC2.

7. CONCLUSION

This paper focuses mainly on the VSC-HVDC performance assessment during steady state and dynamic state where step changes in active power, reactive power and DC voltage have been performed. Indeed, to ensure the improvement of the dynamic performance of the studied VSC-HVDC, two different control techniques have been used based on two different controllers, the conventional PI controller and the fuzzy logic controller. These two controllers have been integrated to achieve high dynamic performance especially under load changes, parameters variations and faults occurrence. Both approaches have been compared regarding their dynamic performance, robustness and simplicity. It was found that the robustness of the proposed fuzzy Logic controller has achieved more improved performance of the HVDC system in comparison with the conventional PI controller. Consequently, the proposed nonlinear controller robustness has allowed improving the overall system dynamic behavior and its stability under various scenarios.

8. APPENDIX

The system parameters of the VSC-HVDC are:

AC voltage and reactive power (230 kV, 2000 MVA),

DC voltage and active power (200 kV, 200 MW),

DC Cable Length (75KM).

REFERENCES

[1] J. Arrillaga, Y. H. Liu, N. R. Watson, and N. J. Murray, **“Flexible Power Transmission the HVDC Option.”** *John Wiley*, 2007.

[2] T. Haileselassie and K. Uhlen, **“Precise Control of Power ow in Multi- Terminal VSC-HVDCs using dc Voltage Droop Control.”** *In Power and Energy Society General Meeting, 2012 IEEE*, pp. 1-9, 2012.

[3] P. Mitra, L. Zhang, and L. Harnefors, **“Offshore Wind Integration to a Weak Grid by VSC-HVDC Links Using Power-Synchronization Control: A Case Study.”** *Power Delivery, IEEE Transactions on*, Vol. PP, No. 99, pp. 1-1, 2013.

[4] R. Rogersten, H. Xu, N. Ozay, U. Topcu, and R. Murray, **“Synthesis and Validation of Control Software For A Vehicular Electric Power Distribution Testbed.”** *accepted by AIAA Journal of Aerospace Information Systems*, 2014.

[5] J. Beerten, D. Van Hertem, and R. Belmans, **“VSC MTDC Systems with a Distributed dc Voltage Control - A Power ow Approach.”** *In PowerTech, 2011 IEEE Trondheim*, pp. 1-6, 2011.

[6] N. Bhookya and V. RamanaRaoP, M. Sydulu, **“Improvement of Power System Stability using Artificial Neural Network based HVDC Controls.”** *Majlesi Journal of Electrical Engineering*, Vol. 7, No. 2, June 2013.

[7] R.K. Brouwer, **"Fuzzy Rule Extraction from a Feed Forward Neural Network by Training a Representative Fuzzy Neural Network using Gradient Descent,"** *IEEE ICIT '04. 2004 IEEE International Conference on Industrial Technology*, Vol. 3, pp. 1168- 1172, 8-10 Dec. 2004.

[8] X.-P. Zhang, C. Rehtanz, and B. Pal, **“Flexible AC Transmission Systems: Modelling and Control.”** *Heidelberg, Germany: Springer- Verlag*, 2012.

[9] O. Heyman, L.Weimars, and M.-L. Bohl, **“HVDC-A Key Solution in Future Transmission Systems,”** In *World Energy Congress*, WEC, Montr_eal, 2010.

[10] M. Imhof and G. Andersson, **“Dynamic Modeling of a VSC-HVDC Converter,”** *In 2013 48th International Universities Power Engineering Conference (UPEC*), Vsc 2. IEEE, Sep. 2013.

[11] A.Hameurlaine ; S-A Zidi ; A Kouzou ; M A Djehaf “**Improvement of the HVDC Link Performances based on the Protection Functions** ,” *2015 IEEE International Conference on Industrial Technology (ICIT).* 2015.

[12] H. Saad, T. Ould-Bachir, J. Mahseredjian, C. Dufour, S. Dennetiere, S. Nguefeu, **"Real-Time Simulation of MMCs Using CPU and FPGA,"** *Power Electronics, IEEE Transactions on*, Vol. 30, No. 1, pp. 255-261, 2015.

[13] K Rama Krishna K Nagarjuna T.Kranthi Kumar “**DC Current Flow Controller for Multilevel Converter Multi terminal HVDC Grids using Fuzzy logic controllers**”, *International Journal of Advanced Engineering and Global Technology I*, Vol. 05, Issue-02, March 2017.

[14] A Ramezani, A Rahimi , A Roosta “**Control of Multi-variable Processes using Self-Tuning Fuzzy”** *Majlesi Journal of Electrical Engineering*, Vol. 10, No. 1, March 2016.

[15] N Nayak, S Keshari Routray,P Kumar Rout **“Non-Linear Control and Stabilisation of VSC-HVDC Transmission System based on Type-2 Fuzzy Sliding Mode Control”** *Int. J. Automation and Control*, Vol. 7, Nos. 1/2, 2013.