Improvement of voltage stability and current limiting strategy for VSC-HVDC Systems using adaptive controllers

N.Balavenkata Muni[1], Dr.S.Sasikumar[2], Dr.P.Nagaraju Mandadi[3]
[1]Research Scholar, Department of Electrical Engineering,
Annamalai University, Annamalainagar, Tamil Nadu, India.
[2]Assistant Professor, Department of Electrical Engineering,
Annamalai University, Annamalainagar, Tamil Nadu, India.
[3]Professor, Dept of Electrical and Electronics Engineering,
Sreenivasa Institute of Technology and Management Studies, Chittoor, AP, India.

Abstract*— *The recent developments in semiconductors and control equipment have made the voltage source converter based high voltage direct current (VSC-HVDC) feasible. Due to the use of VSC technology and pulse width modulation (PWM) the VSC-HVDC has a number of potential advantages as compared with classic HVDC, such as short circuit current reduction, rapid and independent control of active and reactive power, etc. This paper proposes a modified current limit strategy (MCLS) and a frequency hysteresis control (FHC) for improving the disturbance ride-through capability of a VSC-HVDC link supplying passive industrial installations. Since industrial loads are more sensitive to voltage drops than frequency deviations, it's essential to guarantee the stability of voltage during severe faults.

The development of the control methods includes three steps. First, the main factor that affects the ac voltage in the passive industrial system is analyzed in order to enhance the voltage stability more effectively. Secondly, according to the analytical results, the MCLS is proposed to increase the ac voltage in transient conditions. Thirdly, in order to make the MCLS have a better control result, the FHC is added to the VSC controller with the MCLS, which can also further enhance the ac voltage of the passive system. The simulation tests under metallic single-phase and three-phase faults are done in MATLAB/SIMULINK, and the results verify thevalidity of the control methods.

Index Terms*— *passive industrial installations, voltage stability, Voltage Source Converter (VSC), modified current limit strategy, frequency hysteresis control.

I. INTRODUCTION

The ability of the multiterminal VSC-HVDC system to improve power quality and how to deal with DC overvoltages during loss of a converter in the multiterminal VSC-HVDC system is investigated. The protection of multiterminal VSC-HVDCs against DC faults is also studied. Over the last years, a series of research efforts have been made to improve the voltage stability of passive industrial loads. A new VSC controller supplying passive industrial plants is proposed, where the VSC-HVDC uses the ac voltage and frequency controller. The idea of the designed strategy is to give priority to keeping up the ac voltage and slightly decrease the frequency during disturbances[14].

In the electric power industry, alternating-current (AC) systems have been overwhelminglydominant over the direct-current (DC) option for a long time. However, this scenario is changing inrecent years with DC systems playing an ever increasing role in the overall power systems due toseveral potential benefits: long distance water crossing, lower losses, controllability, limit short circuitcurrents, lesser corona loss, and the fact they requires less insulation. Voltage source converter(VSC)-based high voltage direct current (HVDC) transmission is increasing research interest in thestudy of the smart grid in [8]. The topologies of two converters in the VSC-HVDC system have been studied[10-13].

Compared to the classic line commutated converter HVDC (LCC-HVDC), the former hasseveral potential benefits such as self-regulating control of active and reactive power, increased powerquality, comfortable integration of large-scale wind farm, and easy operation with weak AC grids, noreactive power demand, and less operational cost.However, despite the numerous advantages, VSC-HVDC systems face difficulties in dealingwith different grid faults. Fault ride-through (FRT) capability enhancement[17] is one of the mainrequirements for wind farm-integrated VSC-HVDC systems. During system faults, bulk powerinterruptions must be avoided by keeping the HVDC system energized, otherwise, the system mayface serious instability due to this bulk power interruption. Modular multilevel converter-basedVSC-HVDC system topologies can provide enhanced fault ride-through capability. In FRT capability as well as transient stability improvement has been reported by applying variousVSC control techniques.

This paper proposes novel control strategies for a VSC-HVDC link to improve the fault ride–through capability of passive industrial installations. The new VSC controller based on the conventional ac voltage control (CAVC) consists of a modified current limit strategy (MCLS) and a frequency hysteresis control (FHC). The control strategies are designed to enhance the voltage stability of passive industrial systems. Impacts of metallic single-phase and three-phase faults in the sending side of the VSC-HVDC system are simulated and analyzed in MATLAB/SIMULINK to test the proposed approaches.

II. SYSTEM MODELING

During grid disturbances, voltage dips typically lead to WPP disconnections that willcreate even worse system conditions which can cause instability and even yield toblackouts. To avoid these problems, the grid codes require WPPs to continueoperation even if the voltage dip reaches very low levels, support the voltagerecovery by injecting reactive current and restore active power after the faultclearance with limited ramp values[6]. All these features are defined as FRT capabilityof the wind turbine in the following way:

- FRT in terms of minimum and maximum voltage ride through (low and highVRT) and recovery slope for symmetrical and asymmetrical faults that WPPsmust be able to withstand without disconnection from the grid,

- Active power and reactive power limitation during faults and recovery,
- Reactive current injection for voltage support during fault and recovery,
- Restoration of active power with limited ramp after fault clearance.

The VSC-HVDC is a new DC transmission system technology. The valves are built by IGBTs and PWM is used to create the desired voltage waveform. With PWM it is possible to create any waveform, any phase angle and magnitude of the fundamental frequency component. This high controllability allows for a wide range of applications. A typical VSC-HVDC system, shown in Fig. 1, consists of AC filters, transformers, converters, phase reactors, DC capacitors and DC cables.

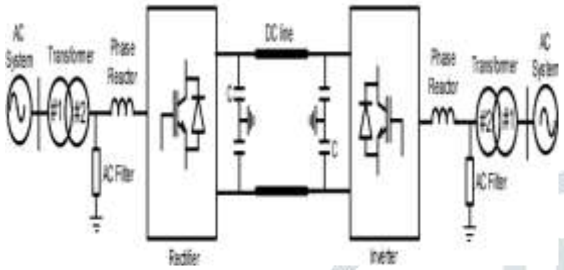

Fig.1 A VSC-HVDC system.

The main operation difference between classic HVDC and VSC-HVDC is the higher controllability of the latter. This leads to a number of potential advantages and applications, where some are given below:

1) Independent control of active and reactive power without extra compensating equipment. With the use of PWM, the VSC-HVDC can control both active and reactive power independently. While the transmitted active power is kept constant the AC voltage controller can control the voltage in the AC network. Reactive power generation and consumption of a VSC-HVDC converter can be used for voltage control to compensate the needs of the connected network within the rating of a converter.

2) Mitigation of power quality disturbances. The reactive power capabilities of the VSC-HVDC can be used to control the AC network voltage and thereby contribute to an enhanced power quality. Furthermore, the faster response, due to increased switching frequency (PWM), offers new levels of performance regarding power quality control such as flickers and harmonics. Power quality problems are issues of priority for owners of industrial plants, grid operators and for the public.

3)Reduced risk of commutation failures. Disturbances in the AC system may lead to commutation failures in a classic HVDC system. As the VSC-HVDC uses self-commutating semi-conductor devices, it is no longer necessary to present a sufficiently high AC voltage. This significantly reduces the risk of commutation failures and extends the application of the VSC-HVDC for stability control.

4) Communication not needed. As the control systems on the rectifier and inverter sides operate independently, they do not depend on a telecommunication connection, which in turn improves the speed and the reliability of the controller.

5) Feeding islands and passive AC networks. The VSC converter is able to create its own AC voltage at any predetermined frequency without the presence of rotating machines. Therefore, it may be used to supply industrial installations or to connect large wind farms.

6) multiterminal DC grid. The VSC converters are suitable for creating a DC grid witha number of converters since little coordination is needed between the VSC-HVDCconverters. One potential application of multiterminal DC grids is to provide powersupply to city centers.

It is depicted in Fig. 2 that the power is delivered from the main grid to the passive industrial system by a VSC-HVDC transmission system. Since induction motors are considered as the dominant load in industrial systems, the analysis of this paper is mainly for induction motors. Variable frequency drives and protective functions are not included in this paper by assuming they are a small part of the passive load.

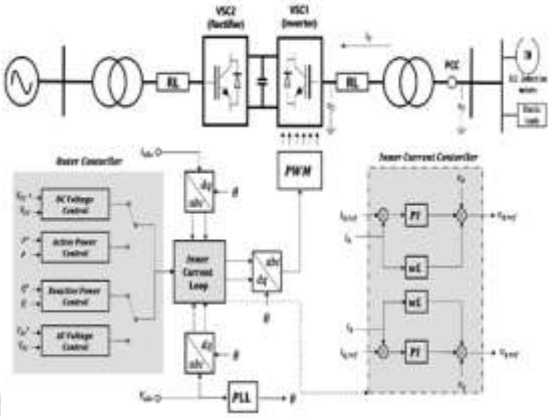

Fig. 2 The topology of the studied system.

The control of the VSC-HVDC is based on the inner and outer control loop. The main function of the VSC inner control loop is to make *dq*-axis current components (i.e., *isd*and *isq*) follow references generated from the outer control loop. In order to suppress negative sequence currents during unbalanced faults[25], When a VSC-HVDC system feeds power into a passive network; the outer control loop of the rectifier station operates on the dc voltage control mode and the ac voltage or reactive power control mode. At the grid side, VSC can achieve synchronization with the main grid using the Phase Locked Loop (PLL). The control scheme of the rectifier station is shown in Fig. 3, where *Q* is the reactive power transferred from ac grid to the rectifier station, *Us1* is the amplitude of the voltage of the ac grid (see Fig. 2),

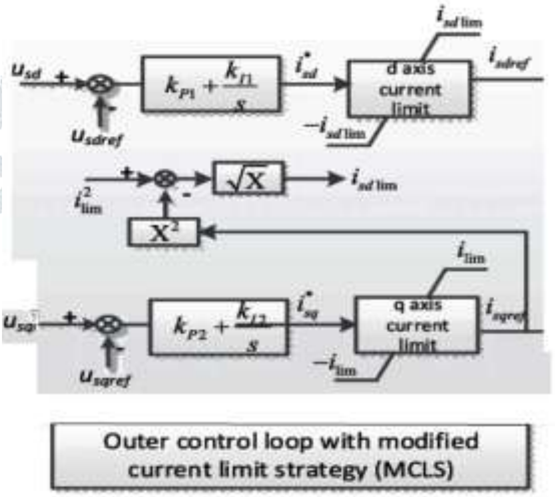

Fig. 3 The outer control loop of the rectifier station with current limiting strategy

The VSC in the receiving side operates on the voltage control mode, which is designed to control the ac voltage at the PCC. The control scheme is illustrated in Fig. 4. Under *dq*-axis form, the active and reactive power, transferring from the VSC inverter. In order to enhance the voltage stability of the passive industrial system, this section presents two ride-through methods, which consist of a modified current limit strategy (MCL) and a frequency hysteresis control (FHC). Both of them are based on the conventional ac voltage control (CAVC) adopted by the VSC at the receiving side. The ac voltages are closely connected, mainly because of the inductive characteristics of high voltage transmission lines[13],[24]. The change of reactive power in the system may have a large impact on the ac voltage of the power grid. When a VSC-HVDC is supplying passive industrial installations, the rectifier station operates on the dc voltage control mode. In case of faults in the sending side, there is an ac voltage drop in the grid and the current of the VSC rectifier reaches the limit. As a result, the VSC at the grid side is unable to maintain the dc voltage. The variation of the active power may cause the fluctuation of the dc voltage, resulting in a disturbance of the ac voltage at the PCC, since the ac voltage in the passive system is modulated from the dc voltage of the VSC-HVDC[26]. Therefore, during severe faults, the active power will have an impact on the ac voltage of the passive industrial installations.

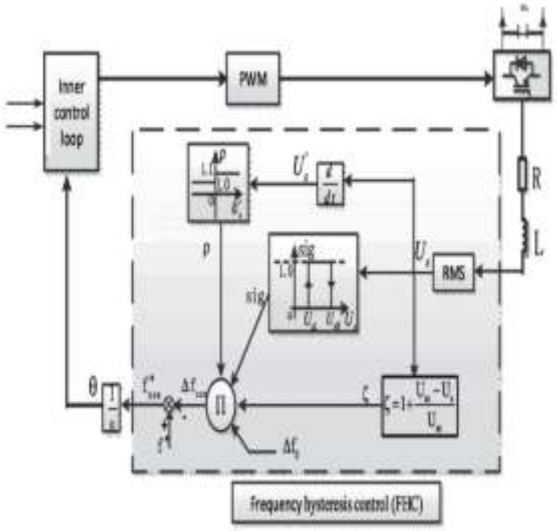

Fig. 4 Block diagram of proposed frequency hysteresis control method of the VSC-HVDC at the receiving side.

On the other hand, the reactive poweris still critical for the voltage stability of the passive system.Thus, an analysis should be done to investigate that the mainfactor affecting the ac voltage at the receiving side is whetherthe active power or the reactive power. In the system shown in Fig. 2, a metallic three-phase fault issimulated at the sending side of the VSC-HVDC. The fault isapplied at 0.5 s and is cleared at 0.6 s.

III. SIMULATION RESULTS

According to the topology in Fig. 2, the paperuses the test system in matlab/simulink to verify the validity of the control strategies proposed above. In the simulation, the VSC at the sending side operates on the dc voltage control mode and the reactive power control mode. An ac voltage controller is used on the inverter of the VSC-HVDC system.

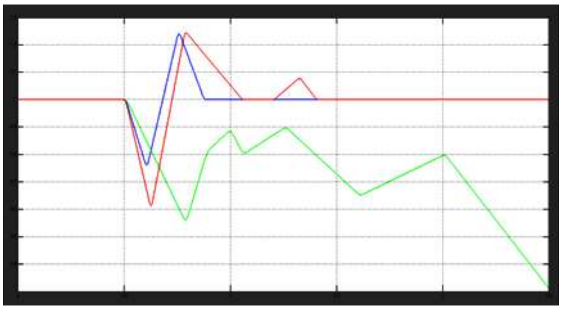

Fig:5(a) AC voltage at the PCC

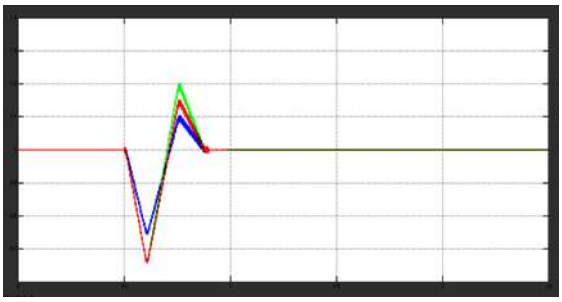

Fig:5(b) DC voltage of the rectifier VSC

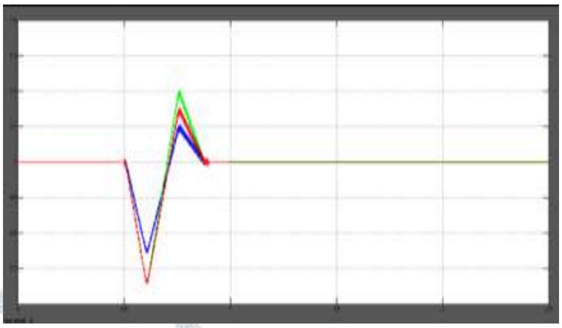

Fig:5(c) DC voltage of the inverter VSC

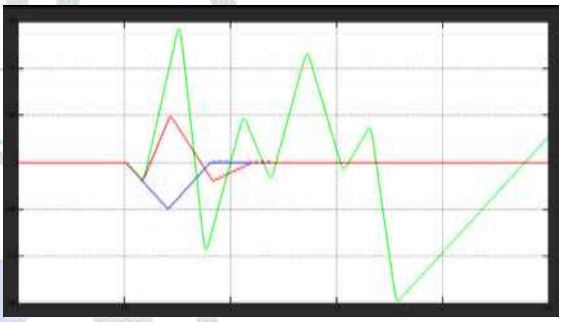

Fig:5(d) Frequency of the passive system

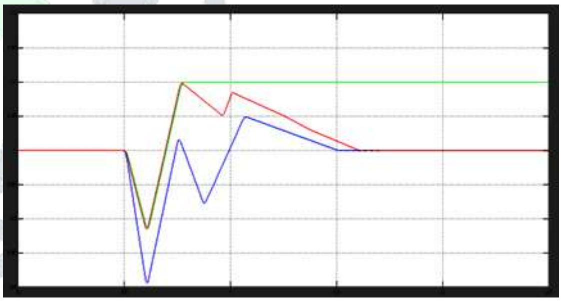

Fig:5(e) VSC current

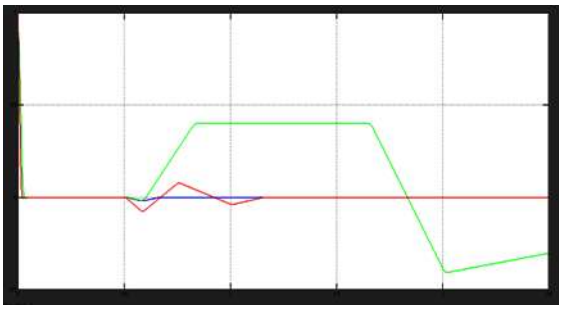

Fig:5(f) The q axis component of voltage at the PCC

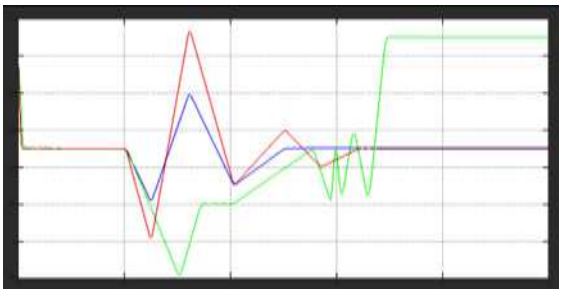

Fig:5(g) The q axis current component of VSC

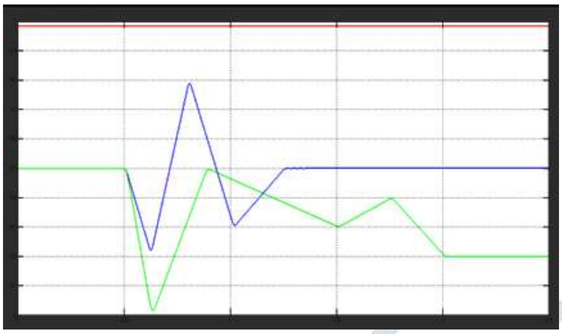

Fig:5(h) Reactive power transferred from the VSC inverter

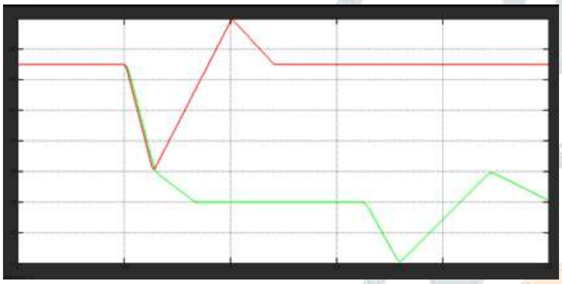

Fig:5(i) IM active power

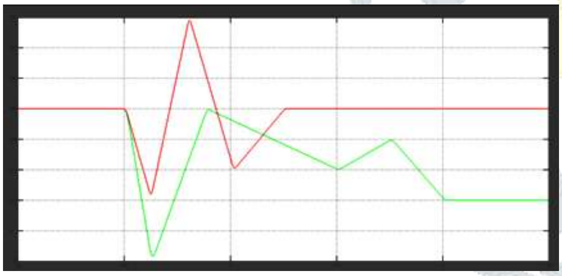

Fig:5(j) IM reactive power

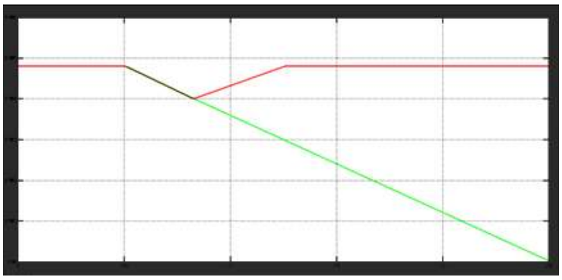

Fig:5(k) IM speed

Fig:5System responses of the metallic single-phase fault with different control methods. (a) ac voltage at the PCC. (b) dc voltage of the rectifier VSC. (c) dcvoltage of the inverter VSC. (d) frequency of the passive system. (e) VSC current. (f) the q axis component of voltage at the PCC. (g) the q axis current component of VSC. (h) reactive power transferred from the VSC inverter. (i) IM active power. (j) IM reactive power. (k) IM speed.

Among all AC faults, single-phase ground fault is the most common fault. To test the fault ride-through capability of the control strategies, a single-phase fault is applied to the sending side of the VSC-HVDC at 0.5 s, when the system is under the steady state. After 0.1 s, the fault is cleared. The simulations have been done under different control strategies used on the inverter of the VSC-HVDC system, i.e., the conventional ac voltage control (CAVC), the CAVC with the MCLS and the CAVC with the MCLS and FHC. The simulation results are shown in Fig.5.

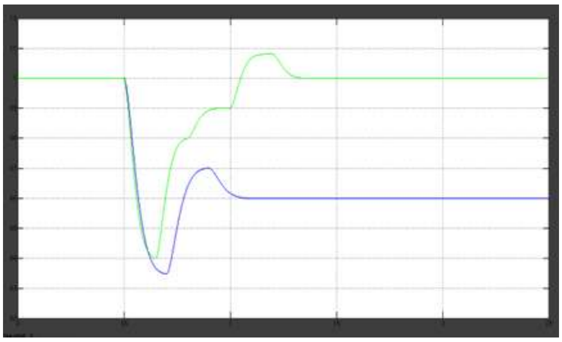

Fig:6(a) AC voltage at the PCC

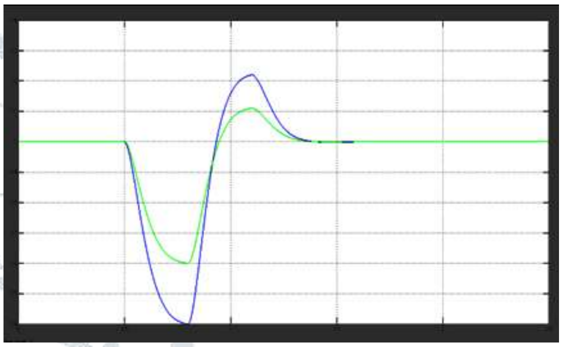

Fig:6(b) DC voltage of the inverter VSC

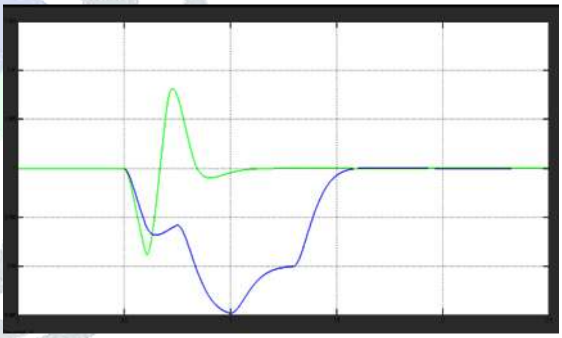

Fig:6(c) Frequency of the passive system

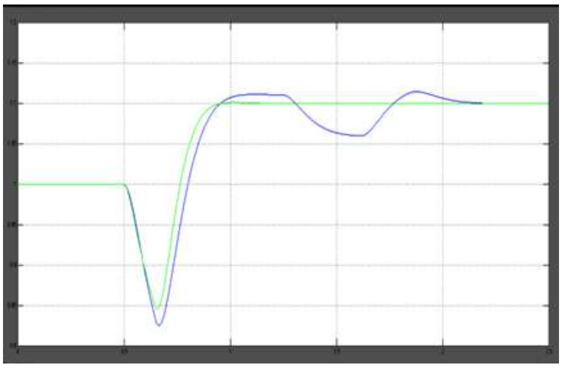

Fig:6(d) VSC current

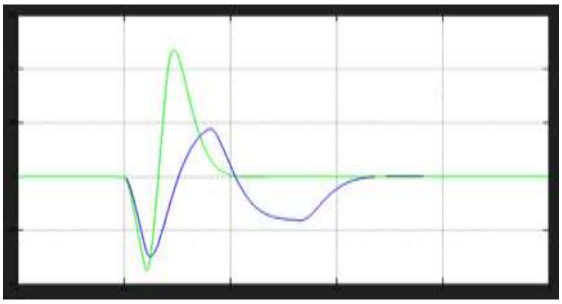

Fig:6(e) The q axis component of voltage at the PCC

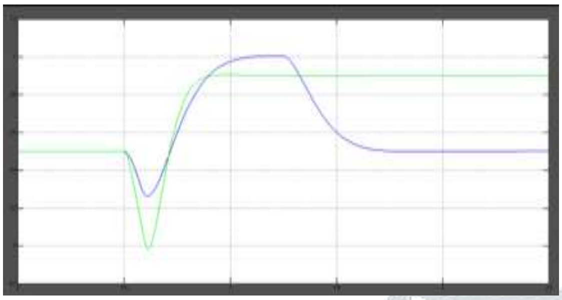

Fig:6(f) The q axis current component of VSC

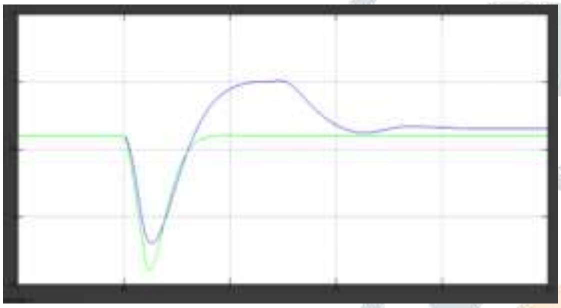

Fig:6(g) Reactive power transferred from the VSC inverter

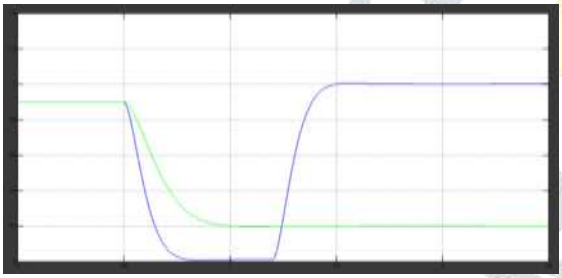

Fig:6(h) Consumed active power

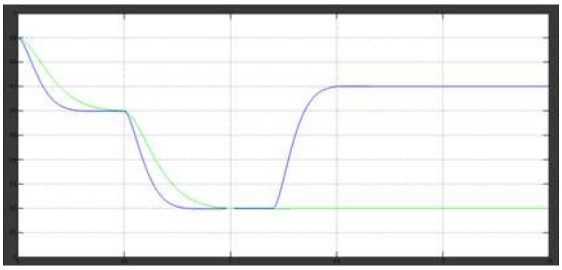

Fig:6(i) Consumed reactive power

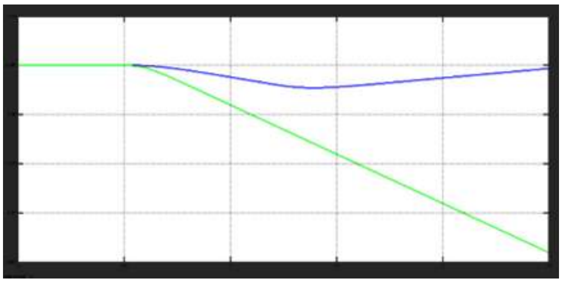

Fig:6(j) IM speed

Fig:6 System responses of the metallic three-phase fault with and without the FHC. (a) ac voltage at the PCC. (b) dc voltage of the inverter VSC. (c) frequency of the passive system. (d) VSC current. (e) the q axis component of voltage at the PCC. (f) the q axis current component of VSC. (g) reactive power transferred from the VSC inverter. (h) consumed active power. (i) consumed reactive power. (j) IM speed.

The most severe fault in power systems, metallic three-phase fault,[6] has also been simulated at the sending side of the VSC-HVDC. A metallic three-phase fault is applied at 0.5 s at the grid side and is cleared after five cycles. It is derived from the previous section that with the CAVC, the passive industrial system is unable to ride through severe faults[6-8]. Therefore, in this section, the simulations have been done only under two control strategies, i.e., the CAVC with the MCLS and the CAVC with the MCLS and FHC. The simulation results are shown in Figs.6.

IV. CONCLUSION

This paper aimed at designing control strategies to enhance the voltage stability of the passive industrial installations supplied by the VSC-HVDC. Based on the analytical result that the main factor affecting the ac voltage of the passive system is the reactive power, the control methods that consist of the modified current limit strategy and the frequency hysteresis control are proposed. The reason of choosing the MCLS is that in steady and transient conditions, the reactive power transferred from the inverter of the VSC-HVDC is mainly decided by *isq*, the *q* axis component of the VSC current. When the MCLS is added to the outer control loop of the inverter station, the setting of *isq* can be met preferentially in order to increase reactive power output from the VSC. On the basis of the MCLS, an additional frequency control is proposed. The idea of the FHC is to decrease the set frequency of the VSC at the receiving side according to the measurement of the ac voltage in the passive industrial system. By this means, the control effect of the MCLS can be improved. What’s more, the reduction of the set frequency can lead to an increase of the *isq*, which further increases the reactive power output. The simulation verifications were respectively carried out during a metallic single-phase fault and a metallic three-phase fault.

V. REFERENCES

[1] Lamell, Jan O., Timothy Trumbo, and Tom F. Nestli. "Offshore platform powered with new electrical motor drive system." IEEE Industry Applications Society 52nd Annual, 2005.

[2] Kim, Tae-O., Hui-Dong Ju, and Gyu-Hong Kang. "Analysis of power system harmonics for an offshore design with VTB dynamic model."*IEEE Vehicle Power and Propulsion Conference*, 2012.

[3] McGranaghan, Mark F., David R. Mueller, and Marek J. Samotyj. "Voltage sags in industrial systems." *IEEE Transactions on industryapplications*, vol. 29, no. 2, pp. 397-403, 1993.

[4] Melhorn, Christopher J., Timothy D. Davis, and George E. Beam. "Voltage sags: their impact on the utility and industrial customers." *IEEETransactions on Industry Applications*, vol. 34, no. 3, pp. 549-558, 1998.

[5] Becker, Carl, et al. "Proposed chapter 9 for predicting voltage sags (dips) in revision to IEEE Std 493, the Gold Book." *IEEE Transactionson Industry Applications*, vol. 30, no. 3, pp. 805-821, 1994.

[6] C. Du, et al. "A new control strategy of a VSC–HVDC system for high-quality supply of industrial plants." *IEEE Transactions on PowerDelivery*, vol. 22, no. 4, pp. 2386-2394, 2007.

[7] Flourentzou, Nikolas, Vassilios G. Agelidis, and Georgios D. Demetriades. "VSC-based HVDC power transmission systems: An overview." *IEEETransactions on Power Electronics*, vol. 24, no. 3 , pp. 592-602, 2009.

[8] Y. Liu, and C. Zhe. "A flexible power control method of VSC-HVDC link for the enhancement of effective short-circuit ratio in a hybrid multi-infeed HVDC system." *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1568-1581, 2013.

[9] Chehardeh, M. Isapour, et al. "An optimal control strategy to alleviate sub-synchronous resonance in VSC-HVDC systems." *Power Electronicsand Intelligent Transportation System (PEITS), 2009 2nd InternationalConference on*.Vol. 1, 2009.

[10]Adeuyi, O.D.; Cheah-Mane, M.; Liang, J.; Jenkins, N.; Wu, Y.; Li, C.; Wu, X. Frequency support from modular multilevel converter based multi-terminal HVDC schemes. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 23 July–2 August 2015; pp. 1–5.

[11] P. Bresesti, W. L. Kling, R. L. Hendriks, R. Vailati, "HVDC connection of offshore wind farms to the transmission system", IEEE Trans. Energy Convers., vol. 22, no. 1, pp. 37-43, Mar. 2007.

[12]Mobarez, M.; Kashani, M.G.; Chavan, G.; Bhattacharya, S. A novel control approach for protection of multi-terminal VSC based HVDC transmission system against DC faults. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 20–24 September 2015; pp. 4208–4213.

[13]Fathabadi,H.,2014.ControlofaDFIG-basedwindenergyconversionsystemoperatingunderharmonicallydistortedunbalanced grid voltage along withn on sinusoidalrotorinjectionconditions.EnergyConvers.Manag.,60–72.

[14] Mohammadpour, H.A., Santi, E., September 2014. Sub-synchronous resonance analysis in DFIG-based wind farms: mitigation methods – TCSC, GCSC, and DFIG controllers – Part II. Proc. IEEE Energy Convers.Congr. Expo, 1550–1557.

[15] Wang, L., Yu, J.-Y., Chen, Y.-T., 2011. Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system. IET Renew. Power Gener. 5, 387–396.

[16] Gavriluta C., Candela I., Luna A., ET AL.: ‘Hierarchical control of HV-MTDC systems with droop-based primary and OPF-based secondary’, IEEE Trans. Smart Grid, 2015, 5, (6), pp. 1502–1510

[17] Renedo J., García-Cerrada A., Rouco L.: ‘Active power control strategies for transient stability enhancement of AC/DC grids with VSC-HVDC multi-terminal systems’, IEEE Trans. Power Syst., 2016, 11, (31), pp. 4595–4604

[18] Li B., He J.W., Li Y., ET AL.: ‘Single-ended protection scheme based on boundary characteristic for the multi-terminal VSC-based DC distribution system’, Proc. CSEE, 2016, 11, (36), pp. 5741–5749

[18] Jin Y., Fletcher J.E., O’Reilly J.: ‘Multiterminal DC wind farm collection grid internal fault analysis and protection design’, IEEE Trans. Power Deliv., 2010, 4, (25), pp. 2308–2318

[19]D’Arco S., Suul J.A.: ‘Generalized implementations of piecewise linear control characteristics for multiterminal HVDC’, Int. Symp. Power Electronics, Electrical Drives, Automation and Motion, Ischia, Italy, June 2014

[20]M. Guan et al., "Synchronous generator emulation control strategy for voltage source converter (VSC) stations", IEEE Trans. Power Syst., vol. 30, no. 6, pp. 3093-3101, Nov. 2015.

[21]P. Kundur, Power System Stability and Control, New York, USA:McGraw-Hill, pp. 647-658, 1994.

[22]G. Tang et al., "Sliding mode robust control based active-power modulation of multi-terminal HVDC transmissions", IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1614-1623, Mar. 2016.

[23]G. Li et al., "Modeling of VSC-HVDC and control strategies for supplying both active and passive systems", Power Eng. Soc. Gen. Meeting, 2006.

[24]M. Guan, Z. Xu, "Modeling and control of a modular multilevel converter-based HVDC system under unbalanced grid conditions", IEEE Trans. Power Electron., vol. 27, no. 12, pp. 4858-4867, Dec. 2012.

[25]Z. Xu et al., Voltage Source Converter Based High Voltage Direct Current Transmission System Chinese, Beijing, China:China Machine Express, 2012.

[26]M. Guan, Z. Xu, H. Chen, "Control and modulation strategies for modular multilevel converter based HVDC system", Proc. IEEE 37th Annu. Ind. Electron. Soc. Conf., pp. 849-854, 2011.