2019 IEEE PES Innovative Smart Grid Technologies Asia

Optimal Hierarchical Voltage Control for VSC-MTDC Distribution Network

Lawrence Bibaya, Chongru Liu, Gengyin Li
School of Electrical and Electronic Engineering
North China Electric Power University
Beijing, China
lawrencebibaya@ncepu.edu.cn, chongru.liu@ncepu.edu.cn, ligy@ncepu.edu.cn

***Abstract*—This paper proposes an effective optimal hierarchical voltage control for VSC-MTDC distribution network. In this scheme the lower control layer used droop control strategy which enables quick response to power fluctuation and ensures a stable DC voltage, and the upper control layer used optimal power flow (OPF) based hybrid particle swarm optimization (HPSO) to efficiently find the optimal reference values of the dc voltage and active power for the voltage-regulating converters in order to minimize the losses during the operation of the flexible MTDC distribution network. In this control structure, the N-1 constraint is added to the upper control layer in order to avoid the DC voltage of a converter station to exceed its DC voltage operating limits. In case of variation in load or generation of the grid, a new stable operating point is achieved based on the proposed control strategy for optimal operation of the MTDC grid. A five terminals VSC distribution network is designed and simulated in PSCAD. First, the steady state analysis is conducted, and then dynamic simulations results are analyzed. The analysis shows that the proposed control strategy achieves dc voltage stability, power balance and minimum losses in a safe manner.**

***Index Terms*—Hierarchical control, hybrid particle swarm optimization (HPSO), optimal power flow (OPF), voltage-droop control, VSC-MTDC distribution network.**

I. INTRODUCTION

The practical benefits of DC grids at different levels have become a common acknowledgment within the scientific community worldwide [1]–[6]. Scholars from research institutes all over the world are sharing the same point of view considering flexible multi-terminal DC technology as the key technology for our future power grid [1]. Flexible multi-terminal DC technology using voltage source converters devices has reached a worthy level of maturity over the years [7]–[9] making it possible for multiple high-voltage and medium-voltage applications considering its great advantages in offshore wind farms exploitation, rehabilitation of urban distribution network, interconnection between AC transmission systems and stable integration of large-scale renewable energy farms into the grid. With the increasing amount of high voltage direct current (HVDC) transmission system installations around the world, flexible MTDC distribution network will definitely have a great impact on our future life through efficient distributed energy access, energy saving, and environmental protection. Unlike High voltage MTDC transmission, the researches of flexible MTDC distribution network in many countries are still in the conceptual and planning stage. In 2013 a four-terminal dc distribution laboratory been set up by the Shenzhen power supply bureau, and in 2014, China Southern Power Grid and several universities collaborate to set up a seven-terminal real-time simulation laboratory for the purpose of additional research on control and protection of MTDC distribution network [1]. DC voltage control is certainly one of the most significant aspects to guarantee efficient operation and stability of a VSC-MTDC grid. Nevertheless, at the present time, the concept of the flexible MTDC distribution grids still requires a lot of research on the topics related to optimal coordinated control. Most of the literature that have addressed the optimal operation of the MTDC grids in terms of loss minimization focuses in transmission level application; also they do not combine droop control characteristics and loss minimization [10]. In such approaches, if there is a communication failure between the upper control and lower control layers the system will not be able to ensure good power balance and dc voltage stability. Gradient-based optimization technique [11] and standard solver from MATLAB optimization toolbox [12]–[14] been proposed to solve the optimal power flow calculation in order to optimize certain systems functionalities. In [15] a cooperative DC grid power flow based PSO is proposed to avoid the possibility of been trapped in the local optimal solution and to increase speed convergence.

In this paper, the operation of a five-terminal VSC-MTDC network is improved by reducing grid losses. The proposed optimal hierarchical voltage control not only ensure dc voltage stability and minimum losses but also integrate the N-1 constraint in order to allow the system to operate in the safety region while reducing grids losses. The optimal power flow (OPF) calculation based hybrid particle swarm optimization (HPSO) converges quickly and give a good result. The rest of this paper is organized as follows. Section II described the proposed optimal hierarchical voltage control strategy. Then a steady state analysis is carried out in Section III. The dynamic response of the system under conditions such as load variation, wind fluctuation, converter out of service and communication failure is tested in Section IV. Finally, conclusions are presented in Section V.

II. PROPOSED CONTROL FRAMEWORK

When the DC voltage droop control strategy is adopted in the multi-terminal flexible DC system, each droop controlled converters can adjust their active power output in real-time and balance the power of the system according to their droop characteristic [16]–[19]. In traditional droop control, high penetration of renewable energy into the system or large load change will create a DC voltage deviation in the system, but the droop characteristics will remain fixed and won't adjust to the large fluctuation. Large power fluctuations can easily lead converters to reach their DC voltage limits and potentially make them going out of operation. The proposed optimal hierarchical voltage control strategy is divided into two control layers. The lower control layer adopts DC voltage droop control strategy for the DC voltage regulating converters and the upper control layer is responsible for the optimization of network loss by sending to the lower control layer optimal parameters values for droop controllers in order to optimize system losses, ensure DC voltage stability and power balance of the system. The different steps for the calculation of the droop controller's optimal values are shown in Fig.1.

The approach works as follows: at first, the upper control layer measures and collects the network data, real-time output of renewable sources and load data. Then, a DC load flow algorithm is run to obtain a first solution for the optimal power flow calculation. Next, the optimal power flow based HPSO algorithm[20] is calculated to find the droop controlled VSC's DC voltage and active power reference values that will minimize the network losses. The optimal DC load flow algorithm runs N load flow scenarios, with one dc node defective at a time, to check whether the MTDC network is N-1 secure for the obtained power-flow scenario. If there is a feasible solution that is N-1, secure, the upper control layer sends the DC voltage and active power reference values to VSC controlling the MTDC network voltage.

A. Lower Control Layer and Droop Control Strategy

For multi-terminal flexible DC systems, the lower control layer should be independent of communication and ensure stable and reliable operation of the system. In this paper, the DC voltage droop control is chosen as the lower control layer strategy of the system, every DC voltage-regulating converter connected to the AC grid uses DC voltage droop control to take on the control of system DC voltage. The DC voltage of converters controlled by droop decreases linearly with the increase of their active power output. When the multi-terminal flexible DC system adopts the droop control strategy, the power can be allocated automatically between the various converters. The system can keep a stable running state without the participation of the upper control layer. The droop control characteristics of the converter can be written in the following mathematical form:

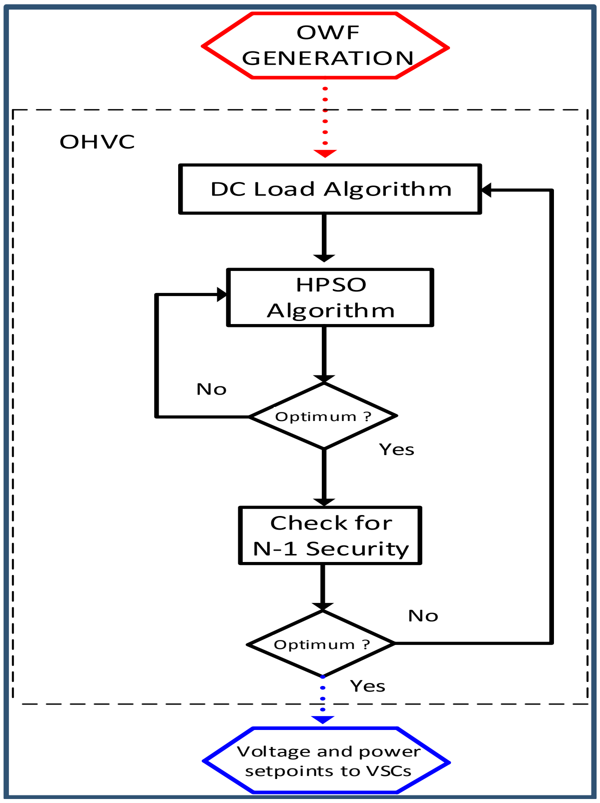


Fig.1. Flowchart diagram for the optimal hierarchical voltage control strategy

$$P_{mea} - P_{ref} + k(U_{dc,mea} - U_{dc,ref}) = 0 \tag{1}$$

In the formula, P_{mea} and $U_{dc,mea}$ are the converters actual values of active power and DC voltage respectively. P_{ref} and $U_{dc,ref}$ are the converters references values of active power and DC voltage respectively. K is the droop coefficient. After the optimal power flow calculation, the upper control layer sends new reference values to the lower control level. These new references values (P_{ref}' and $U_{dc,ref}'$) will shift the droop characteristic and allows the system to operate with minimum losses. The adjustment dynamics of droop characteristic is shown in Fig.2.

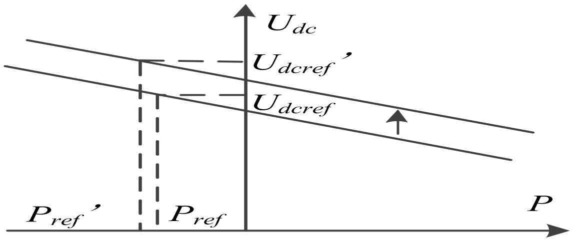


Fig.2. Adjustment of droop characteristic.

B. Optimal DC Power Flow and Objective Function

The idea behind the calculation of the optimal DC power flow is to find the optimal values of the network parameters that will optimize system functionalities such as system losses, total generation cost, operation limits and system security [19]. In this paper, the minimum dc network loss of the system is selected as the goal optimization problem taking into consideration the system N-1 security feature. The core of the upper control layer is the calculation of the dc system optimal power flow. Solving optimal DC power flow problem is to first specify states variables, control variables and fixed variables. In DC system, control variables, *U*, are the voltage references of V-type buses, and fixed variables, *W*, are the net power of P-type buses. The optimal DC power flow problem is formulated by (2)-(6) as follows:

$$\min f(x,U)$$

$$f(x,U)=\sum_{i=1}^{n}\sum_{j=i+1}^{n} g_{ij}(U_{dci}-U_{dcj})^2 \tag{2}$$

In the formula, x represents state variables, U represents control variables, n is the total number of nodes in the system, g_{ij} is the conductance matrix value at ij, U_{dci} and U_{dcj} are the DC voltages of node i and node j respectively.
The objective function is subject to the following constraints:

1. System power balance

$$P_{Gi}-P_{Li}-\sum_{J=1}^{n} G_{ij}U_{dci}U_{dcj}=0,\quad i\in(t+1,n) \tag{3}$$

P_{Gi} and P_{Li} represent the generation and load at terminal I respectively; G_{ij} are the elements of the dc grid's conductance matrix; t is the total number of nodes connected to the DC voltage regulating converters.

2. DC terminals voltage limits

$$U_{dci\min}\le U_{dci}\le U_{dci\max}\quad i\in(1,n) \tag{4}$$

$V_{i\min}$ and $V_{i\max}$ indicate the upper and lower limits on DC voltage at grid's terminals, respectively. In this paper, we consider that they are 0.9 and 1.1 times the rated voltage.

3. Converter's active power limits

$$P_i\le P_{i\max},\quad i\in(1,t+s) \tag{5}$$

$P_{i\max}$ denotes the maximum permissible power of the converter station i; s is the total number of nodes connected to the load or other generations units.

4. DC line current limits

$$\left|g_{ij}(U_{dci}-U_{dcj})\right|\le \mathrm{I}_{\mathrm{m}ax},\qquad i,j\in(1,n),i\ne j \tag{6}$$

I_{max} is the maximum current allowed to flow through a DC line.

5. N-1 Constraints

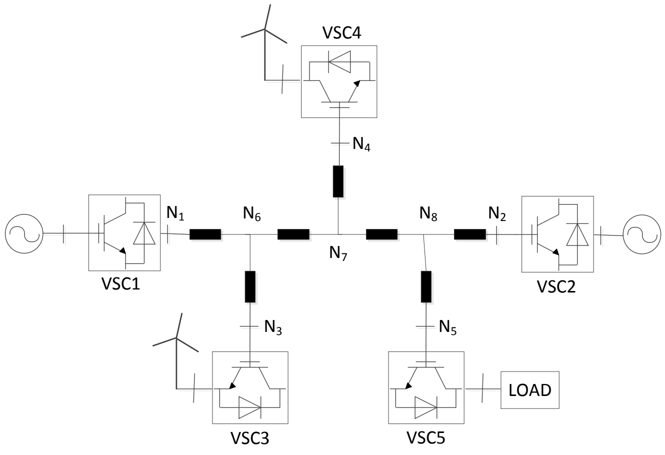


Fig.4. The test five terminals VSC distribution network system.

Higher the DC voltage is, smaller the net losses are. Therefore the result of the optimal DC power flow calculation is that the DC voltage of at least one-converter station will reach the upper limit value in (4). The drawback is that, when a line or a converter fails to operate, the system will have an excess of active power and the DC voltage will rise, potentially exceeds its limits. This will cause the tripping of the protection device. Therefore, the N-1 constraints is added to the upper control layer and will ensure that when any converter station in our flexible DC system is out of operation, the DC voltage of the remaining converter station will not reach and exceeds their limits during the system steady state transition, thus the control strategy will continue to ensure the stable operation of the system. More details on the implementation of this constraint can be seen in section III.b.

TABLE I The Length of DC Lines

Line number	l_{16}	l_{36}	l_{67}	l_{47}	l_{78}	l_{58}	l_{28}
lenght （km）	15	4	12	6	8	5	15

III. CASE STUDY

A. Test System

The system of Fig.4. is used as the study system to evaluate and validate the effectiveness of the proposed optimal hierarchical voltage control strategy. Fig.4 shows a five terminals VSC distribution network. The DC voltage of the system is 10kV, and the rated capacity of the converter station is 10MW. VSC_1 and VSC_2 are connected to different AC grids system. The AC grid voltage is 10kV, the frequency is 50Hz, the connection transformer is 10kV/5 kV. The droop control strategy is used to control the DC voltage, the droop coefficient K is 10;VSC_3 and VSC_4 are connected to the wind farms. VSC_5 is responsible for power supply to the load. The resistance of the DC line is 0.01 Ω/km and the DC line length of the system is shown in Table 1.

B. Steady State Operating Point Calculation

When the system is constrained by N-1, it is necessary to calculate the steady state operating point of the system; the VSC$_1$ will be taken out of operation as an example to explain the calculation of the steady working point and the N-1 constraints.

In order to compare between non-optimal and optimal control strategy, three different scenarios been analyzed and are listed in Table II: In the first scenario only the traditional droop control is adopted by VSC$_1$ and VSC$_2$; in the second example the traditional droop control is considered plus the losses optimization calculation by HPSO, but does not consider the N-1 constraint; in the third scenario there is inclusion of N-1 constraint. In this example, VSC$_3$ and VSC$_4$ power output are 6MW and 8MW respectively, and the load connected to VSC$_5$ is 8MW.

It can be seen from Table II that in the scenario 1 with only lower level droop control and no loss optimization calculation, the net loss of the flexible DC system is the highest at 3.22% and dc voltage level is the furthest from the limit 1.1pu. The net loss of the system is the lowest in scenario 2 with network loss optimization control strategy, and the DC voltage of the VSC$_4$ of the wind farm side converter station is 1.1pu, so the upper limit of the DC voltage is reached. During normal operation, having wind farms voltage close to the maximum allowable voltage is not of concern. Nonetheless, a possible outage in some points of the MTDC network could give rise to an overall increase of the system voltage profile, causing problems to the network nodes that are operating close to the voltage limit. So in scenario 3, N-1 constraints are integrated to solve this problem. After adding the N-1 constraint, the DC voltage of VSC4 dropped from 1.10pu to 1.058pu, but the net loss increased from 2.1% to 2.52%. Even so, in scenario 3 the total net loss is about 22% lower than that of the lower level control in scenario 1 and can ensure that the whole system is N-1 stable. By satisfying the N-1 constraint, the DC voltage of the system will not be too high after the optimal power flow is satisfied. The overall control strategy can ensure that the system can optimize the network loss during the operation of the system while ensuring the voltage stability, power balance, and N-1 security criterion of the 5 terminals flexible distribution network.

TABLE II. Comparison of Three Examples Power Flow Results

Node	Example 1: no optimization		Example 2: optimization, no N-1		Example 3: optimization, plus N-1.	
	U_{dci}(pu)	P_i(pu)	U_{dci}(pu)	P_i(pu)	U_{dci}(pu)	P_i(pu)
VSC1	0.936	-0.365	1.081	-0.480	1.043	-0.384
VSC2	0.919	-0.190	1.075	-0.0901	1.029	-0.180
VSC3	0.953	0.6	1.097	0.6	1.058	0.6
VSC4	0.952	0.8	1.10	0.8	1.058	0.8
VSC5	0.916	-0.8	1.072	-0.8	1.027	-0.8
N6	0.948	0	1.093	0	1.021	0
N7	0.942	0	1.090	0	1.015	0
N8	0.925	0	1.078	0	1.005	0
Total net loss	3.22%		2.1%		2.52%	

IV. DYNAMIC SIMULATIONS RESULTS

Dynamic simulations are needed to confirm the obtained load flow results and to evaluate the dynamic behavior of the complete system operating under the proposed optimal hierarchical voltage control strategy. Because, only wind farm's active power and load data are needed to optimize our system, specific internal electromagnetic and mechanical characteristic of wind farms been neglected. The modeling of VSC connected to wind farms and load only considers their external characteristics and a fixed active power control strategy are used to simplify the modeling. The lower control strategy of each converter station in our multi-terminal flexible DC system is shown in Table III.

TABLE III. Control strategy of VSC

Converters stations	VSC1	VSC2	VSC3	VSC4	VSC5
Control strategy	Droop control	Droop control	Active power control	Active power control	Active power control

The onshore VSC$_1$ and VSC$_2$ are controlled by DC voltage droop, with a droop coefficient of 10, which is responsible for balancing the active power of the system, controlling the DC voltage and ensuring the stable operation of the system. The specific droop characteristic of the controller is given by calculation of the upper network loss. The communication delay between the lower control and the upper control layer is 200ms, and the upper network loss optimization cycle is 2s.

To examine the behavior and effectiveness of the optimal hierarchical voltage control strategy in reliably and safely operating the dc distribution network, three different scenarios have been analyzed:

- Scenario 1: No network loss optimization

In this scenario, the VSC-MTDC system has only lower droop control and no upper layer network loss optimization. At the beginning of the simulation, offshore wind farms VSC$_3$ and VSC$_4$ send out active power of 3MW and 4MW respectively, and the load side VSC$_5$ absorbed active power of 4MW. When t=2s, the active power of the two wind farms is increased to 6MW and 8MW, and the active power of the load is increased to 8MW at t=4s. The DC voltage and the active power of each converter station are shown in Fig. 5(a) and Fig. 5(b). When the active power output of the wind farms increases at t=2s, we notice an excess of active power in the DC system. At the same time, the steady-state DC voltage of the system increased. The system through VSC$_1$ and VSC$_2$ adopts the DC voltage droop control strategy and adjusts their active power, according to the droop characteristic in order to achieve the system power balance again and control its voltage. When the active power of the load is increased at t=4s, we observe a lack of active power in the DC system. The system steady-state DC voltage decreases, VSC_1 and VSC_2 automatically reduce their absorbed active power from the DC side, in order to maintain the voltage stable. The net losses of the three steady-state power flows are 0.013pu, 0.041pu and 0.046pu respectively (Fig.6.)

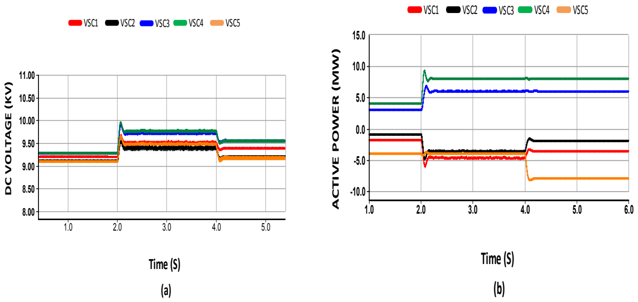
It can be seen that when there is step change of wind or load demand, the onshore converter stations using droop control strategy can automatically adjust their active power according to the system power shortage or excess, so as to ensure the DC voltage stability of the system. However, the droop characteristic of the DC voltage droop control strategy is fixed. It will not change according to the actual operation of the system, and cannot optimize the network loss during the operation of the system, and it may lead to overvoltage when the power is greatly changed.

- Scenario 2: Network loss optimization and N-1 constraint

In order to improve the shortcomings of the traditional droop control strategy, the optimal hierarchical voltage control strategy is proposed. The simulation process of the system is the same as before. The DC voltage and the active power of each converter station are shown in Fig.7 (a) and Fig.7 (b). At the beginning of the simulation, the power balance and voltage stability are achieved under droop control. At t=1s, the upper control layer collects the network data, completes the loss optimization calculation and sends new reference values to the droop controlled converters at t=1.2s. At t=1.2s, VSC_1 and VSC_2 change their DC voltage reference value and their active power reference value according to the optimal power flow calculation of the upper control layer. As shown in Fig.7 (a) and Fig.7 (b), the active power of VSC_1 and VSC_2 has changed, and the DC voltage of the system increases, which reduces the network loss during the system operation. At the time of t=2s, the output power of two wind farms increased, and the system operating state changed. Because the output active power of the wind farm increased, the DC voltage also increased. If one onshore converter station is out of operation at this time, the system will have an excess of dc power, which will makes the DC voltage increase further, and potentially reaches its DC voltage limit, so the upper control layer will have to ensure the safe operation of the system. At t=3.2s, the droop controller of the lower layer adjusts the reference value of DC voltage and the reference value of active power once again according to the new instruction values. After the new steady state running point is reached, the DC voltage of the system is reduced, the reliability of the system is improved, and the system satisfies the N-1 criterion. When t=4s, the load rises from 4MW to 8MW, the DC voltage of the system falls, the upper control layer collects the system data once again at t=5 s. The lower control layer updates the reference value at t=5.2s. At this time, the DC voltage of the system rises, and the system runs on the basis of the N-1 criterion. After the loss optimization of the system, the net losses of the three steady-state power flow are 0.009pu, 0.037pu and 0.036pu respectively (Fig.8.), which is lower than the net losses obtained from the system with only the droop control strategy.

- Scenario 3: Converter station out of service

At the beginning of simulation, VSC_3 and VSC_4 of wind farm side converter stations send out active power of 3MW and 4MW respectively, and VSC_5 connected to the load absorbed an active power of 4MW. At t=2s, VSC_1 is out of operation due to a fault. When t=2.5s VSC_1 is out of trouble and reconnects to the multi-terminal DC system. The DC voltage and active power of each converter station are shown in Fig.9 (a) and Fig.9 (b). At the beginning of the simulation, the system is only under the effect of the droop control strategy, at t=1.2s, VSC_1 and VSC_2 change their DC voltage reference values and their active power reference values according to the optimal power flow calculation of the upper control layer. The curves at this stage are the same as those in the previous section. When VSC_1 is out of operation at t=2s, the absorbed active power of the VSC_1 is reduced to 0, and the DC system appears to have an excess of power, which will drive VSC_2 to increase its absorbed active power in order to maintain the power balance of the system. Due to the existence of droop characteristics, the DC voltage of the system increases. At this time, the DC voltage of VSC_3 is the highest DC voltage amongst others converter stations, reaching the upper limit of 1.1pu of the DC voltage. The DC voltage of the other converter stations is within the DC voltage limit, which verifies the correctness of the proposed N-1 constraints. It can be seen that the system can still operate stably when an AC network side converter station suddenly withdraws from the system, and the system satisfies the N-1 criterion. At t=2.5s, VSC_1 is reconnected to the system, and the system is restored to its original running state.



(a)

(b)

Fig.5. Scenario 1: (a) DC voltage of VSCs, (b) Active power of VSCs

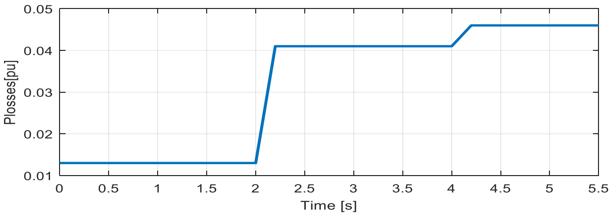


Fig.6. Scenario 1: DC Network losses

V. CONCLUSION

In this paper, an effective optimal hierarchical voltage control for VSC-MTDC distribution network is developed for ensuring dc voltage stability, power balance and minimum losses in a safe manner.

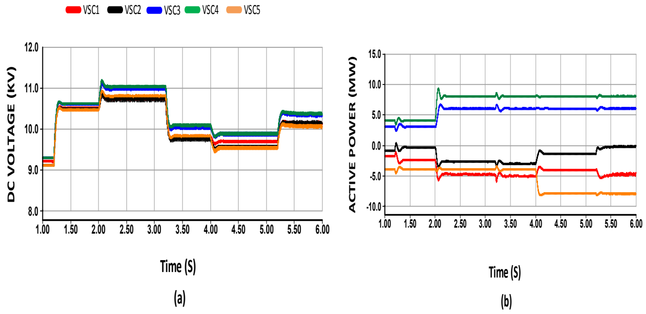


Fig.7. Scenario 2: (a) DC voltage of VSCs, (b) Active power of VSCs

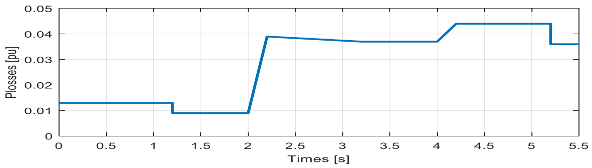


Fig.8. Scenario 2: DC Network losses

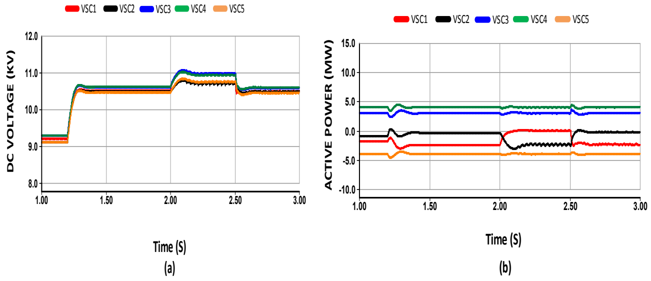


Fig.9. Scenario 3: (a) DC voltage of VSCs, (b) Active power of VSCs

In this scheme, the lower control layer of the system adopts the DC voltage droop control strategy, which is the basis of the control system and is responsible for the DC voltage stability and power distribution within the system;, and the upper control layer used optimal power flow (OPF) based hybrid particle swarm optimization (HPSO) to efficiently find the optimal reference values of the dc voltage and active power for the voltage-regulating converters in order to minimize the losses during the operation of the flexible MTDC distribution network. In order to avoid the DC voltage of a converter station reaching the DC voltage limits, the N-1 constraint is added to the upper control layer optimization. Although this will increase the loss slightly, it can ensure that the DC voltage of the remaining converter station will not exceed the limit when a converter station exits. The simulation results show that the upper control layer can adjust the control characteristics of grid-side converter station according to the changes of active power on the wind farm and load, and reduce the network loss of flexible DC system in operation. The simulation results also show that the remaining converter stations can continue to operate steadily within their voltage limits, even if one of the onshore converter stations is withdrawn from the operation. The system is N-1 stable.

REFERENCES

[1] M. Yang, D. Xie, H. Zhu, and Y. Lou, “Architectures and Control for Multi-terminal DC (MTDC) Distribution Network — A Review,” in *AC and DC Power Transmission, 11th IET International Conference on. IET*, 2015, pp. 1–7.

[2] D. J. Hammerstrom, “AC versus DC distribution systems-did we get it right?,” *2007 IEEE Power Eng. Soc. Gen. Meet. PES*, pp. 1–5, 2007.

[3] M. Starke, S. Member, L. M. Tolbert, and S. Member, “AC vs . DC Distribution : A Loss Comparison,” 2008.

[4] F. Wang, Y. Pei, D. Boroyevich, R. Burgos, and K. Ngo, “Ac vs. dc distribution for off-shore power delivery,” in *IECON Proceedings (Industrial Electronics Conference)*, 2008, pp. 2113–2118.

[5] F. Dastgeer and A. Kalam, “Efficiency Comparison of DC and AC Distribution Systems for Distributed Generation,” *2009 Australas. Univ. Power Eng. Conf.*, pp. 1–5.

[6] *J. Arrillaga, Y. Liu, and N. Watson, Flexible Power Transmission: The HVDC Options. Wiley, 2007, iSBN: 9780470511855.*

[7] J. Zhu and C. Booth, “Future Multi-Terminal HVDC Transmission Systems using Voltage Source Converters,” *45th Int. Univ. Power Eng. Conf. UPEC2010*, pp. 1–6, 2010.

[8] L. Livermore, “MTDC VSC Technology and its applications for Wind Power,” *45th Int. Univ. Power Eng. Conf. UPEC2010*, pp. 1–6, 2010.

[9] J. Beerten, S. Member, D. Van Hertem, S. Member, and R. Belmans, “VSC MTDC Systems with a Distributed DC Voltage Control – A Power Flow Approach,” *2011 IEEE Trondheim PowerTech*, pp. 1–6, 2011.

[10] A. Egea-àlvarez, O. Gomis-bellmunt, and A. Sumper, “Optimum voltage control for loss minimization in HVDC multi-terminal transmission systems for large offshore wind farms,” vol. 89, pp. 54–63, 2012.

[11] D. C. P. Flow, V. Strategy, K. Rouzbehi, S. Member, A. Miranian, and S. Member, “DC Voltage Control and Power Sharing in Multiterminal DC Grids Based on Optimal,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 4, pp. 1171–1180, 2014.

[12] D. Primary *et al.*, “Hierarchical Control of HV-MTDC Systems With,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1502–1510, 2015.

[13] M. Han, D. Xu, and L. Wan, “Hierarchical optimal power flow control for loss minimization in hybrid multi-terminal HVDC transmission system,” *CSEE J. Power Energy Syst.*, vol. 2, no. 1, pp. 40–46, 2016.

[14] Shi zhuo, " Research on Control Parameter Optimization and Operation Optimization of VSC-MTDC, " Master thesis, Dept. Electrical and Electronic Engineering, North China Electric Power University, 2017.

[15] L. Xianzheng, W. Xingcheng, W. Jialiang, and W. Dan, “Cooperative control of DC grid power flow based on particle swarm optimization algorithm Analysis of multi point control,” pp. 65–69.

[16] F. D. Bianchi and O. Gomis-Bellmunt, “Droop control design for multi-terminal VSC-HVDC grids based on LMI optimization,” in *Proceedings of the IEEE Conference on Decision and Control*, 2011, pp. 4823–4828.

[17] S. W. Kim, S. Y. Choi, and R. Y. Kim, “A novel droop control method for distribution loss minimization in DC microgrids with decentralized communication,” *9th Int. Conf. Power Electron. - ECCE Asia "Green World with Power Electron. ICPE 2015-ECCE Asia*, pp. 456–463, 2015.

[18] H. Li, C. Liu, G. Li, and R. Iravani, “An Enhanced DC Voltage Droop-Control for the VSC-HVDC Grid,” *IEEE Trans. Power Syst.*, vol. 8950, no. c, pp. 1–1, 2016.

[19] R. T. Pinto *et al.*, “A Novel Distributed Direct-Voltage Control Strategy for Grid Integration of Offshore Wind Energy Systems Through MTDC Network,” vol. 60, no. 6, pp. 2429–2441, 2013.

[20] L. Bibaya, “Multi-objective Hybrid PSO Algorithm,” *2018 2nd IEEE Conf. Energy Internet Energy Syst. Integr.*, pp. 1–6.