An Improved DC Voltage Droop Control for Interconnection of Wind Farms by VSC-MTDC

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***Abstract*—According to the VSC-MTDC for interconnection of wind farms, an improved DC voltage droop control strategy was proposed. Under this control strategy, the system can automatically modify the power reference value on DC voltage –active power characteristic curve of the VSC station which was connected with the active AC network, realizing the translation of the droop curve. The strategy can ensure the rapid distribution of wind power variation, at the same time it can control the DC voltage within an allowable range. In addition, if the wind power remained stable over a period of time, the strategy can adjust the DC voltage back to the rated value. Finally, taking a typical five-terminal DC transmission system for example, simulation was processed with EMTDC/PSCAD to verify the correctness of the control strategy. The results show that the proposed strategy is suitable for interconnection by VSC-MTDC of wind farms whose flow changes frequently.**

***Index Terms*—wind farms, voltage source converter (VSC), multi-terminal DC (MTDC), DC voltage droop control**

I. Introduction

In the 21st century, energy has become a strong driving force to promote the rapid development of human society. Coal, oil and other fossil fuels are becoming rarer, meanwhile, wind, solar and other renewable energy sources have got extensive attention and vigorous development from the international community. As a kind of renewable and clean energy, wind power has abundant resources and the construction of large-scale offshore wind farms has become an important aspect of wind energy utilization. Because the offshore wind farm is far from the shore and with the increasing installed capacity of wind farms, when connecting to the grid with traditional AC power transmission, there will be great influence on the stability and power quality of the grid [1]-[3]. Random fluctuation of wind power restricts its capacity when connecting to the grid, while flexible HVDC provides a new solution. Using VSC-HVDC in the interconnection of wind farms, it can diminish the impact of the wind power fluctuations on AC voltage by the reactive power provided by VSC stations, meanwhile it can also isolate the fault of AC side to ensure the normal operation of wind farms. Because the single line's capacity of VSC-HVDC is higher than that of AC transmission, in the field of difficult line construction such as offshore wind farms, VSC-HVDC can save a lot of investment. In addition, VSC-HVDC can easily form a DC grid, and it is very suitable for collection of multiple offshore wind power platforms. So VSC-HVDC is becoming the best technology in the interconnection of wind farms [4]-[7]. When developing offshore wind power on a large scale, a multi-terminal DC transmission system based on voltage source converters is needed, we call it VSC-MTDC [8]-[11].

Compared with the two terminal HVDC system, the multi-terminal DC system is more flexible and reliable, but its control is more complicated. Ref. [12] proposed DC voltage margin control strategy, in which when the DC voltage deviation caused by the outage of the main station is greater than a certain value, the slave station will work in the DC voltage control mode. In this strategy, the slave station must have enough spare capacity, which is hard to achieve in practice. In Ref. [13], a control strategy used for active power distribution between the main station and slave stations based on DC voltage and active power regulation characteristics for VSC stations is proposed. The strategy can avoid the overload situation happening in individual station, and can maintain DC voltage control when stations are out of action. Ref. [14] applied multi-point DC voltage control strategy in interconnection of wind farms by VSC-MTDC, in this way the reliability of the system is improved, but at the same time only one station is involved in the power regulation, resulting in the slow response speed of the system. Another shortcoming of the strategy is that multiple slave stations require multiple priorities to set different voltage, the controller's design will be redundant and complex, which limits the number of VSC. Ref. [15] proposed a multipoint DC voltage adaptive droop control strategy, under which, the station which has already operated closely to the rating would share little unbalanced wind power, meanwhile the station which has much available headroom would share more unbalanced

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wind power, but the strategy ignored the situation that the DC voltage deviation might be too large.

Wind power has characteristics of randomness, intermittent and fluctuation, according to which, an improved DC voltage droop control strategy was proposed. Under this control strategy, the system can ensure the rapid distribution of wind power variation, at the same time it can control the DC voltage within an allowable range. In addition, if the wind power remained stable over a period of time, the strategy can adjust the DC voltage back to the rated value. Finally, simulation was processed with EMTDC/PSCAD to verify the correctness of the control strategy.

II. The Structure and Modelling of a VSC-MTDC System

Fig. 1 is the diagram of the topological structure of a VSC-MTDC system applied to the interconnection of offshore wind farms, this paper will take the system as an example to study the control strategy.

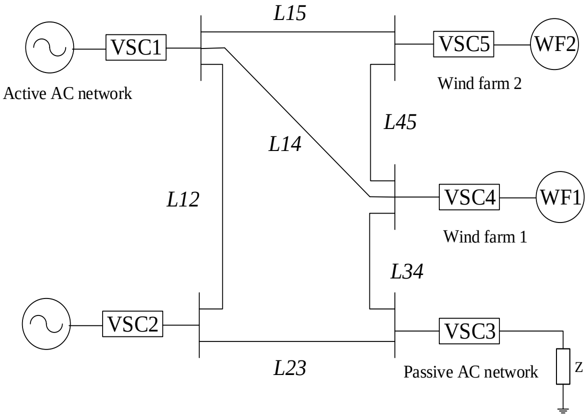

Figure 1. Single-line diagram of offshore wind farm integrating with a VSC-MTDC system.

The ring system consists of five VSC stations: the station 1 and 2 respectively connected to the respective active AC network, use DC voltage droop control strategy for the control of DC voltage and the distribution of wind power; the station 3 connected to the passive AC network is used to realize the power supply to the passive AC network.; the station 4 and 5 using constant frequency and constant AC voltage control respectively connected to the wind farm is 1 and 2 are used to collect the wind power. The direction when power injecting into the DC network is used as the forward direction. Modelling method of VSC and wind farm can be found in [15].

III. The Traditional DC Voltage Droop Control Strategy

DC voltage droop control strategy is the combination of DC voltage control and constant active power control strategy, the basic principle and the outer loop controller is shown in Fig. 2 and Fig. 3.

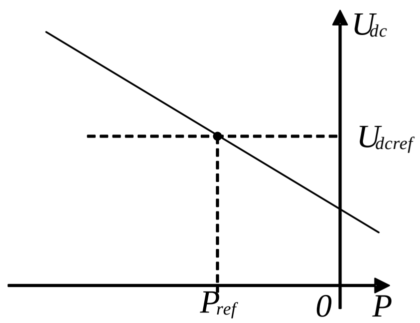

Figure 2. Basic principle of DC voltage droop control.

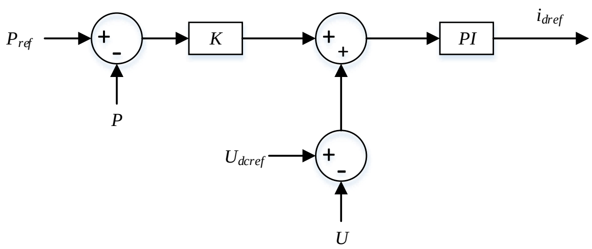

Figure 3. Outer loop controller based on DC voltage droop control.

Under steady-state conditions, the DC voltage of the system and the active power of VSC stations satisfy (1).

$$U_{dc} = U_{dcref} - K\left(P - P_{ref}\right) \tag{1}$$

Changes of U_{dcref}、K、P_{ref} can change the U_{dc}-P drop curve.

Traditional DC voltage droop control strategy can choose different slope K for different VSC station to achieve the distribution of wind power, but there will be a static DC voltage deviation on the DC network, which means this strategy cannot realize the constant voltage control. In situations of interconnection of wind farms, this deviation is especially frequent.

IV. An Improved DC Voltage Droop Control Strategy

In order to prevent the DC bus voltage deviation is too large, affecting the stable operation of the system, this paper proposed a deviation control strategy, as showed in Fig. 4.

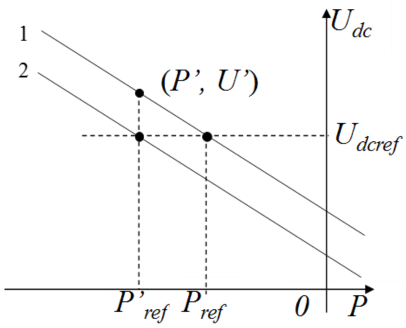

Figure 4. Improved drop curve of U_{dc}-P.

Assuming that the initial operating point of one VSC station is (P_{ref}, U_{dcref}), when the power of the wind farm changes, the VSC station will work on a new stable point (P', U') according to the curve 1, this new state exists a voltage deviation $\Delta U = U' - U_{dcref}$, at the same time, we set P' as the new active power reference value P_{ref}' and get the new drop curve 2. After a while, the operating point will come to (P', U_{dcref}), and the DC bus voltage will come back to U_{dcref}.

Under this improved DC voltage droop control strategy, the power reference value P_{ref} is not a fixed value, it will change according to output steady-state power P of the VSC station. How to judge whether the output power reaches a new steady state value is the key, the judging process is showed in Fig. 5.

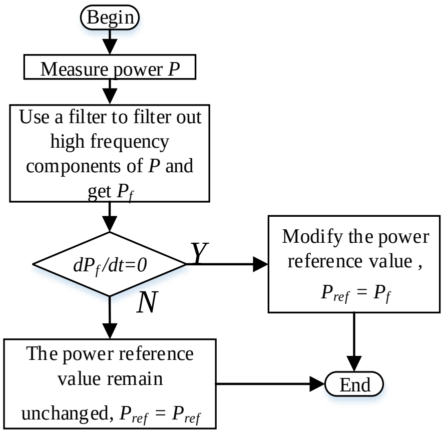

Figure 5. Flow chart of modifying power reference value.

Because the output power P of the VSC station has a small high-frequency fluctuation component, we use a first-order low-pass filter to filter out high frequency components of the power P and then we get P_f.

After differential operation we get dP_f/dt, if $dP_f/dt=0$, then we can determine that the output power has reached a steady state and set P_f as the new power reference value $P_{ref} = P_f$, otherwise P_{ref} will remain unchanged. Here the differential calculation uses numerical approach, the sampling step time is Δt, the value of P_f at the moment t is $P_f(n)$, the value of P_f at the moment t-Δt is $P_f(n-1)$, the value of P_f at the moment $t+m\Delta t$ is $P_f(n+m)$. In order to avoid a large error caused by the disturbance which arose by one or two points in differential calculation, dP_f/dt is calculated by using the method that is calculating the average of differential from multipoint, as shown in (2).

$$\frac{dP_f}{dt} = \frac{1}{m}\sum_{i=0}^{m-1}\frac{P_f(n+m+i) - P_f(n+i)}{m} \tag{2}$$

Because the sampling step time Δt is usually set to microsecond, dP_f/dt is hard to reach a value of 0. Here when it meets the demand that is $|dP_f/dt| \le M$ (Under the platform of EMTDC/PSCAD, the range of M is usually from 1 to 20.), we can determine that the output power has reached a steady state.

Through the above analysis, this strategy can ensure the rapid distribution of wind power variation, meanwhile can maintain the DC voltage at rated value basically. Under this strategy, the premise of modifying the power reference value is that the output power of VSC station must remain stable over a period of time, and after the modification, we also need a short period of time to adjust the DC bus voltage back to the rated value, in this whole process, the output power must remain constant. However, actually the output power of wind farms is changes frequently. As long as the output power is changing and cannot keep constant in a short period time, the requirement to modify the power reference value cannot be achieved, the control strategy which is shown in Fig. 5 will not be completed.

In order to prevent the DC bus voltage deviation is too large, an upper limit value of voltage U_{dcmax} is set as well as the the lower limit value U_{dcmin}, when the voltage reaches the boundary value U_{dcmax} or U_{dcmin}, the feedback output power will be set as the new power reference value at precisely the same moment, the drop curve will be changed. As shown in Fig. 6, when the VSC station operate along the curve 1 and reach the point (P_1, U_1), the voltage reach the upper limit value of voltage U_{dcmax}, the feedback output power P_1 will be set as the new power reference value P_{ref} at precisely the same moment, then the drop curve is changed to curve 2. After that, the VSC station will operate along the curve 2 and find a new operating point. Similarly, when the voltage reaches the lower limit value U_{dcmin}, power reference value will be modified and the curve 3 will appear.

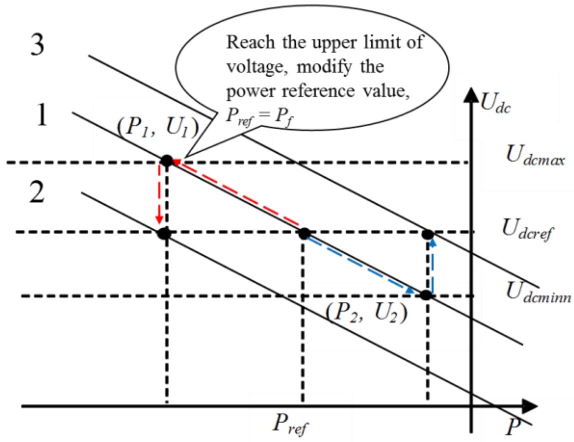

Figure 6. Improved characteristic curve of DC voltage droop control considering the voltage limit.

The process of modifying the power reference value, which the voltage limit is considered, is shown in Fig. 7. There is also a small high-frequency fluctuation component in U_{dc}, a first-order low-pass filter is required to filter out the high frequency components of U_{dc} and then we get U as the judging criteria. When the voltage is running in the allowable range [U_{dcmin}, U_{dcmax}], modification is accomplished only in the situation when the output power has reached a steady state. And once the voltage reached the voltage limit, the power reference value would be modified to get the new drop curve, which can ensure the voltage is running in the allowable range [U_{dcmin}, U_{dcmax}].

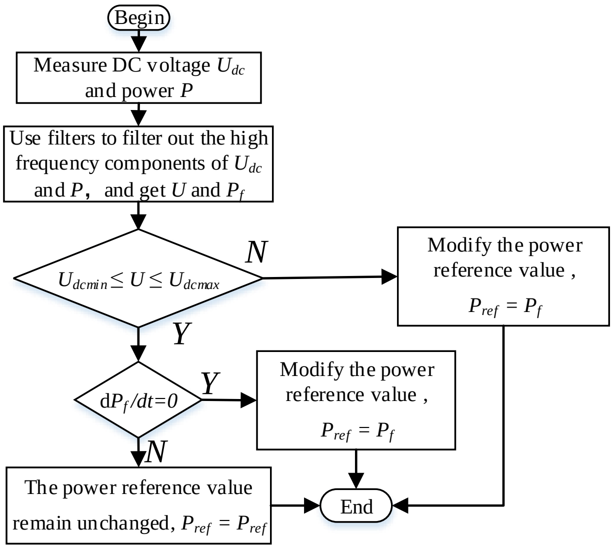

Figure 7. Flow chart of modifying power reference value considering the voltage limit.

V. Example Analysis

In order to verify the correctness of the control strategy proposed in this paper, taking a typical five-terminal DC transmission system which is shown in Fig. 1 for example, simulation was processed with EMTDC/PSCAD. Parts of the system parameters were shown in Table I.

TABLE I. Parts of the System Parameters

Parameter names	Parameter values
Rated DC voltage	400kV
Capacity of VSC1、VSC2	250MW
Capacity of VSC3、VSC4、VSC5	100MW、150MW、300MW
R_{L13}、R_{L25}、R_{L24}、R_{L12}	0.1Ω
R_{L34}、R_{L45}	0.5Ω
Slope of VSC1: K_1	0.2
Slope of VSC2: K_2	0.4
U_{dcmax}	405kV
U_{dcmin}	395kV

At the initial moment, the output power of wind farm 1 (VSC4) was 185MW, the output power of wind farm 2 (VSC5) was 150MW, the output power of load side (VSC3) is -25MW, the power distributed for VSC1 and VSC2 were -117MW and -168MW respectively, the power reference value of VSC1 and VSC2 were -118M and -169MW respectively, the DC bus voltage keep stable at rated value 400kV. Because the impedance between each station is very small, the DC voltage of each VSC station's output port is almost the same, for the convenience to analyse, the voltage of VSC2 from the simulation results is used to illustrate the strategy.

The output power of wind farm 1 kept changing from the moment 2.5s to 4.2s, at the moment 4.2s the output power of wind farm 1 and wind farm 2 both had a step change. The simulation results are shown in Fig. 8.

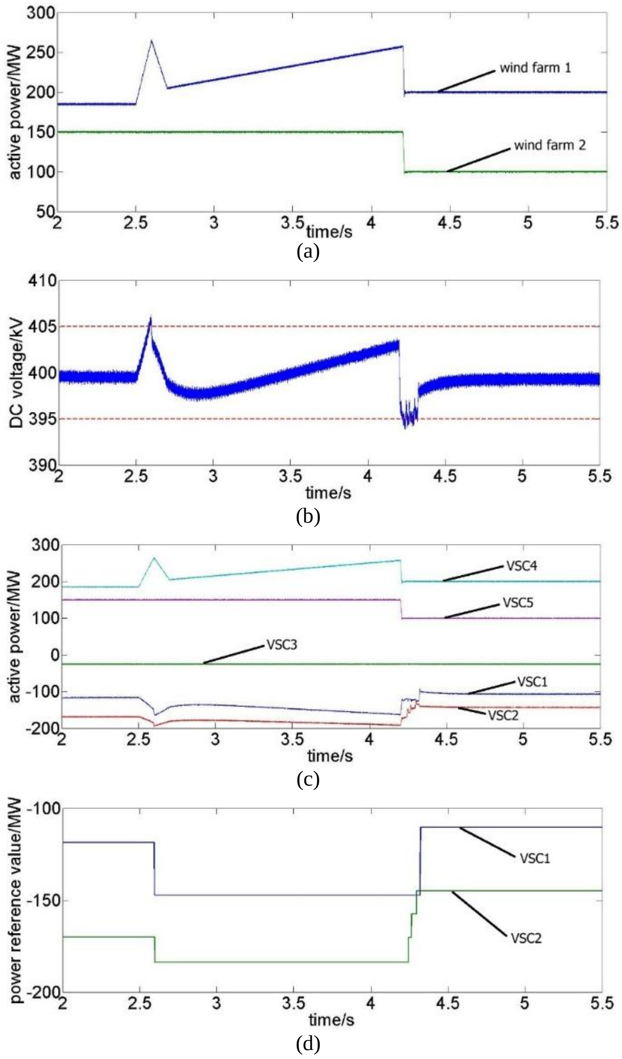

Figure 8. Simulation under the condition of frequent fluctuations of the output power of wind farms.

With reference to Fig. 8, the output power of wind farm 1 began to change from the moment 2.5s, from 2.5s to 2.6s it increased from 185MW to 265MW at the rate of 800MW/s. At the moment 2.59s, the DC bus voltage reached the allowable upper limit value 405kV, the power reference value of VSC1 and VSC2 changed into -147MW and -183MW automatically. From 2.59s to 2.6s, although the output power of wind farm 1 was still increasing, because the drop curve has changed as the power reference changed, the DC bus voltage began to drop. From 2.6s to 2.7s the output power of wind farm 1 decreased from 265MW to 205MW at the rate of 600MW/s, during this period of time the DC voltage began to drop, but it was still no less than the allowable lower limit value, the wind power variation was still distributed according to the pro-rata between VSC1 and VSC2. From 2.7s to 4.2s the output power of wind farm 1 increased from 205MW to 257.5MW at the rate of 35MW/s, during this period of time, the DC voltage increased slowly within the allowable voltage range. During the time from 2.6s to 4.2s, the output power of wind farm 1 kept changing, the output power of VSC1 and VSC2 could not reach a constant value, and the situation that the DC voltage was out of range did not happen. As a result, the power reference value of VSC1 and VSC2 kept unchanged, were -147MW and -183MW respectively.

At the moment of 4.2s, the output power of wind farm 1 and wind farm 2 both had a step change, the output power of wind farm 1 changed from 257.5MW to 200MW and the power of wind farm 2 changed from 150MW to 100 MW, which would lead to the decline of the output power of VSC1 and VSC2, as well as the drop of DC bus voltage. At the moment of 4.24s, the DC bus voltage reached the lower limit value of voltage 395kV, simultaneously the power reference value of VSC2 automatically changed from -183MW to -170MW. After that, the DC voltage began to increase, because the output power of VSC1 and VSC2 did not reach the steady state in the process of declining, the DC voltage would still drop. At the moment of 4.26s, the DC voltage dropped to 395kV after a short period of increasing, the power reference value of VSC2 automatically changed from -170MW to -157MW, this kind of modification happened again at the moment 4.29s. Finally, after three times of modification, the DC voltage operates within the allowable voltage range. At the moment of 4.34s, the output power of VSC1 and VSC2 reached a steady state, so the power reference value changed to -110MW and -145MW respectively, the DC voltage adjusted to the rated value 400kV.

In this section, the selected example did not simulate the operating characteristics of wind farms in a day or longer period. For the convenience of analysis, the simulation was carried on in a short period of time without loss of generality. From the above analysis, under the situation where the flow of wind farms changes frequently, the proposed strategy can maintain the balance of active power of VSC-MTDC system and can keep the DC voltage operating within allowable range, which ensure the safe operation of the system continuously. In addition, if the output power of wind farms can remain stable over a period of time, the strategy can adjust the DC voltage back to the rated value.

VI. Conclusions

According to the VSC-MTDC for interconnection of wind farms, an improved DC voltage droop control strategy was proposed, and simulation was processed with EMTDC/PSCAD to verify the correctness and practicability of the control strategy.

Conclusions are as follows:

Under the situation where the flow of wind farms changes frequently, the proposed strategy can accomplish the rapid distribution of wind power variation, at the same time it can automatically modify the power reference value, which will lead to the translation of drop curve, and keep the DC voltage operating within allowable safe range, which ensure the safe operation of the system. In addition, if the output power of wind farms can remain stable over a period of time, the strategy can eliminate the static voltage deviation and adjust the DC voltage back to the rated value.

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