Scientific Research

Analysis of Transmission Loss in Droop Control of a Multi-Terminal HVDC System

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Abstract

High Voltage Direct Current (HVDC) electric power transmission is a promising technology for integrating offshore wind farms and interconnecting power grids in different regions. In order to maintain the DC voltage, droop control has been widely used. Transmission line loss constitutes an import part of the total power loss in a multi-terminal HVDC scheme. In this paper, the relation between droop controller design and transmission loss has been investigated. Different MTDC layout configurations are compared to examine the effect of droop controller design on the transmission loss.

Keywords

MTDC; HVDC; VSC; Transmission Loss; Droop Control

1. Introduction

Renewable energy is predicted to supply 12% of the world's electricity by 2020 [1]. In order to integrate various renewable energies such as offshore wind farms into the existing AC grid, the concept of multi-terminal HVDC (MTDC) has been proposed. The biggest possible future project is the European Super-grid [2]. A MTDC network can connect AC power grids of different voltages, frequencies with decoupled connection and reduce the effect of wind power fluctuation on power transmission and maximize power transmission efficiency.

Seamless integration of offshore energy into the existing power grid has brought in the utilization of HVDC transmission, which draws little capacitive current compared with the high voltage AC (HVAC) solution [3]. Voltage source converter (VSC) can work as an interface between DC and AC networks. Compared with traditional line commutated converters (LCC), VSC using high voltage IGBT is capable of switching at a higher operating frequency.

Advantages of VSC-HVDC include independent control of active and reactive power, fast and reversible control of power flow, and asynchronously decoupling AC grids, etc. The control of VSC in a MTDC has been well studied in the literature. Its operation modes can be generally classified as DC voltage control or active power control, and reactive power or AC voltage control. For the control of DC voltages involving more than one VSC terminal, two categories of control methods exist: master-slave control and DC voltage droop control. In a mas-

ter-slave controlled network, one VSC terminal works as a master terminal, maintaining the DC voltage at a fixed level. Other slave terminals can be assigned to deliver power out of the DC network using active power control. Power transmitted in the master terminal is thus influenced by other terminals' capabilities. Its normal operation will determine the whole system stability, so fast communication between terminals is needed. While using voltage droop control, there is no DC voltage regulating terminals. Each terminal will maintain the DC voltage, delivering active power at the same time [4]-[6]. Power transmitted by each terminal is determined by the DC voltage so influenced by every terminal. The power transmission duties are shared between different terminals with no communication needed, providing a more reliable network.

The idea of droop control is based on frequency-power control in the traditional AC power systems. It is more widely used compared with the master-slave method, due to its simplicity and the ease of power sharing between different terminals. However, unlike frequency in a traditional AC system, voltage is not a universal measurement of the DC network when using DC voltage droop control. DC voltage error caused by droop control and power loss on the transmission line will add mismatch to the ideal droop control design. This impact on the power dispatch has been analyzed in [5]. Different power dispatch modes using voltage droop control have been compared in [4] [6]. In [7], a methodology to design the required droop gains is proposed to optimize system power transmission. On the other hand, the operation and transmission cost of the MTDC network is part of the overall power loss. In order to minimize the loss, this optimal power flow (OPF) problem of a MTDC networking in traditional AC environment can be solved based on traditional optimal algorithms. In [8], the losses of the different components of a VSC HVDC system and the impact of the installation on overall system losses in meshed networks are studied. A sequential AC/DC power flow algorithm is proposed to solve networks containing VSC MTDC systems in [9]. Two different VSC control strategies, namely the constant DC voltage control (master-slave control) and DC voltage droop control, are considered in [10] to minimize the transmission loss of the whole AC/DC network. Reference [11] combines the OPF approach with the control of a multi-terminal HVDC system. The optimal power flow computes optimal voltages and communicates them to the grid-side VSC in order to ensure minimum losses in the power transmission. However, the relation between the droop control parameters and minimum transmission loss is not clear when OPF is involved in the operation of MTDC using droop control.

In this paper, the dependence of transmission loss on droop control design is analyzed, *i.e.*, the condition for achieving a minimum loss operation point. The requirement on DC voltage is derived in order to minimize the transmission loss and the effect of DC voltage drop is considered in achieving the best droop control design. The paper is organized as follows. Section II introduces different control modes for grid side and wind farm side converters. In Section III, the effect of grid side DC voltage on transmission loss is analyzed. Then DC voltage variations caused by droop control are considered to investigate the changes in the power loss. Simulations using Simulink are carried out in Section V. Finally Section VI is the conclusion.

2. Control Modes for Different Converters

In a typically configured MTDC system, there exist two kinds of converters: grid side converter (GSVSC) and wind farm side converter (WFVSC). GSVSC and WFVSC have different working modes, determined by the DC voltage and current. The voltage–current characteristics of WFVSC and GSVSC have been introduced and studied in [7] [12] [13].

In this paper, a four terminal MTDC network is studied, as shown in **Figure 1**. On the left side of MTDC is the WFVSC integrating various wind farms, such as DIFG or full converter based induction generators. The duty for the WFVSC is to deliver all the possible wind power collected by the wind farm to the DC cable, meanwhile maintaining the AC side voltage or providing reactive power support if necessary.

The GSVSC will try to control the DC voltage at a desired level, delivering the power out of the DC cable. Proper power transfer is indicated by the DC voltage. If the injected power is higher than delivered, the DC voltage will rise, otherwise it will fall. Thus for a MTDC network in normal operation, the basic tasks are to transfer power while maintaining the DC voltage.

2.1. Wind Farm Side Converter Control

The WFVSCs have three operation modes, characterized by Equation (1),
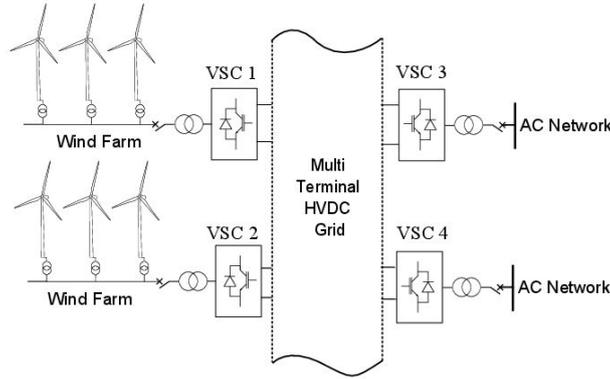
Figure 1. Typical four-terminal HVDC network.

$$I_k = \begin{cases} K_k(E_k - E_{wfL}) & E_k \geq E_{wfL} \\ P_k / E_k & E_k < E_{wfL} \; \& \; I_k < I_{kh} \\ I_{kh} & I_k \geq I_{kh} \end{cases} \tag{1}$$

where I_k is the transmitted DC current from the k-th terminal, K_k is the voltge droop, E_k is the DC voltage, E_{wfL} is the maximum voltage allowed, P_k is the power injected at the k-th terminal, I_{kh} is the maximum current allowed. In normal operation, the WFVSC delivers all the power collected from wind farm to the DC grid, as a constant power source. If fault occurs in the onshore AC grid, the DC voltage will rise. When the DC voltage is higher than E_{wfL}, the WFVSC will enter droop control mode, just like GSVSC, trying to reduce the DC voltage. Otherwise, if the current exceeds the limitation of converter, the WFVSC will also work in the current limitation mode.

2.2. Grid Side Converter Control

Each GSVSC has two operation modes, as shown in Equation (2)

$$I_k = \begin{cases} K_k(E_k - E_{k0}) & I_k < I_{kh} \\ I_{kh} & I_k \geq I_{kh} \end{cases} \tag{2}$$

where E_k is the DC voltage, E_{k0} is the reference voltage, I_{kh} is the maximum current limitation for the converter, K_k is the droop control parameter.

In normal operation, each GSVSC works like constant voltage source with a pure resistance characterized by the droop parameter K_k, so each terminal can deliver power out of the DC grid while contributing to maintain the DC voltage. Under an AC grid fault, the power delivered will be limited by the maximum current I_{kh}.

3. Effect of Terminal Voltages on Transmission Loss

In a four-terminal HVDC system using droop control, the control scheme for each GSVSC in normal operation can be represented by **Figure 2**.

Using the number order in **Figure 1**, the relation between DC current and voltage for each GSVSC and WFVSC is,

$$\begin{cases} I_1 = P_1 / E_1 \\ I_2 = P_2 / E_2 \\ I_3 = K_3(E_3 - E_0) \\ I_4 = K_4(E_4 - E_0) \end{cases} \tag{3}$$

The transmission loss is determined by the cable resistance and cable current.

$$P_{loss} = \Sigma R_i I_i^2 \tag{4}$$

where I_i is the cable DC current and R_i is the equivalent cable resistance.
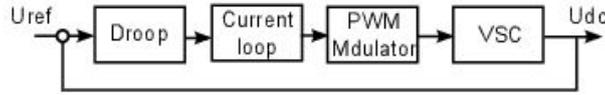
Figure 2. Droop control scheme of a VSC.

In an existing MTDC network, the cable resistance is almost unchanged and the current is determined by the power injected from the power source such as wind farms or generators. In order to analyse the effect of droop parameter on the transmission loss, two steps are carried out. First, each wind farm is simplified with a constant current injection, thus neglecting the voltage change caused by the droop control, to inspect effect of voltage difference between droop controlled terminals on the power transmission loss. Second, the impact of voltage change caused by droop control is analysed.

Three different layout cases are considered for a four terminal HVDC connection, with two WFVSCs and two GSVSCs. In each case, the WFVSC is modelled with constant current injection, thus omitting the DC voltage variations. The requirements for grid side DC voltages are inspected to achieve the minimum transmission loss.

3.1. Case 1: With Wind Farm Interconnection

Case 1 is two wind farms interconnected by a common cable, then connected to grid side converters respectively, as shown in **Figure 3**.

If we define the voltage difference between the two grid side converters as ΔE, the power loss on the line resistance can be calculated as

$$P_{loss} = I_1^2 R_2 + I_2^2 R_3 + I_x^2 R_1 = I_1^2 R_2 + I_2^2 R_3 - \frac{(R_3 I_2 - R_2 I_1)^2}{R_1 + R_2 + R_3} + \frac{\Delta E^2}{R_1 + R_2 + R_3} \tag{5}$$

It can be easily observed that the power consumption can be minimized when $\Delta E^2 = 0$, which means the terminal side voltage should be equal in order for the maximal efficiency. In this case, the minimal power loss is

$$P_{loss} = I_1^2 R_2 + I_2^2 R_3 - \frac{(R_3 I_2 - R_2 I_1)^2}{R_1 + R_2 + R_3} \tag{6}$$

Another important observation is that, the power loss can be further minimized when $R_3 I_2 - R_2 I_1 = 0$, this means that the wind farm side power should be assigned inversely to their transmission line resistance. This result can also be verified if we assume the interconnection current between this two transmission lines is I_x,

$$P_{loss} = (I_1 - I_x)^2 R_2 + (I_2 + I_x)^2 R_3 + I_x^2 R_1 \tag{7}$$

In order to get the minimal power loss, the first order of power loss with respect to current I_x can be deduced as,

$$\partial P_{loss} / \partial I_x = 2R_2(I_x - I_1) + 2R_3(I_x + I_2) + 2I_x R_1 \tag{8}$$

Thus we can get the optimal current for this case with $\partial P_{loss} / \partial I_x = 0$ is

$$I_x = \frac{R_2 I_1 - R_3 I_2}{R_1 + R_2 + R_3} \tag{9}$$

3.2. Case 2: With No Wind Farm Interconnection

If the two wind farm locations are close enough, then the cable resistance can be omitted. This is also the case when only one wind farm is transmitting power to two GSVSCs, or the two GSVSCs have a joint connection, as discussed in [7]. In both situations, the transmission loss is given as,

$$P_{loss} = I_1^2 R_2 + I_2^2 R_3 = I_1^2 R_2 + I_2^2 R_3 - \frac{(R_3 I_2 - R_2 I_1)^2}{R_2 + R_3} + \frac{\Delta E^2}{R_2 + R_3} \tag{10}$$

It can be seen that the minimal power loss can also be achieved when the terminal voltages are the same, which is consistent with the result in [7]. In order to get the same terminal voltage for the two GSVSCs, it is obvious that the DC current should be reversely proportional with the cable resistance, e.g.
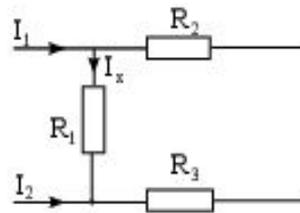
Figure 3. Case 1: with wind farm interconnection.
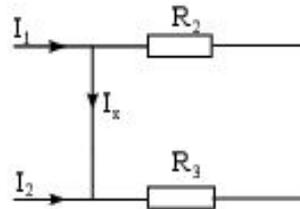
Figure 4. Case 2: with no wind farm interconnection.

$$\frac{I_3}{I_4} = \frac{R_3}{R_2} \tag{11}$$

which is also true that

$$\frac{I_3}{I_4} = \frac{K_3(E_3 - E_0)}{K_4(E_4 - E_0)} = \frac{K_3}{K_4} = \frac{R_3}{R_2} \tag{12}$$

3.3. Case 3: With Grid Side Interconnection

Two grid side converters are connected near on-shore grid and are represented by **Figure 5**.

In this case, the transmission loss is

$$P_{loss} = I_1^2 R_2 + I_2^2 R_3 + I_x^2 R_1 \tag{13}$$

We can get

$$\partial P_{loss} / \partial I_x = 2I_x R_1 \tag{14}$$

Thus it is obvious that

$$I_x = 0 \tag{15}$$

So the minimal loss can be achieved when there is no current flow between the two GSVSCs, which means the voltage difference between them is also zero.

It can be concluded that in all cases the minimum cost can be achieved when the voltages on the power sharing terminals are balanced. However, because the voltage errors caused by droop control are neglected, this will not be the optimal case when using voltage droop control. As the voltage rises, the optimal point will change, and this will be demonstrated in the next section.

4. Impact of Voltage Drop on Transmission Loss

In a real power system, the WFVSC normally works on the mode of constantly injecting all the available wind power into the DC grid. The DC current injected is determined by the wind power and the DC voltage. Since there are no voltage regulators to keep the DC voltage at a fixed level using droop control, the DC voltage will change when the injected wind power varies. Ideally when the two GSVSCs' DC voltages are equal, then the transmission loss is minimized. However, when the DC voltage rises, the injected WFVSC current will decrease if wind power is kept constant. So the transmission loss may be further decreased even though the GSVSC volt-
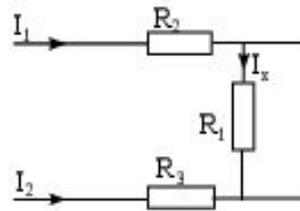
Figure 5. Case 3: with grid side interconnection.

ages do not match. Taking Case 2 as an example, the transmission loss can be divided into two parts, determined by current and voltage difference respectively.

$$P_{loss} = f_1(I_1, I_2) + f_2(\Delta E) \tag{16}$$

The first part is solely determined by current and will decrease with voltage rise, while the second part is determined by voltage difference. So when the injected wind farm current decreases with the voltage difference, the working point will change. The new working point for a given MTDC network with known P_1, P_2 and E_0 can be solved using various algorithms. Meanwhile, boundaries for the minimum loss working point can also be found. If we assume the current injected by wind farms are I_{1a}, I_{2a} with no voltage drop and I_{1b}, I_{2b} with maximum voltage drop E_{wfh}-E_0. The minimum power loss P_{min} should be bounded by,

$$f_1(I_{1a}, I_{2a}) + f_2(\Delta E) < P_{min} < f_1(I_{1b}, I_{2b}) + f_2(\Delta E) \tag{17}$$

5. Simulations

To verify the effect of terminal voltage on transmission loss and impact of droop control on the optimum transmission, simulations are carried out using Matlab SimPowerSystem package. A four terminal VSC-HVDC system has been built in Simulink as shown in **Figure 6** and system parameters are listed in **Table 1**.

The interconnection of HVDC cables are configured using Case 1. Two scenarios are simulated. First, the two wind farms are injecting constant currents, and the grid side voltage varies using droop control. In the second situation, wind farms are working in a constant power mode, and the effect of droop control is demonstrated.

5.1. Scenario 1: Wind Farm Injecting Constant Current

When the WFVSCs inject constant current and grid side converters are under droop control, the droop parameters are changed incrementally to see the effect on transmission loss. **Figure 7** shows the relation between transmission loss and the voltage difference on the two grid side terminals. It can be seen that the minimum transmission loss can be achieved when the voltage difference is zero.

Figure 8 shows the two GSVSCs DC voltage change with droop parameters K_3 and K_4. Each of the hyperbolic lines is the grid side DC voltage varied with droop parameters. The black line shows the trace of $\Delta E = 0$.

5.2. Scenario 2: Wind Farm Injecting Constant Power

In the second scenario, the two wind farms are modelled with constant power injection, thus representing the case when wind speed is almost constant, injecting constant power. **Figure 9** shows the relation between the voltage difference and transmission loss with different K_3 and K_4 combinations. It can be seen that when the voltage difference is zero, the transmission loss is not minimized since a slight voltage rise will reduce the injected current into the DC cable.

Figure 10 shows the two GSVSCs DC voltage change with droop parameters K_3 and K_4. The solid line shows the trace of $\Delta E = 0$ and dashed line is the minimum power loss trace. These two traces are not overlapped when the wind farm is injecting constant power.

The transmission loss with constant power injection is bounded by the upper and lower current, as shown in **Figure 11**, between the transmission loss with upper current limit when there is no voltage drop, and with maximal voltage drop.
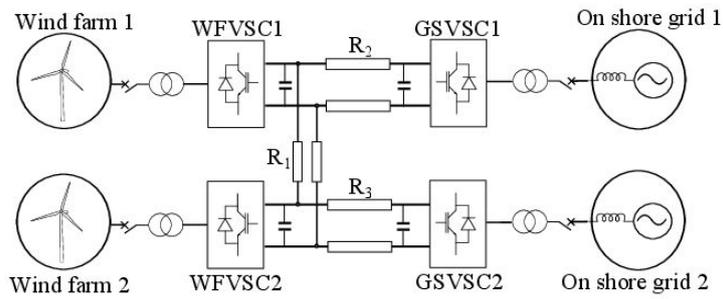
Figure 6. A four-terminal HVDC network simulation.
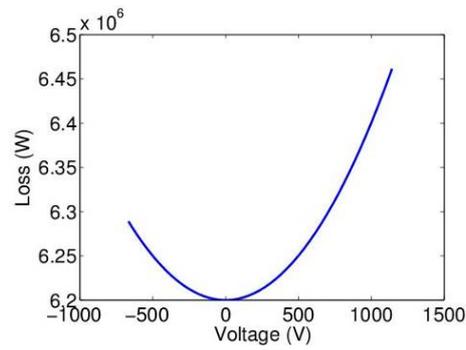
Figure 7. Transmission loss via voltage difference between two GSVSCs.
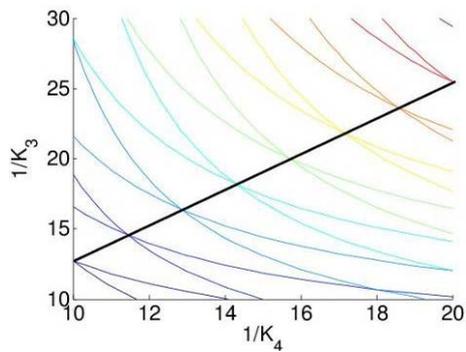
Figure 8. Two GSVSCs DC voltage change via droop parameter.
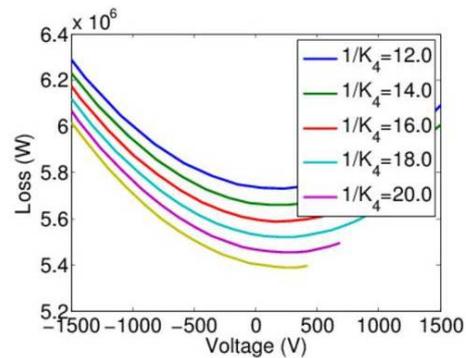
Figure 9. Transmission loss variation via voltage difference between two GSVSCs.
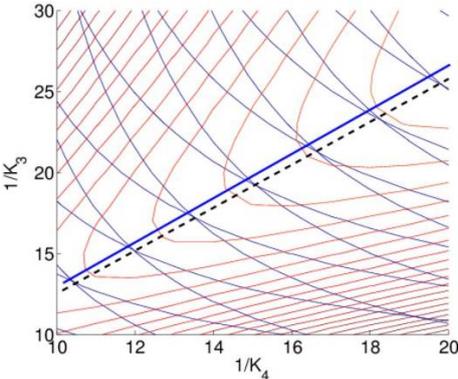
Figure 10. GSVSCs DC voltage change via droop parameters.
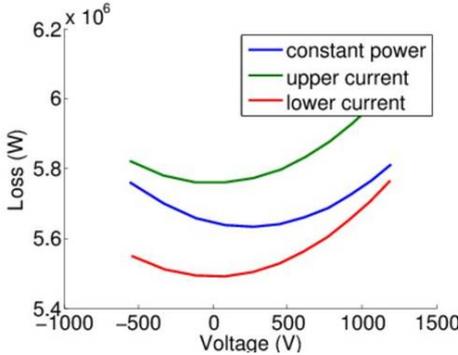
Figure 11. Power loss range bounded by upper and lower current.

Table 1. Simulation parameters.

Base voltage	WF1 power	WF2 power	R_1	R_2	R_3
$400e^3$ V	600 MW	400 MW	0.5 Ω	1.2 Ω	0.8 Ω

6. Conclusion

In this paper, three different configurations of a four terminal HVDC network have been investigated to achieve minimal transmission loss using voltage droop control. The effect of grid side DC voltage change on the transmission loss has been analysed. It is found that in order to achieve the minimal transmission loss the grid side DC voltage should be equal with an ideal constant current input from the wind farm side. However, when the wind farm side VSC works in constant power mode, this requirement will change due to the power characteristic of the wind farm power injection. Simulations have been carried out in Simulink and the analysis is verified by simulation results.

Acknowledgements

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