Article

Optimized Design of Modular Multilevel DC De-Icer for High Voltage Transmission Lines

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Abstract: Ice covering on overhead transmission lines would cause damage to transmission system and long-term power outage. Among various de-icing devices, modular multilevel converter (MMC) based DC de-icer (MMC-DDI) is recognized as a promising solution due to its excellent technical performance. Its principle feasibility has been well studied, but few literature discuss its economy or hardware optimization, thus the designed MMC-DDI for high voltage transmission lines is usually too large and too expensive for engineering applications. To fill this gap, this paper presents a quantitative analysis on the converter characteristics of MMC-DDI, and calculates the minimal converter rating and its influencing factors. It reals that, for a given de-icing requirement, the converter rating varies greatly with its AC-side voltage. Then an optimization configuration is proposed to reduce the converter rating and improve its economy. The proposed configuration is verified in a MMC-DDI for a 500kV transmission line as a case study. The result shows, in the case of outputting same de-icing characteristics, the optimized converter rating is reduced from 151 MVA to 68 MVA, and total cost of MMC-DDI is reduced by 48%. This analysis and conclusion are conductive to the optimized design of multilevel DC de-icer, then to its engineering application.

Keywords: Converter, ice-melting, modular multilevel converter (MMC), optimization design, transmission line, static var generator (SVG)

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1. Introduction

Ice covering on overhead transmission lines is a serious threat to the safe operation of power grids. Overweight ice would break wire or collapse the tower, and then cause disruption of power transmission and large-scale outage [1, 2]. The ice storms in North America 1998 [3], Germany 2005 [4], and China 2008 [5] are good examples of such consequences. In order to protect the grid from ice disaster, dozens of anti-icing or de-icing methods have been proposed [1, 3, 5-7].

Among various de-icing methods, heating of ice-covered line conductors by electrical current is recognized as the most efficient engineering approach to minimize the catastrophic consequences of severe ice events [7-8]. Because it can eliminate the ice covered on hundreds of kilometers of line within an hour, meanwhile without damaging the grid structure or polluting the environment. Both AC and DC current can be used to melt ice, but the AC ice-melting is usually used for transmission lines up to 110kV, while the DC ice-melting is more recommended for higher voltage lines up to 500kV transmission lines [3, 4]. In DC de-icing system, the most critical part is the DC de-icer (DDI) which generates the required ice-melting DC voltage and current.

Nowadays, the most widely adopted DDI is thyristor-based line-commutated converter (LCC), derived from the conventional HVDC technology. It has been widely used in Russia, Canada, China

[5, 9, 10]etc. Due to the inherent characteristics of thyristor, LCCs require multi-winding transformer, a series of harmonic filters and a large number of shunt capacitors to meet grid requirements. Thus, it occupies a large site area, and is bulky, inflexible, and costly. In order to overcome these shortcomings, many proposed to construct the DC de-icer using voltage source converter (VSC). In [11], a 3-level static synchronous compensator (STATCOM) was proposed for de-icer application. It can present excellent harmonic and reactive power features, but it requires complicated transformer and high-power 3-level converters up to 100MVA. Moreover, its output DC voltage has to exceed its AC-side voltage, namely, it has a limited DC voltage output range.

In the last few decades, the modular multilevel converter (MMC) topology has been rapidly developed and widely used in many high-voltage and medium-voltage applications [12, 13]. It can output a smooth and nearly ideal sinusoidal voltage with little filters, and it is modularity, scalability, facile, and flexible. In [14], a MMC-based DC de-icer (MMC-DDI) with full-bridge submodules (SM) was presented, and then it was further studied in [15-17]. It inherits all the aforesaid advantages of MMC topology. Moreover, it can provide both buck and boost functions for dc-link voltage, thus has a wide DC output voltage range to satisfy the de-icing requirements of different line lengths and different conductor sizes. In addition, it can be operated as a static var generator (SVG) to provide reactive power compensation for the gird. Due to these advantages, the MMC-DDI is recognized as a promising de-icing solution [15]. Since MMC-DDI was first proposed in 2013[14], its operation principle and control optimization have been further studied in [15-17]. However, these literatures mainly focus on the technical feasibility of MMC-DDI, and pay little attention to its economy or hardware optimization. According to the existing MMC-DDI circuit configuration, some cases are designed for high voltage transmission lines up to 500kV. It is found that the MMC-DDI usually has far larger converter rating than its output ice-melting power, resulting in a poor economy to apply.

To address this issue, this paper presents a quantitative analysis on the converter characteristics of MMC-DDI, and then calculates the required converter rating and its influencing factors. It reals that, for a certain DC de-icing requirement, converter rating varies greatly with its AC-side voltage, and then an optimized design method is proposed to improve the economy of MMC-DDI. Finally, a design example and its corresponding simulation results are given. As this case shown, under the same de-icing outputting characteristics, the optimized converter rating is reduced from 151MVA to 68MVA, and the total cost of MMC-DDI system is reduced by 48%.

2. Circuit configuration and operation principle

The circuit configuration of the MMC-DDI is shown in Figure 1[14-16]. It contains two sets of star-configured arms and each arm has several full-bridge SMs along with a connection reactance. Structurally speaking, it can be viewed as a pair of three-phase star-configured SVGs. The AC terminals of these two SVGs are in parallel and connected to the grid, whereas their neutral points are respectively led out as the DC positive and negative poles of MMC-DDI, and then connected to the ice-covered overhead lines through a set of de-icing disconnectors.

Since MMC-DDI can provide both buck and boost functions for dc-link voltage, it theoretically does not require a transformer to supply a wide and adjustable DC output voltage. In the existing literatures [14-16], the AC terminal of MMC-DDI is directly connected to the distribution network with no transformer. This is considered as a major advantage of the MMC-DDI scheme, because it can save the cost and floor area of a transformer, making the device small, light, and compact[15].

According to the grid requirements, MMC-DDI can have two different operation modes:

- Ice-melting Mode. When there is icing line to melt in winter, the disconnectors are closed to connect the MMC-DDI and the ice-covered transmission line together, and the other terminal of the transmission line is artificially three-phase short-circuit to form a DC current loop. Then, the MMC-DDI provides a controlled DC voltage to generate the required current through the ice-covered line. At that time, the operation mode of MMC-DDI is similar to the MMC rectifier station in the VSC-HVDC transmission system, except that the DC-side output voltage almost remains unchanged in the VSC-HVDC system while it may vary with the line parameters in the MMC-DDI system. And the typical control methods for the common MMC system are also applicable to MMC-DDI system, such as the capacitor voltage control, the active and reactive current control, the capacitor voltage balancing control, circulating current control etc.

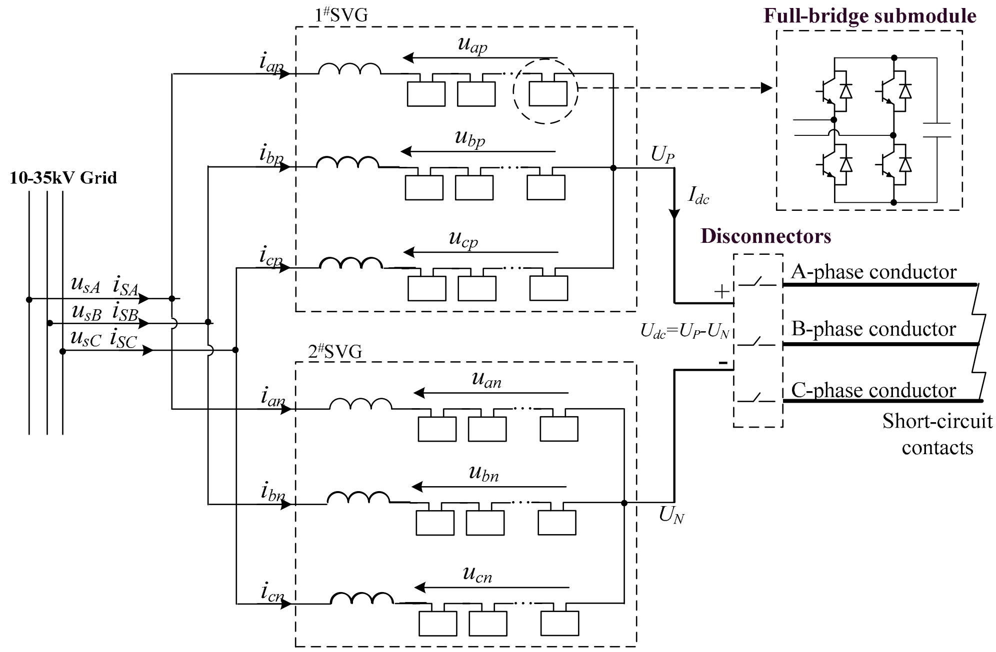

Figure 1. Circuit configuration of MMC based DC de-icer (MMC-DDI).

- SVG Mode. When there is no icing line, the de-icing disconnectors can be open circuit. Then the upper three arms and the lower three arms can operates as two parallel conventional SVGs, and provide reactive power compensation or alleviate other power quality problems.

3. Converter characteristic of MMC-DDI

3.1. Arm voltage and current

According to Kirchhoff's law, the dynamic equations of MMC-DDI can be expressed as:

$$\begin{cases} u_{sA} = Ri_{a1} + L\dfrac{d}{dt}i_{a1} + u_{ap} + U_p \\ u_{sB} = Ri_{b1} + L\dfrac{d}{dt}i_{b1} + u_{bp} + U_p \\ u_{sC} = Ri_{c1} + L\dfrac{d}{dt}i_{c1} + u_{cp} + U_p \end{cases} \tag{1}$$

Where u_{sA}, u_{sB}, and u_{sC} are the AC-side input phase voltage of the converter. u_{ap}, u_{bp}, and u_{cp} are the output voltage of upper three arms. U_p is the electric potential of the neutral point of 1#SVG, relative to the grid neutral point. i_{a1}, i_{b1}, and i_{c1} are arm currents in 1#SVG. R and L represent the equivalent resistance and inductance of the connection reactance in each arm.

$$\begin{cases} u_{sA} = Ri_{a2} + L\dfrac{d}{dt}i_{a2} + u_{an} + U_n \\ u_{sB} = Ri_{b2} + L\dfrac{d}{dt}i_{b2} + u_{bn} + U_n \\ u_{sC} = Ri_{c2} + L\dfrac{d}{dt}i_{c2} + u_{cn} + U_n \end{cases} \tag{2}$$

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Where u_{an}, u_{bn}, and u_{cn} are the output voltage of lower three arms. U_n is the electric potential of the neutral point of 2#SVG, relative to the grid neutral point. i_{a2}, i_{b2}, and i_{c2} are the arm currents in 2#SVG.

$$\begin{cases} i_{sa} = i_{a1} + i_{a2} \\ i_{sb} = i_{b1} + i_{b2} \\ i_{sc} = i_{c1} + i_{c2} \end{cases} \tag{3}$$

Where i_{sA}, i_{sB}, and i_{sC} are the AC-side input phase current of the converter.

$$\begin{cases} I_{dc} = i_{a1} + i_{b1} + i_{c1} = -(i_{a2} + i_{b2} + i_{c2}) \\ U_{dc} = U_p - U_n \end{cases} \tag{4}$$

Where U_{dc} and I_{dc} are the DC-side output voltage and current of the MMC-DDI.

Generally, the voltage and current of each arm in the MMC-DDI are symmetrical, and the circulation current among these arms can be effectively suppressed if proper appropriate control is adopted, moreover, the voltage drop across the connection reactance is far less than other items in the voltage equation (1) (2).As a result, the arm voltages and currents can be expressed as:

$$\begin{cases} u_{ap} = \sqrt{2}U_m \sin(\omega t) - 0.5U_{dc} \\ u_{bp} = \sqrt{2}U_m \sin(\omega t - 120°) - 0.5U_{dc} \\ u_{cp} = \sqrt{2}U_m \sin(\omega t + 120°) - 0.5U_{dc} \end{cases} \tag{5}$$

$$\begin{cases} u_{an} = \sqrt{2}U_m \sin(\omega t) + 0.5U_{dc} \\ u_{bn} = \sqrt{2}U_m \sin(\omega t - 120°) + 0.5U_{dc} \\ u_{cn} = \sqrt{2}U_m \sin(\omega t + 120°) + 0.5U_{dc} \end{cases} \tag{6}$$

$$\begin{cases} i_{ap} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi) + \frac{I_{dc}}{3} \\ i_{bp} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi - 120°) + \frac{I_{dc}}{3} \\ i_{cp} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi + 120°) + \frac{I_{dc}}{3} \end{cases} \tag{7}$$

$$\begin{cases} i_{an} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi) - \frac{I_{dc}}{3} \\ i_{bn} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi - 120°) - \frac{I_{dc}}{3} \\ i_{cn} = \frac{\sqrt{2}}{2} I_m \sin(\omega t + \varphi + 120°) - \frac{I_{dc}}{3} \end{cases} \tag{8}$$

Where U_m, I_m are the RMS values of the AC-side input phase voltage and current of MMC converter.

As shown in (5)-(8), the voltage/current of each arm contains both the AC and DC components. Moreover, their peak values are the same for each arm, and can be expressed as

$$\begin{cases} I_{\text{arm\_peak}} = \frac{\sqrt{2}}{2} I_m + \frac{1}{3} I_{dc} \\ U_{\text{arm\_peak}} = \sqrt{2}U_m + 0.5U_{dc} \end{cases} \tag{9}$$

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Where I_{arm_peak}, U_{arm_peak} present the peak values of arm current and arm voltage.

According to (5)-(8), the RMS values of arm voltage and current can be expressed as

$$\begin{cases} I_{\text{arm\_}RMS} = \sqrt{\frac{1}{2} I_m^{\ 2} + \frac{1}{9} I_{dc}^{\ 2}} \\ U_{\text{arm\_}RMS} = \sqrt{2U_m^{\ 2} + \frac{1}{4} U_{dc}^{\ 2}} \end{cases} \tag{10}$$

Where I_{arm_RMS}, U_{arm_RMS} present the RMS values of arm current and arm voltage.

Compared with that of the common SVG, the converter voltage/current in the MMC-DDI has different characteristics:

(1) The arm voltage/current of MMC-DDI contains both DC and AC components. While in the conventional SVG, there is only AC component.

(2) The arm voltage/current no more equals to the AC-side input voltage/current in MMC-DDI.

(3) The peak value of the arm voltage/current is no longer $\sqrt{2}$ times of its RMS value.

Due to these differences, although the MMC-DDI is structurally similar to a pair of common star-connected SVGs, their inner converter characteristics are quite different.

3.2. Influence of AC side input voltage

Under normal operating condition, the AC side input active power of the MMC converter is substantially equal to its DC side output power (neglecting tiny converter loss). According to the power balance between the AC and DC sides, the output DC ice-melting power can be obtained:

$$P_{dc} = U_{dc} I_{dc} = 3 I_m U_m \cos\varphi \tag{11}$$

Where P_{dc} is the output ice-melting power, $\cos\varphi$ is AC-side power factor and generally $\cos\varphi$=1.0.

With (11), the AC-side input current of converter can be expressed as

$$I_m = \frac{U_{dc}}{3U_m \cos\varphi} I_{dc} \tag{12}$$

Substituting (12) into (9), the peak values of arm voltage and arm current can be expressed as

$$\begin{cases} I_{\text{arm\_peak}} = \left(\frac{\sqrt{2}}{6\cos\varphi} \frac{U_{dc}}{U_m} + \frac{1}{3} \right) I_{dc} \\ U_{\text{arm\_peak}} = \left(\sqrt{2} \frac{U_m}{U_{dc}} + 0.5 \right) U_{dc} \end{cases} \tag{13}$$

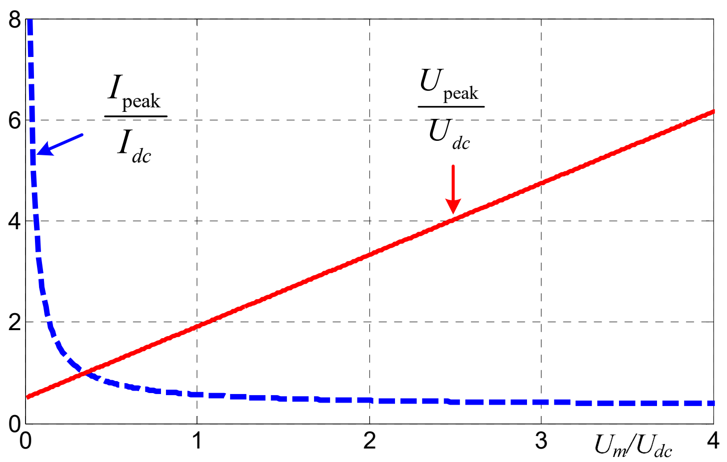

Figure 2. Influence of AC side input voltage on arm current and arm voltage peaks

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According to (13), the influence of AC side input voltage on the arm voltage and current peaks can be plot and shown in Figure 2. As it shown, for a certain DC ice-melting requirement, with the increasing of AC-side voltage , arm voltage peak increases linearly (but not proportionally) while arm current peak decreases and tends to 1/3 I_{dc}. This is quite different from common SVG. In a SVG, in the case of a certain output reactive power, with the increasing of the AC-side voltage, the arm voltage peak increases proportionally while the arm current peak decreases and tends to 0.

3.3. Converter Rating of MMC-DDI

In a power electronics system, the converter rating is an important technical indicator because device cost is closely related with the converter rating. For a MMC converter, its converter rating is mainly determined by the arm voltage peak and arm current peak, because they largely determines the size and quantity of submodules, and then determines the main hardware of the converter. Therefore, the converter rating of the MMC-based devices can be collectively defined as

$$S_c = \sum_1^n \frac{U_{pi} I_{pi}}{2} \tag{14}$$

Where S_c presents the converter rating. n presents the total number of arms. U_{pi}, I_{pi} are the output voltage and current peak of the *i-th* arm.

For a conventional star-connected SVG, there are three arms, and the current peak of each arm is approximately equal to the AC side phase current while arm voltage peak is approximately equal to the AC-side phase voltage (ignoring the voltage drop across the connection reactance). Then its converter rating can be expressed as

$$S_c = 3\frac{U_p I_p}{2} = 3\frac{\sqrt{2}U_{sP} \times \sqrt{2}I_{sp}}{2} = 3U_{sp} I_{sp} = S_{out} \tag{15}$$

Where U_{sp}, I_{sp} are respectively the RMS values of AC-side phase voltage and phase current, S_{out} presents the output apparent power of SVG.

Indeed, equation (15) also applies to the delta-connected SVGs or a SVG group composed of several converters. In summary, for any SVG, the converter rating can be directly characterized by its rated output power.

For the MMC-DDI, the six arms share the same voltage and current peaks. Substituting (9) into (16), and then the converter rating can be expressed as

$$S_c = 6\frac{U_{\text{arm\_peak}} I_{\text{arm\_peak}}}{2} = 3U_m I_m + \sqrt{2}U_m I_{dc} + \frac{3\sqrt{2}}{4} I_m U_{dc} + 0.5 U_{dc} I_{dc} \tag{16}$$

Compared with (15), there are 3 other items in (16), thus the converter rating characteristics of MMC-DDI is significantly different from that of common SVG.

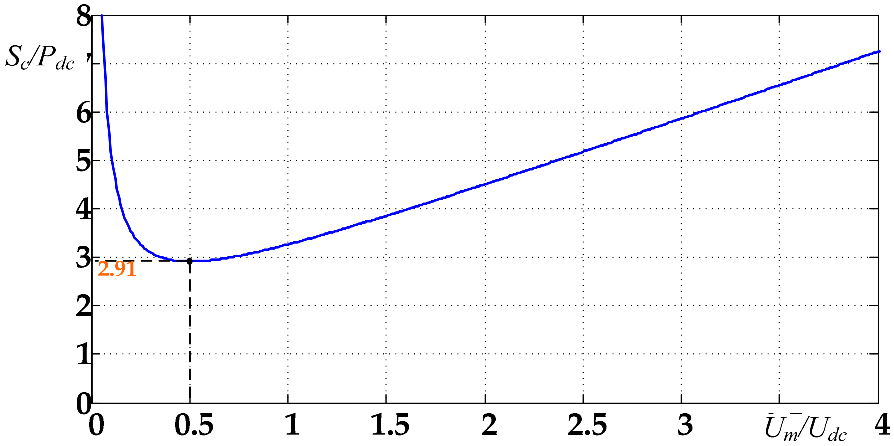

Figure 3. Relationship of the converter rating of MMC-DDI with its AC-side voltage

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Substituting (13) into (16) and considering cosφ=1.0, the converter rating can be simplified as

$$S_c = 3\left(\frac{\sqrt{2}}{6\cos\varphi}\frac{U_{dc}}{U_m}+\frac{1}{3}\right)I_{dc}\cdot\left(\sqrt{2}\frac{U_m}{U_{dc}}+0.5\right)U_{dc} = \left(1.5+\frac{\sqrt{2}}{4}\frac{U_{dc}}{U_m}+\sqrt{2}\frac{U_m}{U_{dc}}\right)P_{dc} \tag{17}$$

With (17), the relationship of the converter rating of MMC-DDI with its AC-side voltage can be calculated and shown as Figure 3. As it shown, under a certain DC-side output voltage and power requirement, the converter rating varies greatly with its AC input voltage. It can be analytically solved that when and only when U_m=0.5U_{dc}, the converter rating gets its minimum value, and the minimum rating is 2.91 times of the output ice-melting power. This conclusion can be expressed as

$$S_{c\_\min} = \left(1.5+\sqrt{2}\right)P_{dc} \quad \text{when} \quad U_m = 0.5U_{dc} \tag{18}$$

4. The proposed optimization design method

4.1 General design process of IMD

For any type of DC ice melting device, its design process generally follows these steps:

1) Step 1: According to the line parameters and meteorological conditions of the transmission lines to be melted，calculate the required DC-side output de-icing current, voltage and power, and then determine the rated DC-side output parameters of IMD.

For a given transmission line, its required de-icing current depends on many parameters, such as conductor type, ambient temperature, wind velocity, ice thickness and de-icing duration etc. The thermal behavior of overhead conductors has been well studied, and some formulas are given to calculate the de-icing current in many industry standards, for example, the IEEE standard [18] and CIGRE standard [19]. Generally, the de-icing current should be greater than the minimum de-icing current and no more than the maximum endure current of line conductor. For some typical conductor types used in China, the minimum de-icing current and the maximum endure current are shown as Table A1[5]. In actual ice melting system, it generally tries to choose the intermediate value of the maximum and minimum values as the rated de-icing current.

After determining the de-icing current, the required de-icing DC voltage can be calculated as

$$U_{dc} = k_{icing}R_{line}I_{icing} \tag{19}$$

Where I_{icing} is the required de-icing current, R_{line} is the phase resistance of transmission line. k_{icing} corresponds to the ice-melting mode, k_{icing}=2 when the de-icing current is passed down one-phase conductor and back along another, and k_{icing}=1.5 when down one and back along the other two[16].

When there are several lines to be melted, the de-icing DC current and voltage of each line can be calculated one by one, then the rated DC-side output parameters of the IMD is determined by the output DC voltage range, the maximum de-icing current, and the maximum de-icing power.

2) Step 2: According to the optional voltage levels of the power substation as well as the rated IMD output power，select the proper access voltage of the IMD.

For typical transmission lines, their DC ice-melting power is generally among several MW and hundreds of MW. Within this range, the IMD is usually connected to the low-voltage distribution network of the substation, generally 10kV or 35kV in China.

3) Step 3: According to the DC-side output parameter requirements and the grid access voltage, design the internal structure and parameters of the IMD.

In the process of designing the internal IMD parameters, it is usually necessary to consider both the technical feasibility and the economy.

4.2 The proposed circuit configuration and its economic analysis

According to the above calculation，for a certain ice-melting requirement, the converter rating of MMC-DDI varies greatly with its AC-side voltage. Traditionally, MMC-DDI is directly connected

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to the grid[14, 15], thus its AC-side input voltage always equals to the grid voltage. This may correspond to very high converter rating, resulting in a poor economy. To solve such problem, this paper proposes an optimization MMC-DDI configuration structure as shown in Figure 4, i.e., a transformer should be inserted between the grid and the converter in some cases. In order to realize this idea, there are two main questions:

A) When the transformer should be desired and when it is undesired?

B) If a transformer is inserted, what are the specifications and parameters of the transformer?

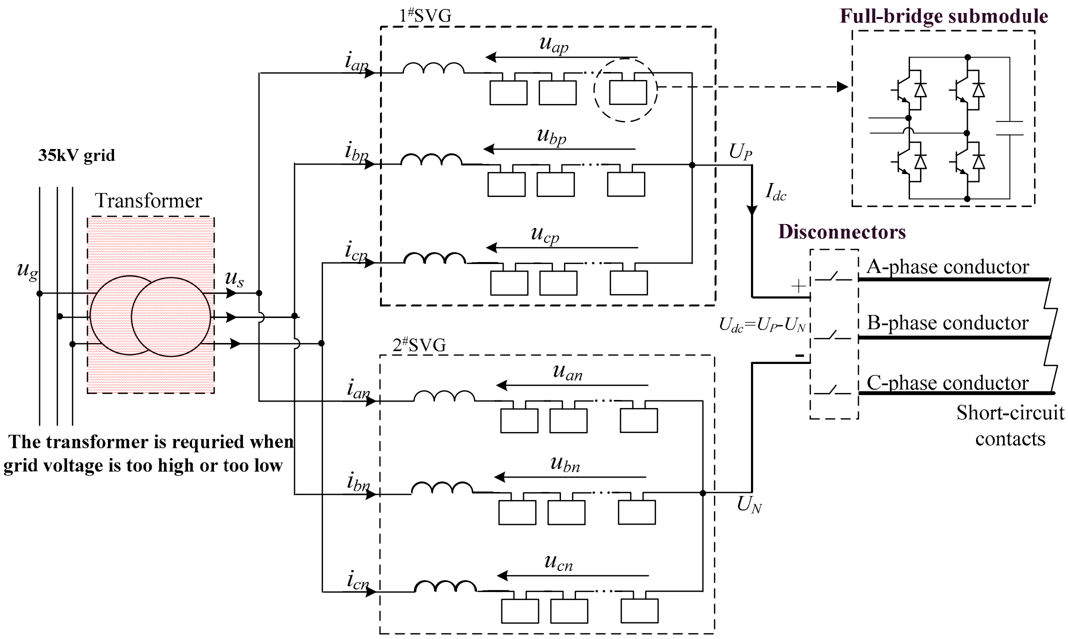

Figure 4. The proposed configuration structure of MMC-DDI

According to (11), when the power factor is controlled as cosφ=1, the input apparent power of MMC-DDI always equals to its DC side output power regardless of the AC-side voltage. Therefore, if a transformer is inserted, the transformer rating only needs to equal to the output de-icing power rather than the converter rating. In order to get the minimum converter rating as shown in (18), the output phase voltage of the transformer can be set as $U_m= 0.5U_{dc}$, corresponding to a line voltage $\sqrt{3}\times 0.5U_{dc}$. In summary, the specification of the transformer can be determined as

$$\begin{cases} S_{Tran} = P_{dc} \\ T_r = U_g / (\sqrt{3}\times 0.5U_{dc}) \end{cases} \tag{20}$$

Where S_{Tran} is the transformer rating, T_r is the transformer rating voltage radio.

For the time of transformer insertion question, the cost of converter and transformer should be compared. Since the MMC-DDI is rarely applied, it is difficult to obtain its market cost; here its cost is estimated by referring to that of SVGs. That is due to two reasons, 1) MMC-DDI is structurally equivalent to a pair of three-phase star-connected SVGs, 2) SVG has been widely used and its cost is transparent. Table A2 shows the deal prices of several typical SVGs in China from 2013 to 2018.

As(15) shown, the converter rating of a SVG is approximately equal to its rated output power, the converter cost can be directly evaluated with the SVG cost list in Table A2. As Table A2 shown, SVG cost is basically proportional to the rating, and the unit cost is around 15,000 $/Mvar. For some SVGs over 60Mvar, the unit cost is slightly higher. This is because there are only a few applications for such high-power SVGs, thus the R&D cost is high. On the other hand, high-power SVG usually requires higher reliability and larger configuration margin, and this also increases the device cost.

When a transformer is inserted as Figure 4, the transformer would bring a cost itself. Table A3 shows the deal prices of several 10MVA-class rectifier transformers in China.

It can be seen that the cost of a 10 MVA rectifier transformer is about 86000 $, about 1/2 of the same rating SVG. Moreover, with the growth of transformer rating, the unit cost decreases rapidly.

For a 56 MVA transformer, its unit cost is 4400 \$/Mvar and about 1/3 of a similar rating SVG. For a 100 MVA transformer, its unit cost reduces to 3300 \$/Mvar and about 1/6 of the same rating SVG.

In order to quantitatively compare the economics of the proposed configuration structure, the costs of the MMC-DDI with and without the transformer can be expressed as

$$\begin{cases} P_{no} = P_{con}(u_s = u_g) \\ P_{with} = P_{trans} + P_{con}(u_s = \sqrt{3}\times 0.5U_{dc}) \end{cases} \tag{21}$$

Where P_{no} presents the cost of MMC-DDI with no transformer, $P_{con}(u_s = u_g)$ presents the cost of the MMC converter when its AC-side voltage equals to the grid voltage. P_{with} presents the cost of the MMC-DDI with a transformer; P_{trans} presents the transformer cost. $P_{con}(u_s = \sqrt{3}\times 0.5U_{dc})$ presents the cost of the MMC converter with a AC-side input voltage of $u_s = \sqrt{3}\times 0.5U_{dc}$.

After inserting the transformer, the cost reduction of the total MMC-DDI can be expressed as:

$$\Delta P = P_{no} - P_{with} = \underbrace{P_{con(u_s=u_g)} - P_{con(u_s=\sqrt{3}\times 0.5U_{dc})}}_{\Delta P_{con}} - P_{trans} \tag{22}$$

Where $\triangle P_{con}$ presents the cost saving of the converter.

As long as the cost reduction is greater than zero, namely, the converter cost saving is greater than the transformer cost, the proposed configuration structure is cost-effective. In order to obtain a quantitative guidance, here makes an approximation of the cost of converter and SVG.

1） The converter cost is approximately considered to be proportional to the converter rating.

2） The transformer cost is a quarter of the same rating MMC converter cost.

Based on the above approximation and considering (17), the equation (22) can be rewritten as

$$\Delta P = k_1\left(1.5 + \frac{\sqrt{6}}{4}\frac{U_{dc}}{U_g} + \sqrt{\frac{2}{3}}\frac{U_g}{U_{dc}}\right)P_{dc} - k_1\times 2.91P_{dc} - \frac{k_1}{2.5}P_{dc} = k_1P_{dc}\left(\frac{\sqrt{6}}{4}\frac{U_{dc}}{U_g} + \sqrt{\frac{2}{3}}\frac{U_g}{U_{dc}} - 1.81\right) \tag{23}$$

Where k_1 presents the unit cost of MMC converter, it approximately equals to 15000\$ / Mvar.

With (23), it can be analytically solved that when U_g>1.96U_{dc} or U_g<0.25U_{dc}, the cost reduction is positive, namely, the insertion of the transformer is cost-effective.

4.3 Applicable scope of the proposed configuration

Compared with the traditional MMC-DDI structure, the proposed MMC-DDI configuration structure requires an extra transformer. It seems that this would increase the cost of the total system, and partially offset the advantages of the MMC topology. However, in fact, the converter rating of traditional MMC-DDI varies greatly with its AC-side voltage, thus the insertion of transformer can sometimes reduce the converter rating and its cost. As long as the reduction of the converter cost is sufficient to offset the transformer cost, the proposed MMC-DDI structure is cost-effective.

According to the cost comparison data of the converter and transformer in the previous section, the unit cost of a MMC converter is generally much higher than that of a conventional transformer, especially for large-capacity converters above 50MVA. Moreover, the saved converter rating by the introduction of a transformer is sometimes much higher than the transformer rating. Therefore, the introduction of the transformer is worthwhile in some cases. Under the cost model established in the previous section, it can be obtained that:

1) When the ratio of the grid line voltage to DC-side output voltage exceeds 1.96 or falls below 0.25, the overall cost of MMC-DDI with the transformer is less than that with no transformer, i.e., a transformer can be inserted on the AC side of converter to improve the system economy.

2) When the ratio of the grid line voltage to the DC-side output voltage is among 0.25-1.96, the cost of the transformer exceeds the revenue that it brings. In that case, no transformer is required.

Indeed, for the common high-voltage transmission lines up to 500 kV, the required ice-melting DC voltage is generally less than 15kV. Under such ice-melting voltage range, if the MMC-DDI is connected to the 35kV distribution network, the grid voltage is more than 2 times of the ice-melting DC voltage. In that case, the proposed MMC-DDI configuration as Figure 4 is more applicable than the traditional MMC-DDI configuration as Figure 1. But if the MMC-DDI is connected to the 10kV distribution network, the grid voltage is usually among 0.25-1.96 times of the DC-side voltage. In that case, the traditional MMC-DDI configuration is more applicable.

5. Design Example and Simulation Result

5.1. A typical design example

In order to verify the above analysis and the proposed configuration, a design example of MMC-DDI is given here. For a 500kV transmission line, the wire type is 4×LGJ-400, the line length is 40km, and its single-phase resistance is 0.72 Ω. The minimum ambient temperature along the line is -5°C, and the maximum wind speed in winter is about 5m/s. In the 500kV substation at one end of the transmission line, the distribution grid voltage is 35kV, corresponding a 20.2kV phase voltage.

With the data shown in Table A1, the required de-icing current of the above transmission line should be between 3475-4768A. Within this range, the smaller the current, the longer the de-icing process lasts. Considering a balance between ice-melting rapidity and IMD economics, the rated DC de-icing current can be set as 4.0kA. Then with (19), the required de-icing voltage can be calculated as 5.76kV($2\times 4.0\text{kA}\times 0.72\,\Omega$). Thus, the rated de-icing output power is 23.2MW(=5.76kV×4.0kA).

If the MMC-DDI is directly connected into the 35kV grid without a transformer as [15], the AC-DC voltage ratio U_m/U_{dc} is 3.5 (20.2kV/5.8 kV). According to (17) or Figure 3, the converter rating will be 6.5 times of its output ice-melting power, i.e., it will reach up to 151MVA(=6.5×23.2MW). Such huge converter leads to high cost and poor economy.

With the formulas in chapter 3, the detailed electrical parameters of above MMC-DDI can be calculated and then listed in Table 1. The voltage and current peaks of the six arms are respectively 31.5kV and 1.6kV, thus the converter is equivalent to two conventional star-connected SVGs and each SVG has a 38.5kV rated line voltage ($31.5\text{kV}/\sqrt{2}\times\sqrt{3}$), a 1.13kA rated current ($1.6\text{kA}/\sqrt{2}$), a 75.4Mvar rating ($\sqrt{3}\times 38.5\text{kV}\times 1.13\text{kA}$). Referring to the SVG price list in Table A2, the unit cost of MMC converter can be approximated as 15000 $/Mvar, and then the converter cost can be estimated as about 2.26 million dollar (15000$/Mvar×75.4×2=2.26 million). With respect to its 23.2MW output de-icing power, such cost is too high to be acceptable.

Table 1. Electrical parameter comparison of the MMC-DDI under conventional configuration and optimized configuration

Parameter	Symbol	Conventional configuration (With no transformer)	Optimized configuration (With transformer)
Rated DC voltage	U_{dc}	5.8kV	5.8kV
Rated DC current	I_{dc}	4.0kA	4.0kA
Rated output DC power	P_{dc}	23.2MW	23.2MW
AC-side phase voltage	U_m	20.2kV	2.9kV
AC-side phase current	I_m	0.38A	4.6kA
Arm voltage peak	U_{arm_peak}	31.5kV	7.0kV
Arm current peak	I_{arm_peak}	1.6kA	3.2kA
Converter rating	S_c	151MVA	68MVA
Transformer	-	None	23 MVA-35 kV/5 kV

If the proposed optimization method is adopted, a 23 MVA-35 kV/5 kV transformer should be inserted between the MMC converter and the 35kV grid. At this time, the optimized MMC-DDI is

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mainly composed of a MMC converter and a transformer, and the detailed electrical parameters of MMC-DDI are also listed in Table 1. As it shown, the voltage and current peaks of the six arms are 7.0 kV and 3.2kV, thus the converter is equivalent to two common SVGs and each SVG has a rated line voltage 8.57 kV ($7.0\text{kV}/\sqrt{2}\times\sqrt{3}$), 2.26kA rated current ($3.2\text{kA}/\sqrt{2}$) and 33.5 Mvar rating ($\sqrt{3}\times 8.57\text{kV}\times 2.26\text{kA}$). Considering the approximate SVG unit cost (15000 $/ Mvar), the converter cost can be estimated as 1.01 million dollar(15000 $/Mvar×33.5 Mvar×2). In addition, in Table A3, the cost of a 24MVA transformer is 166000 $. Then the total cost of the optimized MMC-DDI can be estimated as 1.18 million dollar. The above cost comparison results are listed in Table 2. Compared with the cost of the original MMC-DDI with no transformer, the optimized cost of the IMD device has dropped by 48%.

Table 2. Cost comparison of the MMC-DDI under conventional configuration and optimized configuration

Component	Original cost (million dollar)	Optimized cost (million dollar)
Converter	2.26	1.01
Transformer	-	0.17
Total	2.26	1.18

5.2. Simulation Results

To verify the above analysis and calculation on the converter characteristic, a corresponding MMC-DDI system is built in Matlab/Simulink, and the simulation parameters are set as given in the previous section. For comparison, a dual-SVGs system(2×11.6Mvar), which is similar to Figure 1 but has no DC-side output voltage, is also simulated. The simulation results are shown in Figure 5.

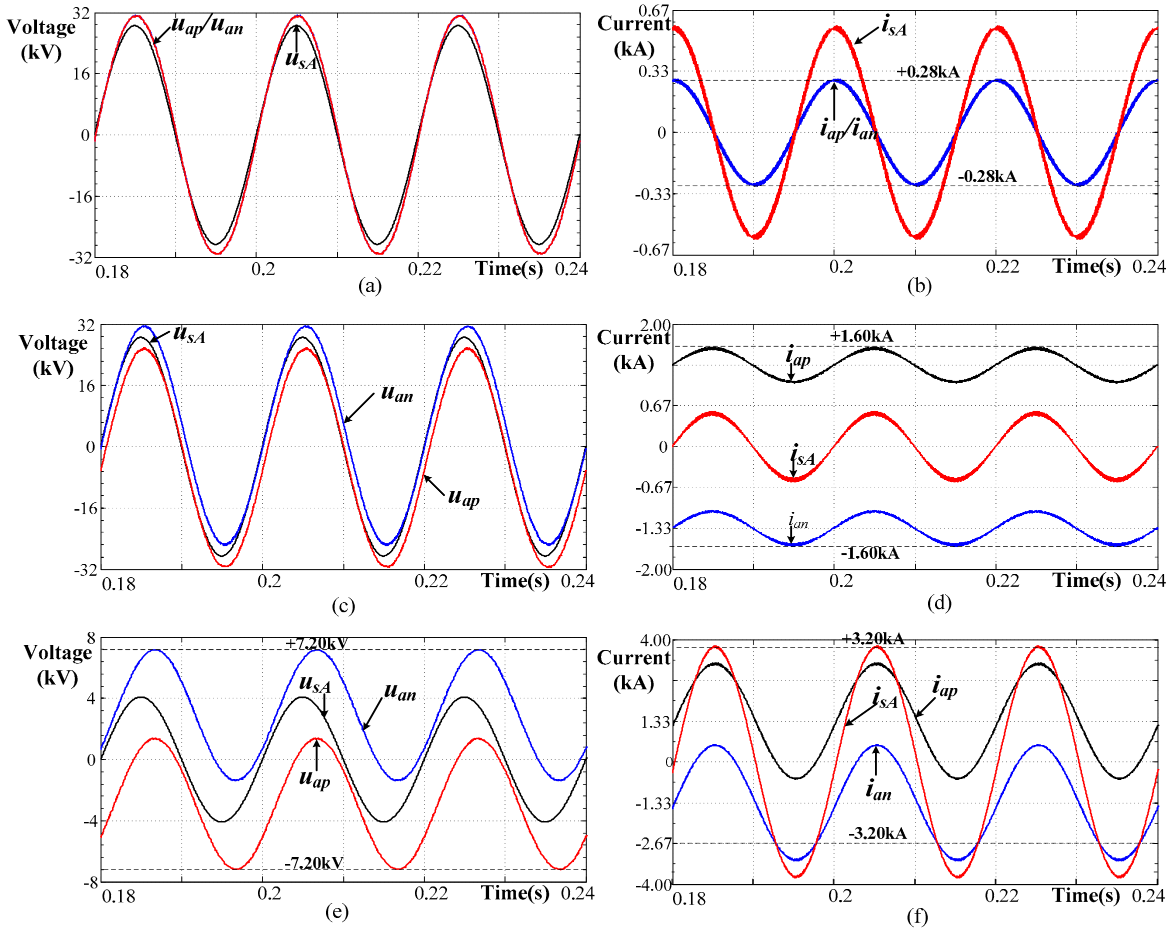

Figure 5. Simulation results of the converter voltage and current. (a) arm voltage of the dual-SVGs system, (b) arm current of the dual-SVGs system,(c) arm voltage of the original MMC-DDI as Figure

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1, (d) arm current of the original MMC-DDI as Figure 1, (e) arm voltage of the optimized MMC-DDI as Figure 4, (f) arm current of the optimized MMC-DDI as Figure 4

As Figure 5a and 5b shown, in the dual-SVGs system, the arm voltage is slightly higher than the AC-side phase voltage, and the arm current equals to half of AC-side phase current. Their peaks are respectively 30.7kV and 0.28kA. With (15), the corresponding converter rating can be calculated as 25.8MVA, which is slightly higher than its output reactive power.

As Figure 5c and 5d shown, in the conventional MMC-DDI that has no transformer, the arm voltage contains mainly AC component and the DC component only occupies a small part. The arm voltage peak is 31.5kV, slightly higher than AC phase voltage. The arm current contains mainly DC component and its peak is 1.6kA, far higher than the AC phase current. With (15), the corresponding converter rating can be calculated as 151MVA, about 6.5 times of the DC-side output power.

As Figure 5e and 5f shown, in the optimized MMC-DDI system that has a transformer, the arm voltage contains about 40% DC and 60% AC components, and the arm current is similar. The arm voltage and current peaks are respectively 7.2kV and 3.2kA, corresponding to a 39.9 MVA converter rating. Compared with the original MMC-DDI without transformer, the arm current peak increases by 100% while the arm voltage peak reduces by 78%, thus the converter rating is only 44% of its original value.

The converter characteristics in such simulation results are consistent with the above analysis and calculation. And the values of the converter voltage and current are also consistent with the theoretical results listed in Table 1. This proves the accuracy of the analysis and calculation on the MMC converter rating present in the paper.

6. Discussion and Further Improvements

Concerning the converter rating of MMC-DDI presented in this paper, the goal is to improve the economics of MMC-DDI while maintaining the same output de-icing characteristics. It turns out that, for a given DC ice-melting requirement, the converter rating of MMC-DDI varies greatly with its AC-side input voltage. Then it is proposed to insert a transformer on the AC side of the MMC converter so that the converter rating as well as its cost can be significantly reduced, and then the economics of MMC-DDI can be improved.

It seems that this proposed configuration scheme is contradict with traditional understanding of the MMC structure. Conventionally, in the common MMC system such as SVG, the AC side input transformers are expected to be avoided as much as possible.

This difference can be explained for the reason that the converter characteristic of MMC-DDI has significant differences with that of the common MMC system. In a SVG, both the arm voltage and current contain only AC component. As a result, in the case of a certain output power, the arm voltage is inversely proportional to arm current, thus the converter rating keeps basically constant under any AC-side voltage. In that case, if a transformer was configured on the AC side of MMC converter, it has little influence on the converter rating while increases a transformer. Therefore, in the common SVG, it tries to avoid a transformer. However, in the MMC-DDI, the arm voltage and arm current of converter contain both DC and AC components. As a result of the crossover between the DC components and the AC components, the converter rating of MMC-DDI varies greatly with its AC-side voltage. Due to such converter characteristics, a transformer can affect the converter rating. In this case，although the introduction of transformer will increase a transformer cost, it can cause a cost increment or reduction of the converter. As long as the reduction of the converter cost is sufficient to offset the transformer cost, the introduction of the transformer is cost-effective. In addition, because the unit cost of MMC converter is generally much higher than that of transformer, the above condition is easy to satisfy under the typical DC ice melting system parameters. Therefore, the optimized configuration scheme proposed in this paper is cost-effective in many cases.

It should be noted, the MMC-DDI can have two operation modes, ice-melting mode and SVG mode. This paper only considers the requirement of the ice melting mode, while does not analyze the operating characteristics of the SVG mode. In the optimization design process, the requirements

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of SVG mode has not been take into account. This requirement can be further studied to get more comprehensive optimization result.

7. Conclusions

MMC-based ice-melting device has recognized as a promising de-icing solution. In this paper, the converter characteristic of MMC-DDI was quantitatively analyzed. It is revealed that, for a given DC ice-melting requirement, the converter rating varies greatly with its AC-side input voltage, and its minimum is 2.9 times of the output ice-melting power. When the gird access point voltage of the MMC-DDI is far more or far less than the required DC de-icing voltage, the conventional MMC-DDI structure will result in a much higher MMC converter rating than its output ice-melting power, thus the economy of the MMC-DDI is very poor.

In order to reduce the converter rating and then improve the economy of MMC-DDI, this paper proposes an optimized MMC-DDI configuration structure that a two-winding transformer should be inserted between the grid and the converter in some cases. As a result, the converter rating can be significantly reduced. A cost comparison of typical transformer and MMC converters was given in this paper. Considering the cost, the introduction of the transformer is cost-effective in many cases. Under the typical cost range of converter and transformer, we can get the following conclusions.

1) When the ratio of grid line voltage to the DC-side output ice-melting voltage exceeds 1.96 or falls below 0.25, the overall cost of MMC-DDI with transformer is less than that with no transformer, namely, a transformer should be inserted on the AC side of converter to improve system economy.

2) When the ratio of the grid line voltage to the DC-side output voltage is among 0.25-1.96, no transformer is required.

A design example and simulation results are given in this paper. In the case of outputting the same de-icing characteristics, the optimized converter rating is reduced from 151MVA to 68MVA, and the total cost of MMC-DDI is reduced by 48%. It fully proved the effectiveness of the proposed optimization design.

This analysis and conclusion are conductive to the optimized configuration of the modular multilevel DC de-icer, then to its engineering application for high voltage transmission lines.

Appendix A

Table A1. The minimum de-icing current and maximum endure current for typical power lines[5]

conductor type	Min. de-icing current(A) (-5 ℃, 5 m/s, 10 mm, 1 hour)	Max. endure current(A) (5 ℃, 0.5 m/s, No icing)
LGJ-4×400/50	3475	4764
LGJ-2×500/45	1989	2698
LGJ-2×240/40	1218	1716
LGJ-1×240/40	609	858
LGJ-1×185/45	515	733
LGJ-1×150/35	441	633
LGJ-1×95/55	345	500
LGJ-4×400/50	3475	4764

Table A2. Deal prices of several typical SVG projects in China from 2013 to 2018

No.	Project location	Rated Voltage (kV)	Rating (MVA)	Deal price[1] (1000 $)	Unit cost (1000 $/MVA)
1	Kunming, Yunnan	35	10	154	15.4
2	Zhangjiakou, Hebei	35	12	175	14.6

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3	Huimin, Shandong	35	15	215	14.4
4	Huangpi, Hubei	35	16	251	15.7
5	Tongyu, Gansu	35	20	269	13.5
6	Hua County, Henan	35	20	257	12.8
7	Chenzhou, Hunan	10	20	330	16.5
8	Qiaojia, Yunnan	35	30	385	12.8
9	Linwu, Ningxia	35	40	458	11.5
10	Dabancheng, Xinjiang	35	50	615	12.3
11	Yinan, Shandong	35	60	1023	17.1
12	Haixi, Xinjiang	35	60	1154	19.2
13	Hami, Xinjiang	35	80	1508	18.8
14	Huaping, Yunnan	35	100	2109	21.1
15	Xiangtan, Hunan	35	120	2615	21.8

[1] The deal price covers a complete set of SVG equipment (including the converter chain, connection reactance, startup circuit, cooling system, control system and other ancillary facilities) and its technical service.

Table A2. Deal prices of several 10MVA-class rectifier transformers in China

No.	Project location	Rated Voltage (kV)	Rating (MVA)	Deal price (1000 $)	Unit cost (1000 $/MVA)
1	Baoding, Hebei	10/5	10	86	8.6
2	Changsha, Hunan	10/7	14	110	7.8
3	Changsha, Hunan	35/6	24	166	6.9
4	Xinyu, JiangXi	35/12	56	246	4.4
5	Chongqing	35/15	86	284	3.3
6	Zhuzhou, Gansu	35/17	100	323	3.2
7	Hengyang, Hunan	35/19	120	361	3.0

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