Parameter Design of Modular Multilevel Converter for DC Fault Ride-Through Capability in Multi-Terminal HVDC System

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Abstract

The purpose of this paper is to provide the design guide line of the module capacitor, the arm inductor and the DC inductor in Modular Multilevel Converter (MMC). Especially, this design method is proposed for the MMC to have the DC fault ride-through capability in Multi-terminal HVDC system. An MMC system connected to two DC grids and an AC grid is formulated according to the design guide line and the performance of the MMC system has been analyzed through computer simulating. The rationality of the proposed guide line has been confirmed by the simulation results.

I. Introduction

Globally, the electric power demand increases at a fast-growing rate, and rapid urbanization has caused the power demand centralization. Moreover, the recent concern about environmental issues has brought the need of development of the sustainable energy sources: wind energy, solar energy, and so on. These renewable energy resources have penetrated into a conventional Alternating Current (AC) power grid and the AC electric power transmission systems are getting complicated. The High Voltage Direct Current (HVDC) power transmission system has been considered an alternative to solve many problems from the AC power transmission.

Actually, many HVDC power transmission systems have already been installed as point-to-point power transfer. Most of these HVDC systems use Line Commutated Converter (LCC-HVDC) as AC/DC converter. The LCC-HVDC is suitable to transfer massive electric power through long distance transmission line. However, the electric power flows one way and a strong AC grid is required to operate LCC-HVDC. On the other hand, the Voltage Source Converter (VSC) based HVDC system has been also implemented in the real grid. The VSC-HVDC can control the reactive power of interfaced AC grid, and has black start capability. Since the polarity of the DC link voltage does not change according to the power flow direction, the VSC-HVDC is regarded as the unique converter type to be applied to the Multi-Terminal HVDC (MTDC) system. However, two-/three-level PWM converter which is the typical Voltage Source Converter has high switching losses and needs bulky AC filters. Especially, high losses of converter have been the barrier to be employed to the HVDC transmission systems. Recently, Modular Multilevel Converter (MMC) which is a kind of VSC-HVDC has been proposed. Since the MMC consists of many half-bridge modules, it generates so many output voltage levels and does not need AC filter. And, the switching frequency of each module is very low and the total loss of the MMC is comparable that of LCC-HVDC. Therefore, the MMC is considered ad the strong candidate to be used in MTDC system.

However, the MTDC system requires that the converter has the ability to manage the DC grid short circuit fault. Namely, the converter should immediately disconnect the faulty DC line and continuously transfer the power between the AC grid and other DC grids. In this paper, this ability is called as DC fault ride-through capability.

The DC Circuit Breaker (DC-CB) is considered as a solution against the DC short circuit fault in VSC-HVDC. Until now, existing or proposed DC-CB can be divided into three groups: mechanical circuit breaker, solid-state circuit breaker, and hybrid circuit breaker. All DC-CBs have their own pros and cons in various aspects: cost, efficiency, operating time, implementation, and so on. Whatever kind of the DC-CB is used, however, the surge current flows through the VSC for the operation time of the DC-CB. Therefore, the DC current capability of VSC-HVDC should be designed to cover this fault surge current. To have the DC fault ride-through capability, moreover, the VSC-HVDC should maintain the capacitor voltage enough to control the DC voltage and the AC currents during the DC short circuit fault condition. To satisfy these specifications such as the fault surge current and the capacitor voltage during the DC short circuit fault, the parameters of the MMC should be properly designed considering not only AC grid fault but also DC grid fault.

In this paper, the design guide line to size the parameters of MMC such as the module capacitor, the arm inductor and the DC inductor is provided. This design guide is prepared for the MMC to have the DC fault ride-through capability in MTDC system. To set the parameters generally, the Per Unit (PU) value of the inductance and the capacitance in the DC system are newly defined. And, a simple DC model of the MMC is introduced. Using these PU values of the inductance and the capacitance and the DC model, the parameters of the MMC such as arm inductor, the DC inductor and the module capacitor can be generally set in various DC voltage and current system. And, some criteria for the DC fault ride-through capability are addressed. Under the consideration of the criteria, the MMC can generate the DC output voltage and control the AC current during the DC short circuit fault condition.

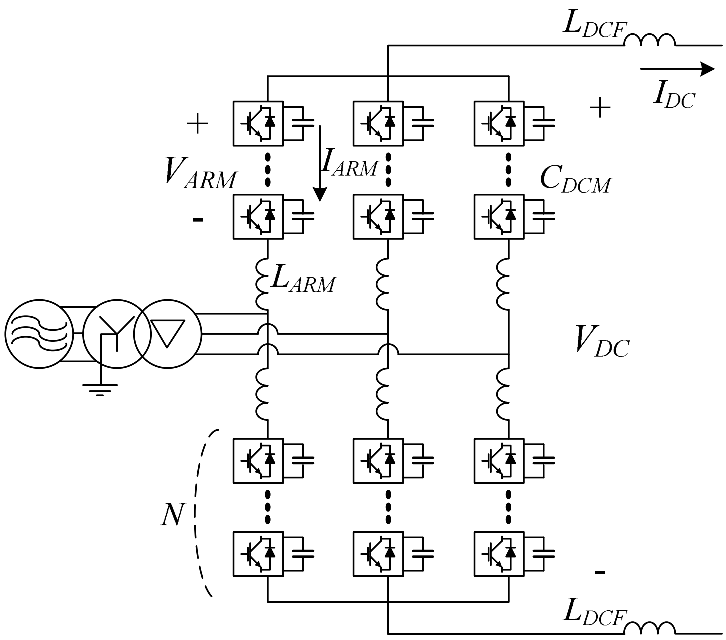


Fig. 1: Structure of MMC.

II. MMC Model in MTDC System

The MMC shown in Fig. 1 has many modules with their own capacitor. The DC grid voltage can be generated by connecting the capacitors. Every arm has series connected modules and the number of modules in one arm is N. Leg has two arms: upper arm and lower arm. Every arm has its inductor, L_{ARM}. These arm inductors work as three phase inductor in the viewpoint of AC grid. At the same time, arm inductors function as the DC inductor. Additionally, the DC inductor, L_{DCF} is required to smooth the DC current and to limit the increasing rate of the DC short circuit fault current. To design the MMC, the arm inductor, the DC inductor and the module capacitor, C_{DCM} should be properly sized after considering the various aspects of the system requirement. Generally, the DC capacitor is decided to suppress the voltage variation of the capacitor voltage in the rated power transfer condition. The arm inductor is designed for two purposes: to suppress the circulating current and to limit the rate of the DC short circuit fault current [1]. And, the DC inductor is used to limit the DC short circuit fault current.

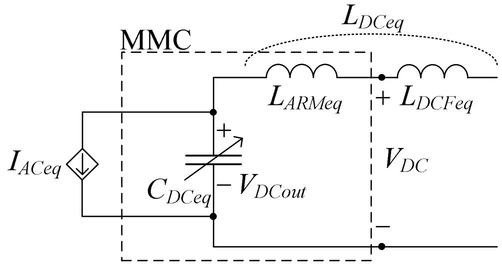


Fig. 2: Simple DC model of MMC.

To install the MMC in the MTDC system, however, the MMC should have the DC short circuit fault ride-through capability. If not, single DC grid fault may cause the breakdown of the whole DC grids. The structure of the MMC is quite complicated to design the component of MMC in the viewpoint of the DC grid short fault condition. Therefore, the simple MMC model is necessary to design the MMC parameters for DC fault ride-through capability in the MTDC system. In the proposed simple DC model of the MMC in Fig. 2, AC grid is modeled as dependent DC current source. The capacitors in modules, the arm inductor and the DC smoothing inductor are modeled as the equivalent values in Fig. 2.

$$C_{DCeq} = C_{DCM} \times \frac{6}{N}, \quad L_{DCFeq} = 2L_{DCF}, \quad L_{ARMeq} = \frac{2}{3}L_{ARM}, \quad L_{DCeq} = L_{ARMeq} + L_{DCFeq} \tag{1}$$

The output DC voltage of the MMC is synthesized by selecting the capacitors of modules. Therefore, the DC voltage V_{DCout}, is not identical with the voltage of the equivalent capacitor. It can be controlled by controller even though the capacitor voltages of the modules are varying within allowable range.

To discuss the general quantities in the DC short fault condition, it is necessary to define the inductance and the capacitance values in the term of Per Unit. One PU of the inductance is defined as the inductance of which the inductor current can go from zero to rated current for 1 millisecond with one rated DC voltage.

$$Z_{DCbase} = \frac{V_{base}}{I_{base}} \triangleq \frac{V_{DCrated}}{I_{DCrated}}, \qquad L_{base} = \frac{V_{base}}{I_{base}}\frac{1}{1000} = \frac{Z_{base}}{1000}, \qquad L_{DCeqpu} = \frac{L_{DCeq}}{L_{base}} \tag{2}$$

The PU value of the capacitor can be defined in similar way. At one PU of the capacitance, with the rated DC current of the MMC, the voltage of capacitor can go from zero to the rated value of the MMC for 1 millisecond.

$$C_{base} = \frac{1}{Z_{base}}\frac{1}{1000}, \qquad C_{DCeqpu} = \frac{C_{DCeq}}{C_{base}} \tag{3}$$

In Fig. 3, the inductance and capacitance are depicted according to their rated voltage and the current values, respectively. As an example, if the rated DC voltage and current of the MMC are 600kV and 3kA, one PU inductance and capacitance are 200mH and 5uF.

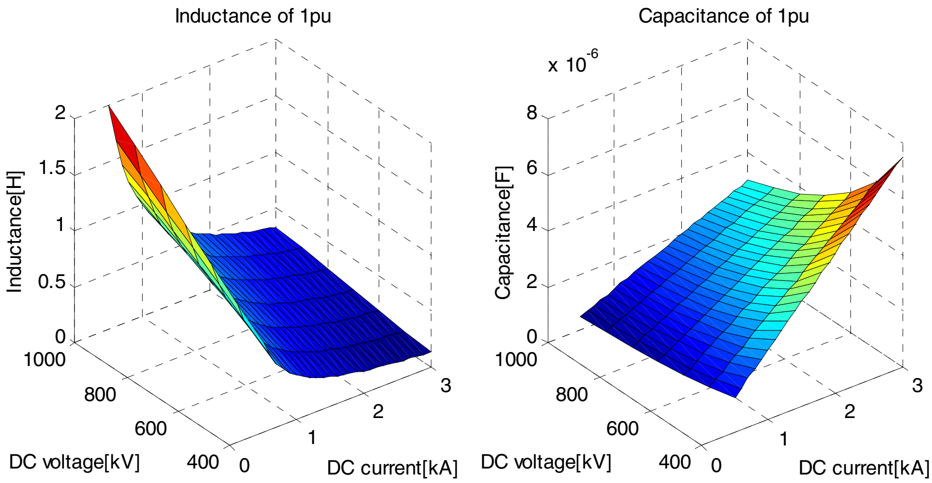


Fig. 3: Real value of one PU inductance and capacitance.

III. DC Short Circuit Fault Analysis in Two Terminal HVDC System

A simple HVDC system in Fig. 4 is used to analyze the DC fault response in MTDC system consisted of two terminals. To protect the MMC, the DC Circuit Breaker (DC-CB) is the critical most component. Still, the DC-CB in the power transmission system has not been available. However, several companies are competitively announcing their new DC-CB in the power transmission system. According to the technical data released by a company, its DC-CB can disconnect the DC fault current in 2 milliseconds including the fault detection time and the maximum interruption current is up to 16kA [2]. Fig. 5 shows the general DC current response under the DC short circuit fault condition. Before the DC short circuit fault, it is assumed that the rated DC current flows into the DC grid. The DC current and the DC output voltage are shown in PU value. To consider the worst DC fault condition, it is assumed that the DC short circuit fault happens just after the DC inductor of the MMC. Many DC short circuit fault detection methods have been proposed. In this paper, the DC short fault accident is simply distinguished by measuring the magnitude of the DC current. The reference value of the fault current is the fault critical current, I_{fcrit} in Fig. 5. After detecting the DC short fault accident, it takes some time for opening the DC-CB. The operating time to disconnect the DC grid and the MMC is defined as the DC-CB operating time, T_{CB}. And, the sum of the fault detection time and the DC-CB operating time is defined as the fault time, T_{fault}. After the fault time, the DC-CB opens completely. Then, the fault current is suppressed by the surge arrester. The voltage of the DC-CB for the fault clearing time is determined by the applied arrester. The DC fault current is suppressed by the voltage difference between the output DC voltage of MMC and the arrester voltage. When the clamping voltage of the arrester, V_{SAcrit} is designed as 1.5pu of rated DC voltage, the fault clearing time, T_{clear} is about two times of the fault time, T_{fault}. As the result, the DC fault has strong influences on the arm current and the capacitor voltage of the MMC for not only the fault time, but also the clearing time.

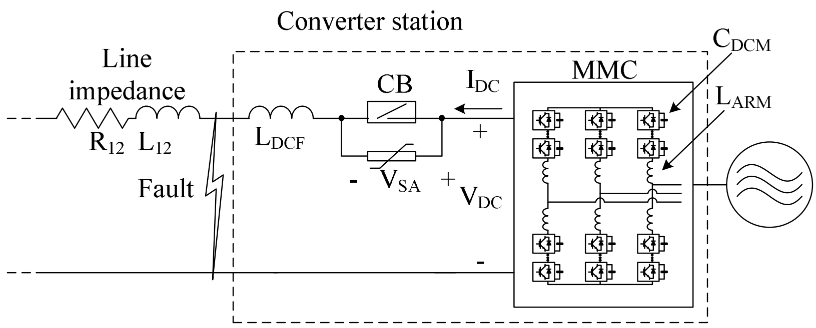


Fig. 4: Simple MMC station with DC Circuit Breaker (DC-CB).

The fault time, T_{fault} is mainly determined by the DC-CB operating time which is given by the characteristics of DC-CB. And, the fault clearing time, T_{clear} is determined by the clamping voltage of the arrester, which is the system specification and is limited by the voltage insulation level of the transmission system. The maximum fault current is determined by the rated DC voltage, the equivalent DC inductance, the fault time, T_{fault}, and the initial DC current, I_{DCini} as (4). In this equation, all current, voltage and inductance values are represented in PU values and the unit of time is millisecond.

$$I_{fmax} = \frac{V_{DC}}{L_{DCeq}} T_{fault} + I_{DCini} \tag{4}$$

IV. Parameters of MMC

During the DC short circuit fault condition, the MMC in the MTDC system should generate the output DC voltage matched to DC link voltage of the DC grid and control the AC current continuously. If the MMC fails to match its output DC voltage to DC link voltage the DC short circuit fault expands into the neighbor DC grids and the whole DC grid may collapse successively. And, if the MMC loses the ability to control the AC current, the AC circuit breaker of MMC station may be activated and the AC grid may be disconnected from the DC grid even though the MMC station still keeps other normal DC grids in the MTDC system. Therefore, the MMC should prevent the expansion of DC short circuit fault to the neighbor DC grids and to the connected AC grid. Additionally, the fault current in MMC should be limited under the allowable current level of the power semiconductors such as IGBT in the MMC. To fulfill these requirements under the DC fault, the DC inductor, the arm inductor and the module capacitor should be sized adequately.

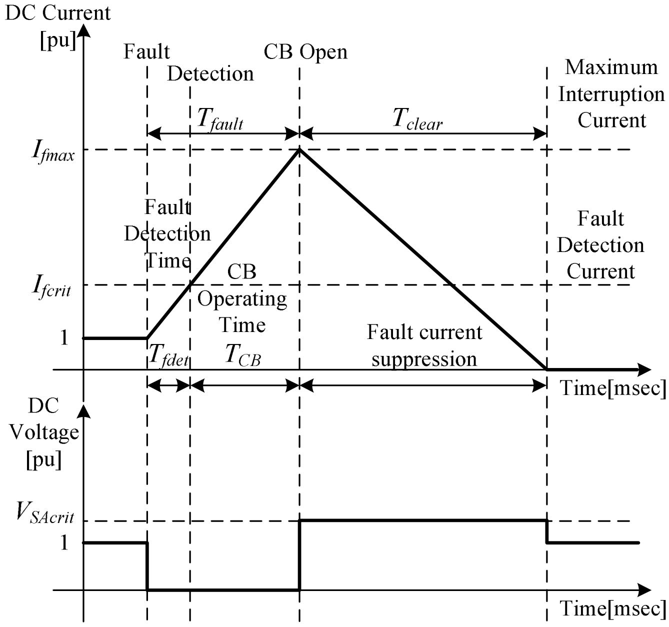


Fig. 5: DC fault current response.

A. DC equivalent inductance of MMC

Ideally, the DC fault current flows into the three legs in the MMC. Since the increased arm current by the DC fault current may exceed the current level of Safe Operation Area (SOA) of IGBT, the arm current during the DC short fault condition should be analyzed. The arm current in the MMC is the sum of the one third of the DC current and the half of the AC current as (5).

$$I_{ARM} = \frac{1}{3} I_{DC} + \frac{1}{2} I_{AC} \tag{5}$$

To analyze the arm current in general, the AC current needs to be expressed in PU of DC system. When the Modulation Index (MI) is defined as the ratio of the AC phase peak voltage, V_S and the half of DC link voltage, the rated AC peak current can be expressed by the DC rated current. Then, the Root-Mean-Square(RMS) of the arm current can be calculated by the DC rated current as (6) because of DC and AC power equality.

$$MI = \frac{V_S}{\frac{1}{2} V_{DC}}, \qquad I_{AC} = \frac{4}{3MI} I_{DC}, \qquad I_{armRMS} = \sqrt{\frac{1}{9} + \frac{2}{9MI^2}} I_{DC} \tag{6}$$

When the MI is 0.75, the RMS value of arm current is about 0.7pu of the rated DC current in the normal rating operation. Then, the rated current of the IGBT would be in the range from 0.7pu to 1pu of the rated DC current. The surge current level of IGBT is typically six or seven times of the rated current [3]. When the rated current of the IGBT is 0.7 of the rated DC current, the DC fault current reaching 12 or 15 times of the DC rated current can be handled by the IGBT surge current rating. Therefore, it may be appropriate that the maximum interruption current of the DC fault current is determined as about ten times of the DC rated current. Fig. 6 shows the maximum interruption current, I_{fmax} according to the DC equivalent inductance. From this figure, the equivalent inductance can be sized from the given DC-CB operating time and the acceptable maximum interruption current. If the maximum interruption current is 10pu, for example, the proper DC equivalent inductance would be 0.012, 0.125, 0.25, 0.37 and 0.625pu according to the operating time of the DC-CB, 0.1, 1, 2, 3, and 5msec, respectively.

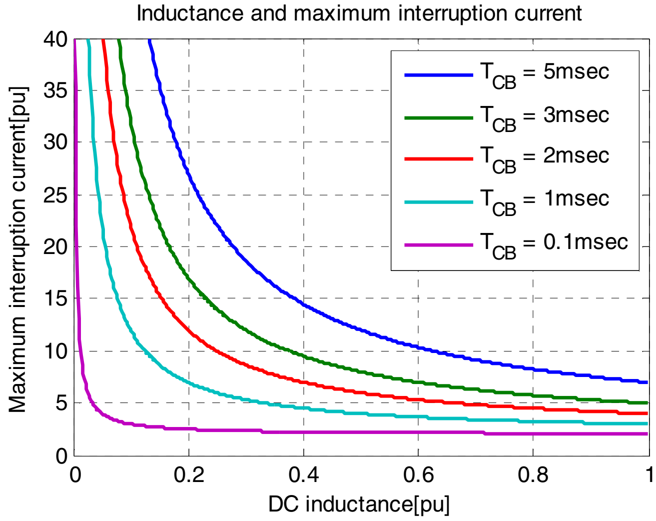


Fig. 6: Maximum interruption current according to the DC equivalent inductance and the operating time of DC-CB.

B. Equivalent capacitance of MMC

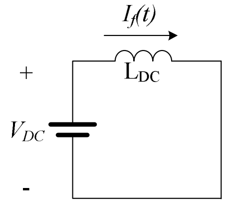
To generate the output DC voltage and to control the AC current under the DC short circuit fault condition, the voltage of the module capacitor should be kept high enough to synthesize the output DC voltage and the AC voltage continuously. Under the DC short circuit fault, however, the DC current increases rapidly and the voltage of the module capacitors decreases accordingly. If the module capacitor voltage decreases lower than certain limiting value, the MMC may lose the control ability of the AC current and the output DC voltage decreases until the voltages of the module capacitors are recovered. Therefore, the voltages of the module capacitors should be kept above a certain level. Generally, the arm voltage reference is the sum of the half of the DC output voltage and the AC reference voltage. If the MI is 0.75, there is some DC voltage margin, 0.125pu. To decide the minimum DC voltage of the module capacitor during the DC short circuit fault, the behavior of the capacitor voltage needs to be analyzed according to the operating time of the DC-CB and the DC equivalent inductance. The MMC generates the output DC voltage by selecting the module capacitors instantaneously. Even though the voltage of the module capacitor decreases within the voltage margin, the output DC voltage can be matched to the DC link voltage of the DC grid. During this period, the MMC can be modeled as a constant voltage source. If the capacitor voltage of the modules decreases and there is no voltage margin, the output DC voltage becomes to be lower than the DC link voltage. In this case, the MMC is modeled as an equivalent capacitor. When the voltage of the equivalent capacitor decreases and the voltage margin go down zero, the time point can be defined as the capacitor margin time, T_{cm}. The voltage of the equivalent capacitor of the MMC can be considered in three cases according to the capacitor margin time, T_{cm}. Table I. shows three cases of the equivalent model of MMC in the DC short circuit fault condition. If the capacitor margin time, T_{cm} is longer than the sum of the fault time, T_{fault} and the fault current suppression time, T_{clear}, the voltage of the equivalent capacitor does not decrease below the voltage margin. Therefore, the MMC is assumed as a constant DC voltage source. The DC short circuit fault current and the current flowing through the equivalent capacitor of the MMC can be calculated from the constant DC voltage source model in

Table I. After the DC-CB opening operation, the DC voltage generated by the DC inductor is limited by the surge arrester. The DC voltage limited by the surge arrester is named as V_{SAcrit}, and modelled by the constant DC voltage as shown in Table. I.

If the capacitor margin time, T_{cm} is longer than fault time, T_{fault} but shorter than the fault current suppression time, T_{clear}, the equivalent model is different with the previous case. The voltage of the equivalent capacitor does not decrease below the voltage margin before the capacitor margin time, T_{cm}. Until T_{cm}, the MMC can be modelled as the constant DC voltage. After T_{cm}, however, the capacitor voltage of the MMC is not high enough to generate the DC voltage reference. Instead of that, therefore, the MMC generates the maximum DC voltage as it can. The MMC can be modelled as the capacitor. Because the MMC is assumed the capacitor, the DC voltage of the MMC is getting lower and the DC short circuit current is influenced by the lower DC voltage of the MMC.

If the capacitor margin time, T_{cm} is shorter than fault time, T_{fault}, the equivalent model of the MMC is assumed as the capacitor after the capacitor margin time, T_{cm}. The DC short circuit current and the capacitor voltage can be calculated from the equivalent capacitor model.

Table I. The equivalent model of MMC in the DC short circuit fault condition

<table>
<tr><th rowspan="2"></th><th>Case I</th><th>Case II</th><th>Case III</th></tr>
<tr><th>$T_{fault} + T_{clear} < T_{cm}$</th><th>$T_{fault} \leq T_{cm} < T_{fault} + T_{clear}$</th><th>$0 \leq T_{cm} < T_{fault}$</th></tr>
<tr><td>Before T_{fault}</td>
<td>$0 \leq t < T_{fault}$

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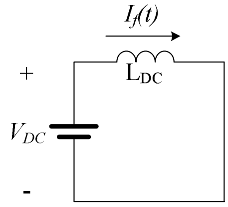
<td>$0 \leq t < T_{fault}$

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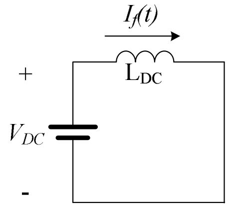
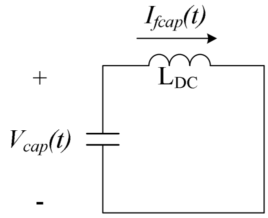
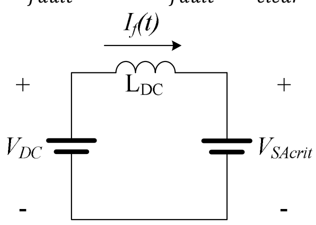
<td>$0 \leq t < T_{cm}$


$T_{cm} \leq t < T_{fault}$

</td></tr>
<tr><td>After T_{fault}</td>
<td>$T_{fault} \leq t < T_{fault} + T_{clear}$

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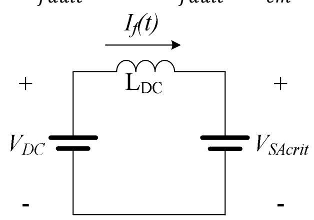
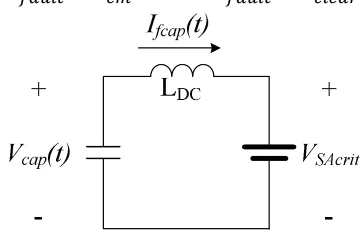
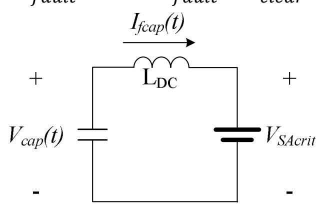
<td>$T_{fault} \leq t < T_{fault} + T_{cm}$


$T_{fault} + T_{cm} \leq t < T_{fault} + T_{clear}$

</td>
<td>$T_{fault} \leq t < T_{fault} + T_{clear}$

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From these equivalent models, the voltage variation of the equivalent capacitor can be obtained from Fig. 7. Fig. 7 shows three DC voltage variation according to the initial DC current. And, each figure in Fig. 7 depicts the DC voltage variation depending on the DC-CB operating time and DC inductance. The DC inductance was designed to limit the maximum interrupt current was 10pu with the given DC-CB operating time.

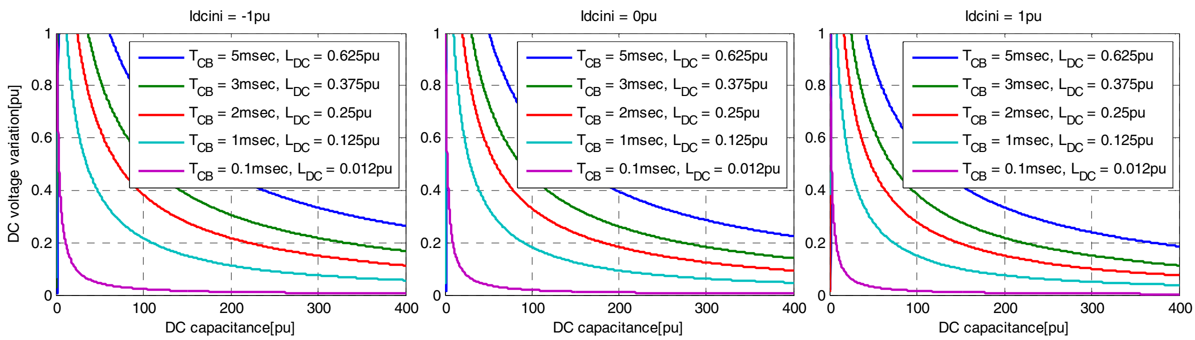

Fig. 7: DC voltage variation of the module capacitor.

C. Parameter region for DC short circuit fault ride-through capability

For the MMC to obtain the DC fault ride-through capability, the parameters of the MMC can be generally set by the PU values. In Fig. 8, the region of parameters satisfying the three criteria is shown. To limit the maximum interruption current, the inductance is determined as 0.25pu under the assumption that the DC-CB operating time, T_{CB} is 2ms. And, the voltage variation of the module capacitor is less than 0.1pu in the normal rated condition with about 70pu of the equivalent capacitance when the frequency of AC gird is 50~60Hz. The voltage variation of the equivalent capacitor during the DC fault condition is less than 0.2pu in the red region in Fig. 8. If the acceptable voltage variation of the equivalent capacitor during the DC short circuit fault is designed as larger value, the red region in Fig. 8 is getting wider.

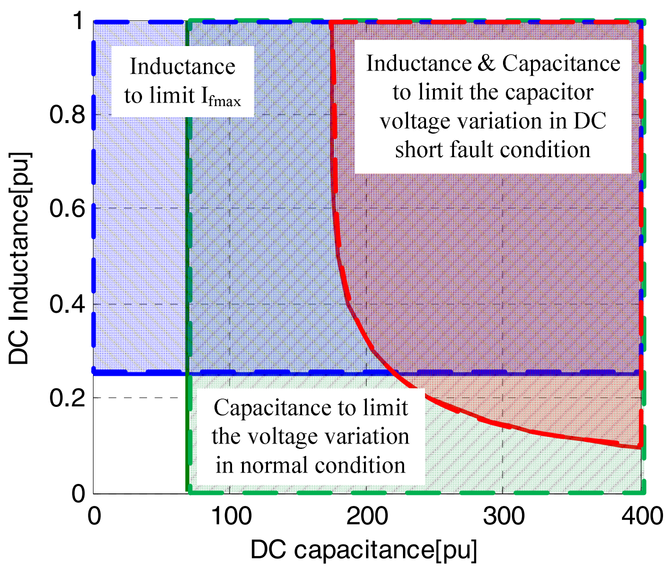

Fig. 8: Parameter region with 2ms T_{CB}.

V. Simulation Results

To verify the proposed design method, one MMC which is interfaced with two DC grids and one AC grid is simulated in Matlab/Simulink and PLECS as shown in Fig. 9. The specification of the MMC is listed in Table II.

Table II. Specification of the MMC

Rated Power	**1.8GW**
Rated DC voltage/Current	**600kV / 3kA**
Module number, N	**3**
Module DC voltage	**200kV**
Modulation Index(MI)	**0.75**

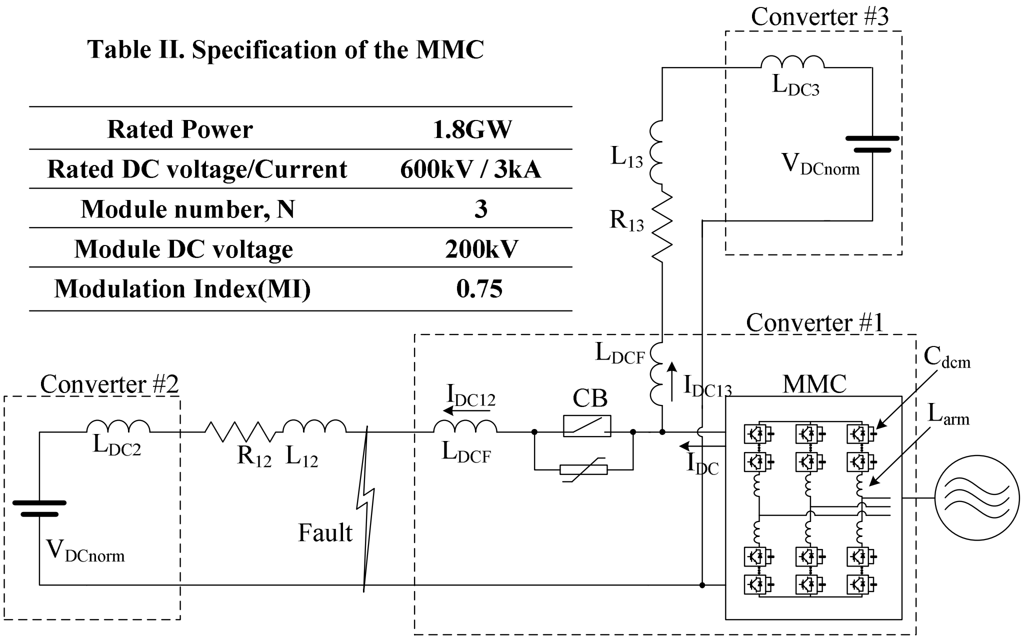

Fig. 9: Diagram of one MMC with two DC grids and one AC grid.

In Fig. 10, the MMC transfers the rated power from two DC grids into the AC grid. At 0.4s, the DC short circuit fault happens at DC line between converter #1 and #2. Even the DC short circuit fault, the MMC transfers the rated power from the DC grid into the AC grid continuously. Here, the DC-CB operating time was 2ms, and the maximum interruption current was 10pu. The clamping voltage of the arrester was set as 1.5pu of the rated DC voltage. Therefore, the equivalent DC inductance was 0.25pu. The real inductance of the DC inductor and the arm inductor in this MMC were 40mH and 15mH, respectively. The voltage variation of the module capacitors in the DC fault condition was designed to be 0.2pu. Therefore, the equivalent DC capacitance was 200pu and was equivalent to 500uF of the module capacitor. Even under this severe DC fault, the DC current on the line #13 and the AC current of the MMC were controlled well. Since 0.2pu of the voltage variation under the DC fault condition is quite conservative, the capacitance of the module capacitor is quite large.

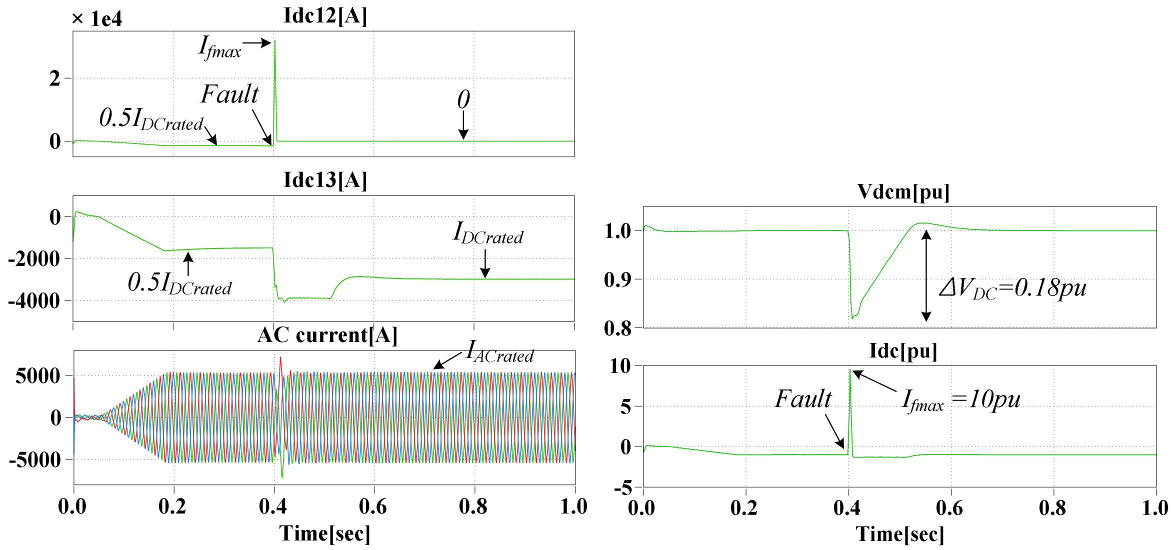

Fig. 10: DC and AC current and voltage variation.

Fig. 11 shows the DC currents, the voltage variation of the module capacitor, and the AC current according to the equivalent capacitance. When the capacitance is lower than 150pu, the AC currents were not controlled for 1-2 periods just after fault. The peak value of the AC current was higher than two times of the rated AC current. And, the DC current which flowed through the other DC grid increased to two times of the rated DC current. By the specification of the whole grid system such as DC fault condition and AC fault condition, it can be decided whether these uncontrolled DC and AC currents is acceptable or not. If the whole grid system can handle uncontrolled DC and AC currents for 1-2 periods, the criterion of the voltage variation in the DC short fault condition can be adjusted and the equivalent capacitance can be set as lower value.

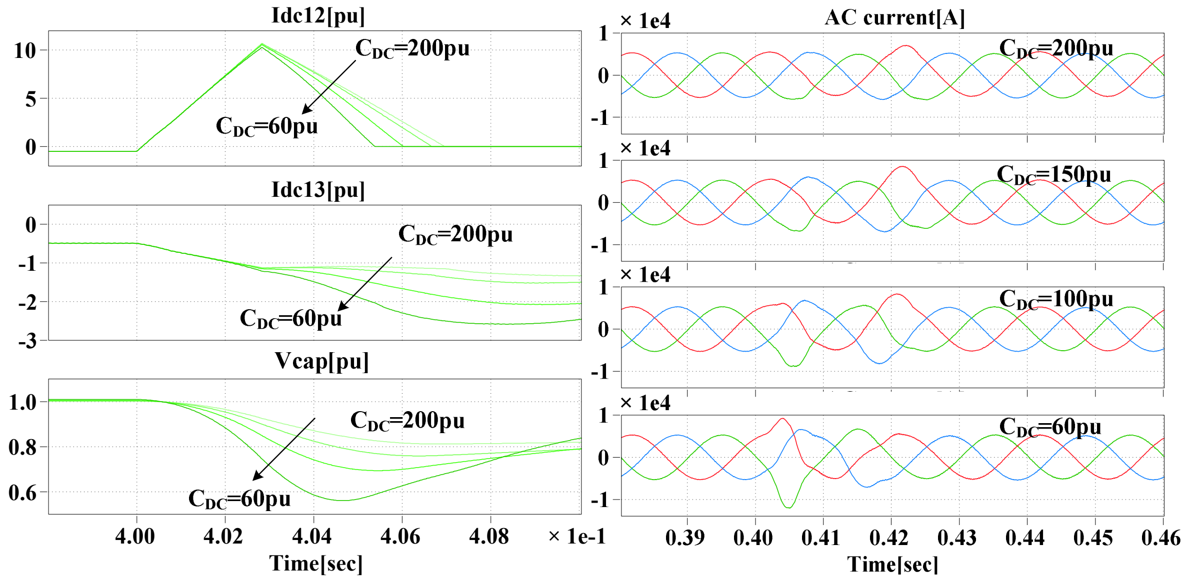

Fig. 11: Voltage variation of module capacitors and DC current of MMC.

VI. Conclusion

In this paper, a design guide line to size the parameters of the MMC under the DC short circuit fault condition has been proposed. To generally design the DC capacitor of the module, the arm inductor, and the DC inductor, the definition of the Per Unit value of the inductance and the capacitance are newly suggested. From the simple DC model of the MMC, the current variation and the voltage variation of the MMC can be estimated. Given the specification of the DC-CB, the relationship between the equivalent inductance and the capacitance of the MMC model and the current and voltage responses have been obtained. To achieve the DC fault ride-through capability, the parameter of the MMC can be designed without expanding the DC short fault into other DC and AC grids. A MMC system connected to two DC grids and an AC grid is formulated according to the design guide line and the performance of the MMC system has been analyzed through computer simulation. The rationality of the proposed guide line has been confirmed by the simulation results. And, the design guide line proposed in this paper could be applied into the conventional two-/three-level VSC in the MTDC system.

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