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전력계통 전압 변동과 순환 전류 보상 성분을 고려한 MMC 기반 VSC-HVDC의 최대 변조 지수 선정에 관한 연구

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Maximum Modulation Index of VSC HVDC based on MMC Considering Compensation Signals and AC Network Conditions

Chan-Ki Kim[1], Negesse Belete Belayneh[2], Chang-Hwan Park[2], and Jang-Mok Kim†

Abstract

This study deals with the modulation index (MI) of a voltage source converter (VSC) HVDC system based on a modular multilevel converter (MMC). In the two-level converter, the purpose of the MI is to maximize the achievable AC voltage of the converter from a fixed DC voltage. Unlike that in a two-level converter, the MI in the MMC topology plays a role in making the converter a voltage source using a capacitor. The circulating current in the MMC distorts the AC voltage reference, and the distortion affects the MI. In addition, the AC network conditions, such as AC voltage variation and reactive power, affect the MI. Therefore, the MI should be optimized with consideration of internal and external factors. This study proposes a method to optimize the MI of an MMC HVDC system.

Key words: MMC HVDC system, Modulation index, AC network system

1. Introduction

Modulation index (MI) is defined as the ratio of the peak value of the AC reference voltage to half of the DC voltage of the converter. The fact that MI is "1" means that the peak value of the AC reference voltage and the magnitude of half of the DC voltage are the same.

In a converter system, MI has an important meaning. The main consideration for MI in a 2-level converter is to maximize the AC reference voltage at a fixed DC voltage by utilizing methods such as space vector method, min/max method and a third harmonic injection method. Unlike the 2-level

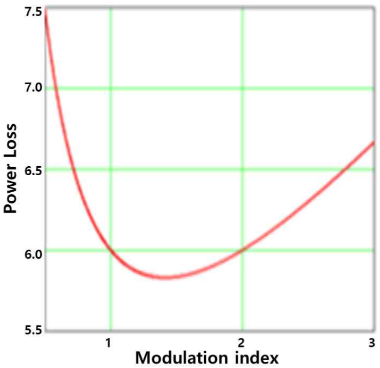

Fig. 1. Relation between power loss and modulation index.

converter, in the MMC based VSC HVDC system[1],[2], the factors affecting the MI are divided into internal and external factors. The influence of the second harmonic component flowing inside the MMC and the falling the DC voltage of MMC converter when a fault occurs in the AC system in which the VSC HVDC converter is connected are considered as internal and external factors, respectively.

The traditional design for the MI of MMC is to find the minimum cost of IGBTs. In other word, the

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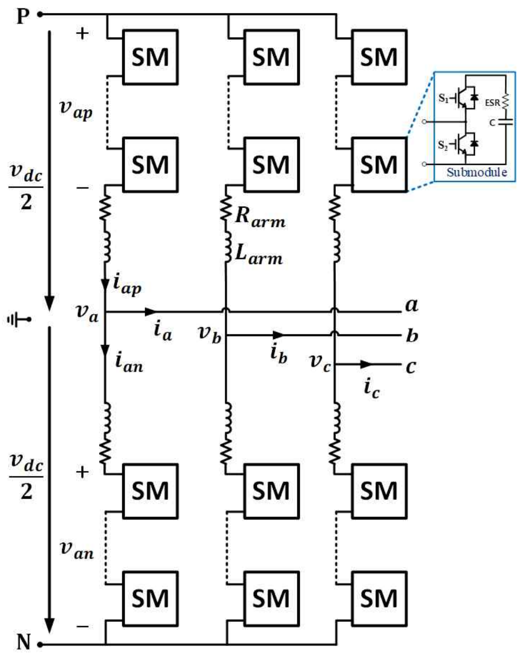

Fig. 2. MMC HVDC system topology.

design procedure focus on finding the minimum power loss point on the curve showing the relation between power loss and MI shown in Fig. 1. In the industrial practical converters, the MI is required to consider the stress exerted by the steady-state values and sufficient margin to allow for additional rise in currents and voltages during faults and abnormal operation mode of the MMC System. Fig. 1 illustrate the relation between Power loss and Modulation Index.

The basis for determining MI in the MMC converter is to avoid over-modulation condition. The over-modulation conditions in MMC converter can be caused by the following conditions.

- The AC network voltage suddenly changes (typically 10%).
- 2^{nd} harmonic current flows inside the converter.
- The negative sequence is compensated by the unbalance of the AC network.

2. Review of Previous Works

2.1 Fundamental of the Operation of MMC

Fig. 2 shows the three phase MMC HVDC topology and the half bridge submodule used to make each arms. The three phase converter is composed of three lags each having two arms. The arms of the MMC are constructed from a series connection of arm inductor and N half bridge submodules which have two IGBTs and a capacitor as shown in fig. 2. With this arrangement, the voltage of the submodule can be switched to zero or the capacitor voltage. Under this condition, the converter should be controlled in such a way that the DC-link voltage is constant and the capacitor voltages in all arms are balanced. The arm voltages and currents for phase A can be developed from the single phase equivalent circuit shown in fig. 3.

$$i_{ap} = \frac{I_{DC}}{3} + \frac{i_a}{2} \tag{1}$$

$$i_{an} = \frac{I_{DC}}{3} - \frac{i_a}{2} \tag{2}$$

$$v_{ap} = n_{ap} * N * v_{cap} \tag{3}$$

$$v_{ap} = n_{ap} * N * v_{cap} \tag{4}$$

Where i_{ap}, i_{an}, I_{DC} and i_a are the upper arm current, lower arm current, dc current and the phase A line current respectively. In Eq. (3) and (4), n_{ap} and n_{an} represents the insertion index of the upper and lower arm which are the ratio of the number of inserted submodule to the total number of submodule in one arm, N. v_{cap} and v_{can} are the capacitor voltages.

$$\frac{dv_{cap}}{dt} = \frac{1}{c_{sub}} * n_{ap} * i_{ap} \tag{5}$$

$$\frac{dv_{can}}{dt} = \frac{1}{c_{sub}} * n_{an} * i_{an} \tag{6}$$

In (5) and (6), c_{sub} is the capacitance of a single half bridge submodule. By applying KVL to the loops formed by the upper and lower arms with the output side, the mathematical representation of the ac equivalent circuit and the internal dynamics of the MMC can be given by Eq. 7 and 8, respectively[3].

$$v_a = \frac{(v_{an} - v_{ap})}{2} - \frac{L_{arm}}{2} * \frac{d(i_{ap} - i_{an})}{dt} - \frac{R_{arm}}{2} * (i_{ap} - i_{an}) \tag{7}$$

$$V_{DC} = (v_{an} + v_{ap}) + L_{arm} * \frac{d(i_{ap} + i_{an})}{dt} + R_{arm} * (i_{ap} + i_{an}) \tag{8}$$

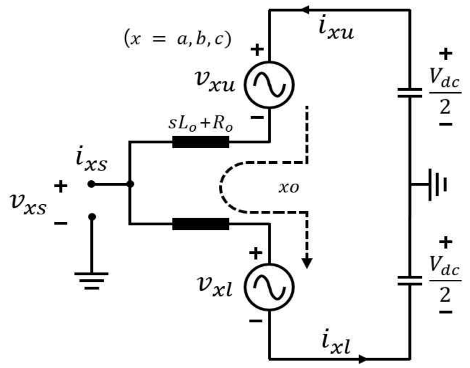

Fig. 3. Single-phase equivalent circuit of MMC.

Where R_{arm} and L_{arm} are the resistance and inductance of the arm inductor, and V_{DC} is the dc link voltage.

The DC currents, I_{DC}, is derived from the power balancing equation between the DC power and the active power at the output of the 3-phase converter.

$$p = V_{DC}{}^{*}I_{DC} = 3^{*}\frac{v_{apeak}{}^{*}i_{apeak}}{2}{}^{*}\cos(\phi) \tag{9}$$

With this I_{DC} the minimum capacitor has been calculated to be (10).

$$c_o = \frac{1}{2n\epsilon(V_c)^2}\frac{\cdot 2}{3}\frac{\cdot p_s}{\omega_N M}\cdot(1-(\frac{M\cdot\cos\phi}{2})^2)^{\frac{3}{\cdot 2}} \tag{10}$$

Where, n is the number of levels, ε is the relative voltage ripple, V_c is the average capacitor voltage, p_s is the output power, M is the Modulation Index, ω_N is the angular frequency of the output voltage and $\cos(\phi)$ is the displacement factor. From this formula it can be seen that the amount of capacitive energy storage is directly proportional to the output power of the inverter. Furthermore, it is inversely proportional to the output frequency. The AC voltage in (7) can be rewritten as (11).

$$\frac{L_{arm}}{2}\frac{d(i_a)}{dt}+\frac{R_{arm}}{2}i_a = -v_a + N.n_{a\_dm}\cdot v_{c\_a\_cm} + N.n_{a\_cm}\cdot v_{c\_a\_dm} \tag{11}$$

$$i_{a\_cm} = \frac{(i_{ap}+i_{an})}{2}, \qquad i_a = i_{ap}-i_{an} \tag{12}$$

$$v_{c\_a\_am} = \frac{v_{c\_an}+v_{c\_ap}}{2}, \quad v_{c\_a\_dm} = \frac{v_{c\_an}-v_{c\_ap}}{2} \tag{13}$$

$$n_{a\_cm} = \frac{n_{an}+n_{ap}}{2}, \quad n_{a\_dm} = \frac{n_{an}-n_{ap}}{2} \tag{14}$$

Where i_{a_cm}, is the common mode component of the arm currents. Similarly, the MMC inner dynamics can be rewritten as:

$$2L_{arm}\frac{di_{a\_cm}}{dt}+2R_{arm}i_{a\_cm} = V_{dc}-2N..n_{a\_cm}\cdot v_{c\_a\_cm}-2N.n_{a\_dm}\cdot v_{c\_a\_dm} \tag{15}$$

2.2 Modulation Index in MMC HVDC System

Modulation index is the ratio of the peak of the AC voltage which can be obtained from the converter to half of the DC voltage. Various mechanisms such as min/max offset method and third harmonic injection are being used to maximize the modulation index above unity.

2.2.1 Min/Max offset voltage method

A zero-sequence voltage, can be added to the phase output-voltage and is selected so that, at every time instant, the maximum and minimum values of the phase-voltage references are equal, but with opposite signs. The phase-voltage references become symmetrized, hence the name symmetrical references. This is obtained by selecting

$$v_o = -\frac{\max(v_{sa}^*, v_{sb}^*, v_{sc}^*)+\min(v_{sa}^*, v_{sb}^*, v_{sc}^*)}{2} \tag{16}$$

The peak value of the total waveform resulting from symmetrical references is the same as for 3rd harmonic injection, $\frac{\sqrt{3}v_s}{2}$, given a peak value of v_s for sinusoidal references.

2.2.2 Third harmonic injection

The 3rd harmonic injection which used in MMC control has the significant advantages over sinusoidal modulation, from the viewpoints of the system power losses, submodule capacitance, circulating current, and fault current. By injecting the 3rd harmonics, the DC voltage utilization ratio is increased from $\frac{1}{2}$ to $\frac{1}{\sqrt{3}}$.

Compared with sinusoidal modulation, the maximum output voltage peak with reference to the mid-point

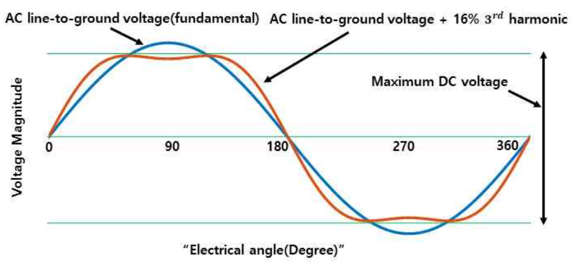

Fig. 4. Third harmonic injection.

of the DC link is reduced from $\frac{V_{DC}}{2}$ to $\frac{\sqrt{3}\,V_{DC}}{4}$ as demonstrated in Fig. 4, while the amplitude of the output fundamental voltage remains half of the DC voltage. That is, only $\frac{\sqrt{3}\,N}{2}$ of the SMs are utilized when third harmonic injection is used compared with the sinusoidal modulation which utilizes N SMs. The AC reference voltage with the 3rd harmonic injection is given in (17)~(18)[5].

$$v_{as}^{*} = A\cos(\omega t), \qquad v_{sn}^{*} = B\cos(3\omega t + \phi) \tag{17}$$

$$v_{an}^{*} = v_{as}^{*} + v_{sn}^{*} = A\cos(\omega t) + B\cos(3\omega t + \phi) \tag{18}$$

where $B = \frac{A}{6}, \qquad \phi = 0(rad)$

The 3rd harmonics injection has an additional advantage of reducing the SM capacitance by 24[%] compared to that when using sinusoidal modulation, which significantly reduces both the volume and capital cost of SMs. Additionally, station converter conduction losses are reduced by 11[%] by injecting a 3rd harmonic and hence the capacity of cooling system is reduced[5].

2.3 Modulation Index Considering Compensation Signal

The equivalent AC voltage can be obtained from fig. 2 and mathematically represented by (19)

$$v_{ac} = v_{ac}\cos(\omega t) = v_a + \frac{L_{arm}}{2}\frac{di_a}{dt} + \frac{R_{arm}}{2} i_a \tag{19}$$

From Eq. 10, the maximum capacitor voltage ripple depends on the converter operating range. Also, the maximum reactive power is usually defined as half of the maximum active power. So the minimum power factor for MMC operating at full apparent power is $\frac{\sqrt{3}}{2}$. Thus the maximum capacitor voltage ripple is given by 20.

$$V_{Ripple} = 0.73 * \frac{1}{c_{sub}} \frac{1}{4\omega} I_{ac} \tag{20}$$

where, maximum M=1 is considered. The coefficient 0.73 is related to the maximum reactive power limitation.

Thus it is reasonable to neglect $\triangle v_{c\_a\_cm}$ in the analysis.

$$v_{ac}\cos(\omega t) = v_{dc} \cdot n_{a\_cm} + N \cdot n_{a\_cm} v_{c\_a\_dm} \tag{21}$$

$$n_{a\_dm} = \frac{v_{ac}\cos(\omega t)}{v_{dc}} - \frac{N \cdot n_{a\_cm} v_{c\_a\_dm}}{v_{dc}} \tag{22}$$

As the circulating current control regulates i_{a_cm} to its DC component, the left hand side of (15) should be equal to zero considering R_{arm} is small.

$$2\triangle n_{a\_cm} v_{dc} + N \cdot \triangle v_{c\_a\_cm} + 2N \cdot n_{a\_dm} v_{c\_a\_dm} = 0 \tag{23}$$

$$\triangle n_{a\_cm} = \frac{1}{2v_{dc}} \frac{N}{c_{sub}} \frac{M}{8\omega} I_{ac} [-\frac{3}{2} sin(\phi)\cos(2\omega t) + (\frac{3}{2} - \frac{M^2}{2})\cos(\phi)\sin(2\omega t)] \tag{24}$$

It is shown that the compensating component is a 2nd harmonic, and is related to the system parameters (c_{sub} and N) and operating conditions (M, I_{ac} and ϕ). Based on (20), the maximum relative SM capacitor voltage ripple can be defined as in (25).

$$\varepsilon = 0.73 \cdot \frac{N}{v_{dc}} \frac{1}{c_{sub}} \frac{1}{4\omega} I_{ac} \tag{25}$$

Since ε can be considered as a fixed value, (24) can be simplified as in (26).

$$\triangle n_{a\_cm} = \epsilon \frac{M}{2.92} [-\frac{3}{2} sin(\phi)\cos(2\omega t) + (\frac{3}{2} - \frac{M^2}{2})\cos(\phi)\sin(2\omega t) \tag{26}$$

The insertion index for the lower arm (upper arm is similar) can be obtained as:

$$n_{an} = \frac{1}{2} + \frac{M}{2} cos(\omega t) + \epsilon \frac{M}{2.92} [\frac{3}{2} sin(\phi)\cos(2\omega t) + (\frac{3}{2} - \frac{M^2}{2})\cos(\phi)\sin(2\omega t)] \tag{27}$$

The insertion index should satisfy

$$0 \leq n_{an} \leq 1 \tag{28}$$

According to (27), the maximum and minimum of the lower arm insertion index are obtained when $\cos(\phi)$equals to its minimum value:

$$n_{ap}(\max) = 0.5 + (0.5 + 0.26\varepsilon).M \tag{29}$$
$$n_{an}(\max) = 0.5 - (0.5 + 0.26\varepsilon).M$$

Hence, from here it is possible to determine the maximum limit of the MI which is given in (30).

$$M \leq \frac{1}{1 + 0.52\varepsilon} \tag{30}$$

Also, in the case of the 3rd harmonic injection,

$$n_{a\_dm} = \frac{M}{2}[\cos(\omega t) - \frac{1}{6}cos(3\omega t)] \tag{31}$$

With the similar calculation in (20), the maximum relative capacitor voltage ripple can be obtained as in (32).

$$\varepsilon = 0.68.\frac{N}{v_{dc}}\frac{1}{c_{sub}}\frac{1}{4\omega}I_{ac} \tag{32}$$

The compensating component can then be calculated by (33).

$$\triangle n_{a\_cm} = \epsilon\frac{M}{2.72}[(\frac{19}{12} - \frac{7M^2}{12})\cos(\phi)\sin(2\omega t) - \frac{17}{12}sin(\phi)\cos(2\omega t)] \tag{33}$$

By calculating the maximum and minimum values of n_{an}, the limitation on the modulation index is obtained as in (34).

$$M \leq \frac{1}{0.87 + 0.70\varepsilon} \tag{34}$$

3. Modulation Index of MMC Considering System and AC Network Condition

3.1 Considering MMC System Conditions

As shown in (26), the capacitor variation is related to the MI of the MMC system. The factors affecting the capacitor voltage ripple are capacitor, frequency, DC voltage and AC current assuming that the capacitor value is changed by the aging or temperature, sensor error.

In a practical system, $\triangle v_{dc\_Error}$ and $\triangle I_{ac\_Error}$ are 0.5[%] which depend on the sensor error (PT and CT). The value for $\triangle c_{Error}$ is 5[%] which is determined by the aging characteristic curve of the capacitor. $\triangle \omega_{Error}$ means the frequency deviation during the abnormal condition of AC network which is often 3[%]. $\triangle N_{Error}$ is system error including sampling time error and control error and is normally below 1[%].

Equation (25) is changed to (35) by considering the MMC HVDC System conditions mentioned above.

$$\epsilon = 0.73.\frac{1}{2v_{dc}(1 + \triangle v_{dc\_Error})}\frac{N(1 + \triangle N_{Error})}{c} \tag{35}$$

For an MMC converter which operates with a pure sinusoidal AC voltage. “M” in the (35) is given by (30). In the case that the converter outputs the AC voltage with the 3rd harmonic, “M” is given by (34).

3.2 Considering AC Network Condition

To calculate MI for MMC system considering the AC network condition, the equation in (30) is changed to (36).

$$M \leq \frac{\alpha_1}{1 + \alpha_2} \tag{36}$$

In (36), the parameter α_2 is related to MMC HVDC condition while α_1 represent the AC network condition. Eq. 32 gives the modulation index with an expanded representation for parameter α_1. In (32) $\triangle v_{ac}^-$ is the AC negative sequence voltage with a value below 2[%], $\triangle v_{ac}$ is the AC voltage variation and $\triangle v_{load}$ is normally 5~10[%]). The Dead time, $\triangle T_{Dead}$, is also considered.

$$M \leq \frac{1 - (\triangle v_{ac}^- + \triangle T_{Dead} + \max(\triangle v_{ac} + \triangle v_{load})}{1 + 0.52\varepsilon} \tag{37}$$

In (37), the dead time effect in MMC system is negligible when the number of SMs is high. $\triangle v_{ac}$ is below 5[%] and 10[%] with a tap changer’s effect and without a tap changer effect, respectively.

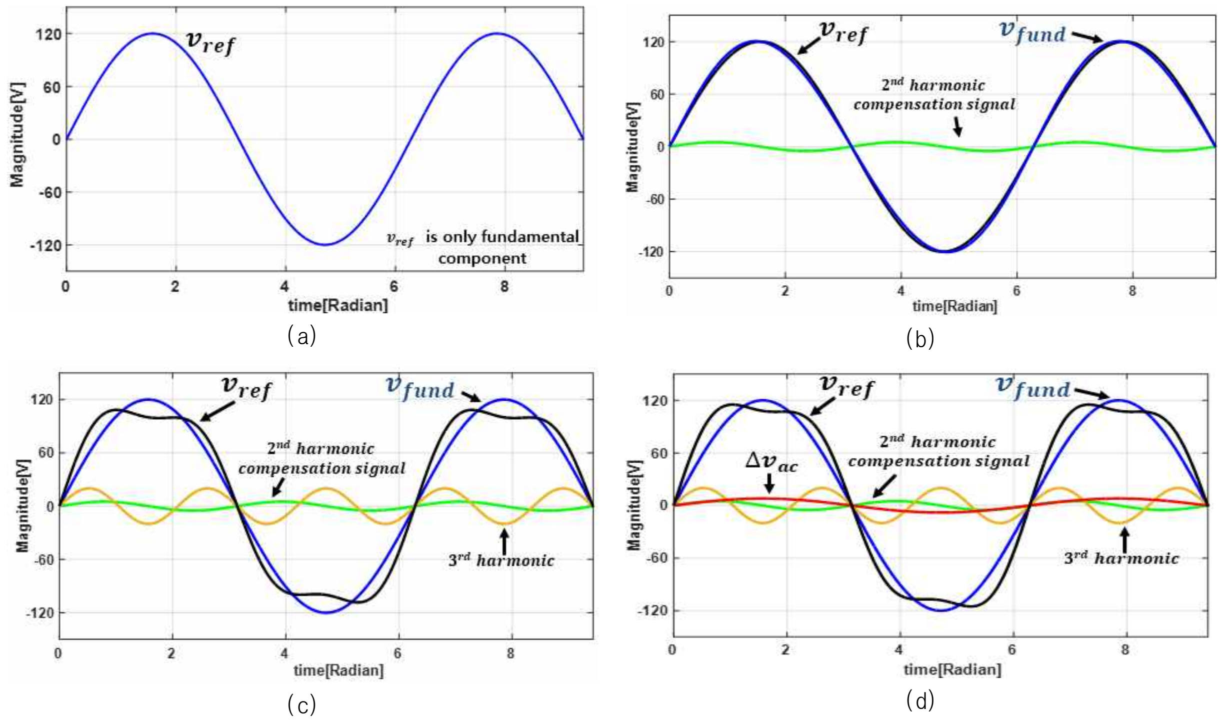

Fig. 5. Simulation Result.

TABLE I
MODULATION INDEX EQUATIONS WITH AND WITHOUT 3rdHARMONIC

Without 3rdHarmonic	With 3rdHarmonic
$M \le \frac{\alpha_1}{1+0.577\epsilon}$	$M \le \frac{\alpha_1}{0.87+0.777\epsilon}$

TABLE II
MAXIMUM MI WITH α_1=12[%]

Without 3rdHarmonic	With 3rdHarmonic
$M \le \frac{0.88}{1+0.577\epsilon}$	$M \le \frac{0.88}{0.87+0.777\epsilon}$
$\epsilon = 0.1$	$\epsilon = 0.1$
$M \le 0.832$	$M \le 0.929$

By calculating the value of α_2 using (35) where $\triangle v_{dc\_Error}$, $\triangle I_{ac\_Error}$ and $\triangle c_{Error}$ are 5[%], $\triangle \omega_{Error}$ is 3[%] and $\triangle N_{Error}$ is 1[%] gives the maximum MI equation summarized in Table I.

Case 1) α_1=12[%]
($\triangle v_{ac}^{-}$=2[%] and $\triangle v_{ac}$=10[%](with tap changer))

The maximum modulation index then is calculated for different values of α_1 and the results are shown in Table II and Table III. The value of α_1 is determined by the value of the $\triangle v_{ac}$ and $\triangle v_{ac}^{-}$. Table II shows the maximum modulation index calculated for α_1=12[%]. In Table III the maximum MI when α_1=7[%] with and without third harmonic injection.

TABLE III
MAXIMUM MI WITH α_1=7[%]

Without 3rdHarmonic	With 3rdHarmonic
$M \le \frac{0.93}{1+0.577\epsilon}$	$M \le \frac{0.93}{0.87+0.777\epsilon}$
$\epsilon = 0.1$	$\epsilon = 0.1$
$M \le 0.879$	$M \le 0.982$

Case 2) α_1=7[%]
($\triangle v_{ac}^{-}$=2[%] and $\triangle v_{ac}$=5[%](with tap changer))

4. Simulation Result

Fig. 5(a) shows the AC reference voltage which is completely a fundamental component. In fig. 5(b) the second harmonic compensation signal (circulating current compensation) is added to the waveform in fig. 5(a). In this case the reference signal is a little bit distorted and different from the fundamental component. This affects the modulation index of the MMC to be changed. The 15[%] voltage drop in the pick value of the reference voltage in fig. 5(c) while the fundamental component is maintained at a similar value to fig. 5(a) is due to a third harmonic injection. This shows that it is possible to increase the reference voltage without causing saturation and hence possible to get a fundamental component higher than the one given in fig. 5(a). This indicates that the third harmonic injection increases the modulation index of the MMC system. Finally, the waveform in fig. 5(d) is the reference voltage and fundamental component voltage when all the second harmonic compensation, a 10[%]AC voltage variation and third harmonic injections are included. The AC voltage variation makes the reference higher than the one in fig. 5(c) while the fundamental component is still the same with fig. 5(d). Therefore, the AC voltage variation decreases the modulation index of the MMC system.

5. Conclusion

In addition to the second harmonic component imposed on the modulation signal by the circulating current suppression controller, the AC voltage variation and load voltage variation affect the modulation index of MMC system. In this paper a mathematical representation for the maximum modulation index considering the AC network condition is derived. The simulation result is also given to show the relationship between the modulation index and various factors such as circulating current controller, third harmonic injection and the AC voltage variation.

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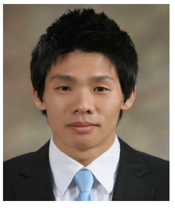

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