Analysis of Average Neutral Point Current in 3-level NPC Converter under Generalized Unbalanced AC Input Condition

Kyungsub Jung and Yongsug Suh

Dept. of Elec. Eng., Smart Grid Research Center, Chonbuk Nat'l. Univ.

Abstract

This paper presents a neutral point deviation compensating control algorithm applied to a 3-level NPC converter under generalized unbalanced ac input conditions. The neutral point deviation is analyzed with a focus on the current flowing out of or into the neutral point of the dc-link in 3-level NPC converter. The model of neutral point deviation and neutral current are also constructed. The positive and negative sequence components of the pole voltages and ac input currents are employed to accurately explain the behavior of 3-level NPC converter and its impact on neutral point deviation. This paper includes the harmonic characteristic of neutral point current under various imbalance AC operating conditions.

1. Introduction

Multi-level converters are widely used in high-power applications such as motor drives, utility applications, and, most recently, in wind generation systems. Extensive research has been carried out/on multilevel topologies, modulation, and control strategies [1]. Multilevel converters can provide more than two voltage levels at the output. As a result, the voltage and current waveforms generated have lower Total Harmonic Distortion (THD). Consequently, high voltages can be handled on both the dc and ac sides of the converter [2]. The multilevel converter topology that is most extensively applied at present is the Neutral-Point-Clamped (NPC) converter, which is a 3-level NPC Voltage Source Converter (VSC) in Fig. 1. One of the essential problems of the 3-level NPC converters is that how to keep the voltage of dc-link capacitors balanced, in other words, keep the Neutral-Point (NP) potential stable and suppress the ripple. If the NP potential is not controlled effectively, the output voltage of the converter would deviate from the reference value; moreover, the devices and equipment might be damaged [3]. In practical operations of 3-level NPC VSC, the NP potential variation, i.e. the unbalanced dc-link voltages often lead to a frequent trip of converters due to the over-voltage of either upper dc-link capacitor or lower dc-link capacitor.

If Space Vector PWM (SVPWM) is used, the voltage vectors can be classified into four categories by their magnitude: zero, small, middle, and large vectors. Then, the relationship between NP potential and each switching state vector can be analyzed. It is known that the zero vectors and large vectors have no effect on NP potential, but the middle vectors and small vectors can have an influence on it. It is noticed that there are two switching states (positive and negative) that have reverse action (charging or discharging) on NP potential for one small vector. Therefore, the main task is set to adjust the dwell time between the duplicate switching states of small vectors [4]–[9]. In many solutions of the SVPWM strategies for the 3-level NPC converter, one or two switching sequences are strictly assigned to specific subsectors [10], [11]. The control strategies of the dc-link voltage balance are based on the change of switching sequences depending on the unbalanced dc-link voltage. When Carrier-Based PWM (CBPWM) is used, the control of the NP potential can be considered as the problem of identifying the zero sequence voltage. The zero sequence voltage added to the reference voltages does not change the output line voltages, but influences the switching states and of course the NP potential. The NP potential variation caused by the injected zero sequence voltage has been studied, and some algorithms to keep the NP potential balancing by injecting the appropriate zero sequence voltage were presented [12].

Among many possible causes of NP deviation in 3-level NPC converters, unbalanced grid supply can generate NP deviation of significant level. The impact of unbalanced grid input on the NP deviation and suitable compensating control strategies have been paid less attention considering its importance in a practical operation. Also, none of previous works have deeply analyzed the relationship between unbalanced grid condition and NP deviation under the wide range of unbalanced condition within a 3-level NPC converter. This paper proposes a CB-PWM strategy for a 3-level NPC converter with a zero sequence voltage injection. In this paper, the variation of the neutral point potential is analyzed on the basis of an average current flowing out of or into the neutral point. It is shown that the zero sequence voltage of the NPC-VSI output has an important influence upon the neutral potential variation. The principle of the neutral point potential control by adding a suitable zero sequence voltage is also described. Moreover, this paper proposes NP deviation control scheme for the 3-level NPC converter under generalized unbalanced grid operating conditions. The positive and negative sequence components of the pole voltages and ac input currents are employed to accurately explain the behavior of 3-level NPC converter and its impact on NP deviation.

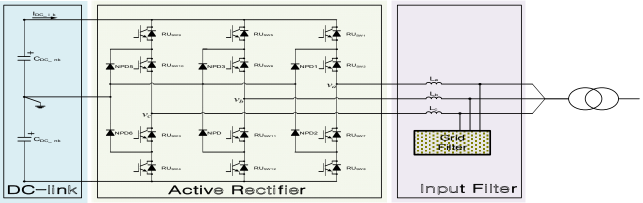

Fig. 1. 3-level NPC voltage source converter

2. Relationship between Neutral Point Deviation and Average Neutral Current

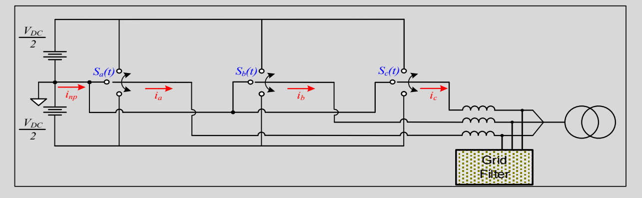

Fig. 2. Simplified 3-level NPC converter model using SPTT (Single-pole-Triple-Throw) Switches

Figure 2 describes simplified 3-level NPC converter using Single-Pole-Triple-Throw switches. Average neutral current and zero sequence voltage components in dc-link are expressed as following. In general, neutral current can be described by each phase current and switching function as in (1)-(2). Neutral current can be explained by fundamental voltage of switching function and its corresponding current as in (3).

$$V_{ss} = (S_a, S_b, S_c), S_x = [-1,0,1] \,\&\, x = a,b,c \tag{1}$$

$$\begin{aligned} i_{np}(t) &= [1-|S_a|]\cdot i_a + [1-|S_b|]\cdot i_b + [1-|S_c|]\cdot i_c \\ &= -(|S_a|\cdot i_a + |S_b|\cdot i_b + |S_c|\cdot i_c) \end{aligned} \tag{2}$$

$$i_{np} = -(2/V_{dc})(|v_a|\cdot i_a + |v_b|\cdot i_b + |v_c|\cdot i_c) \tag{3}$$

3. Analysis of Neutral Point Deviation based on Generalized Unbalanced 3-phase Grid Conditions

Under unbalanced ac grid conditions, the three-phase input currents flowing through the input filter stage of the grid-side converter also become unbalanced if any proper compensating control measures are not employed. This means that the ac input currents start to contain the negative sequence component under unbalanced grid input. This negative sequence component of ac input current further deteriorates the neutral point deviation of 3-level NPC converter on top of typical causes of dc-link imbalance such as the mismatch of upper and lower dc-link capacitance, switching dead time, asymmetric modulation effects, etc. Therefore, in order to correctly explain the behavior of neutral point deviation and neutral point current under the ac grid imbalance, the negative sequence components of ac input current as well as converter output voltage at the pole of converter should be incorporated into the description of neutral current in (4). The symmetric components of ac input current and converter output voltage are defined as shown in (5). The description of neutral current given in (6) provides useful information in understanding the relationship between the ac grid imbalance condition and neutral potential deviation of 3-level NPC converter. In (6), the values of coefficients (X, Y, Z) depend on the particular sign combination of converter output voltages.

$$i_{np}(t) = -\frac{2}{V_{dc}}\left\{\begin{array}{l} \mathrm{sgn}(v_{a\_fund})\cdot(v_{ap}+v_{an}+v_o)\cdot(i_{ap}+i_{an}) + \mathrm{sgn}(v_{b\_fund})\cdot(v_{bp}+v_{bn}+v_o)\cdot(i_{bp}+i_{bn}) \\ +\,\mathrm{sgn}(v_{c\_fund})\cdot(v_{cp}+v_{cn}+v_o)\cdot(i_{cp}+i_{cn}) \end{array}\right\} \tag{4}$$

$$\begin{cases} v_{a\_fund} = v_{ap}+v_{an}+v_o, \quad v_{b\_fund} = v_{bp}+v_{bn}+v_o, \quad v_{c\_fund} = v_{cp}+v_{cn}+v_o \\ i_a = i_{ap}+i_{an}, \quad i_b = i_{bp}+i_{bn}, \quad i_c = i_{cp}+i_{cn} \end{cases} \tag{5}$$

$$i_{np}(t) = -(1/V_{dc})\{(X+Z)+(X-Z)\cos 2\omega t + Y\sin 2\omega t\} \tag{6}$$

4. Characteristics of Neutral Point Current under Generalized Unbalanced 3-phase Grid Conditions

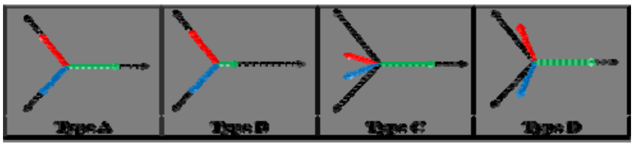

Fig. 3. Generalized 3-phase imbalance conditions (Type A: voltage sag of 3Ø, Type B: voltage sag of 1Ø, Type C: single-line ground fault in delta-wye transformer, Type D: double-line ground fault in delta-wye transformer

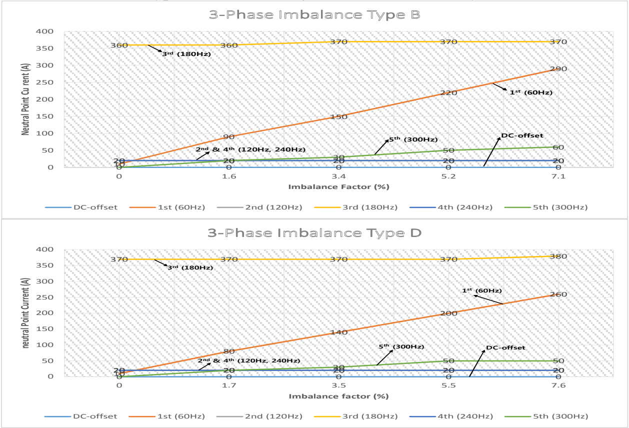

Fig. 4. Frequency components of neutral point current under unbalanced 3-phase grid condition (from the top: Type B and Type D)

Figure 4 presents the frequency spectrum of neutral current under two different types of unbalanced ac grid; Type B and Type D. The dominant low-order harmonic components up to 5th-order as well as the dc offset and fundamental component of neutral point current are plotted with respect to various Imbalance Factor values. It is noted from Fig. 4 that even under normal balanced grid input condition the neutral current is rich in 3rd-order harmonic component. This observation is consistent with the model of (3). In (3), the product terms of the absolute value of converter output voltage and ac input current result in the neutral current of 3rd-order harmonic. As the depth of unbalanced ac grid becomes severe, i.e. increasing IF, the amplitude of fundamental frequency component increases almost linearly while having relatively constant 3rd-order harmonic component as shown in Fig. 4. Both Type B and D exhibit a similar pattern of increased fundamental component vs. increased IF.

5. Conclusion

This paper presents the analysis of the neutral point potential variation of 3-level NPC converter under unbalanced ac grid conditions. An analysis is carried out based on the average current flowing at the neutral point of the dc-link. A control scheme to keep the dc-link voltages balanced is also proposed. The neutral point potential variation can be eliminated or reduced by controlling the zero sequence component of converter output voltage. In this paper, control scheme for compensating a neutral point deviation under unbalanced ac grid conditions is also investigated. This control scheme can be effectively analyzed by using both positive and negative sequence components of converter output voltages and ac input currents.

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