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Three-Phase Cascaded High-Frequency Link Matrix Rectifier and Its Commutation Strategy (Postprint)

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Abstract

A three-phase line voltage cascaded high-frequency link matrix rectifier (LVCHLFMR) topology for high-voltage applications is proposed. This topology consists of a three-phase line voltage cascaded converter based on HLFMR unit modules, a high-frequency transformer, and a single-phase rectifier, enabling direct connection to three-phase systems. It offers advantages including a reduced number of switches, elimination of DC energy storage elements, and a compact structure. The modulation strategy of HLFMR is analyzed, and based on this, an improved commutation strategy for HFLMR is proposed to address the characteristics of the three-phase bridge direct cascaded structure. This strategy resolves the load open-circuit problem encountered with conventional commutation and the instantaneous inter-phase short-circuit issue that arises when the converter operating state transitions to the zero vector. Simulation results validate the correctness of the proposed topology and the effectiveness of the improved commutation strategy.

Full Text

Preamble

Three-Phase Line-Voltage-Cascaded High-Frequency Link Matrix Rectifier and Its Commutation Strategy

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Abstract

This paper proposes a three-phase line-voltage-cascaded high-frequency link matrix rectifier (LVC-HLFMR) topology for high-voltage applications. The topology consists of a three-phase line-voltage-cascaded converter based on HLFMR unit modules, a high-frequency transformer, and a single-phase rectifier. It can be directly connected to three-phase systems and offers advantages such as reduced switch count, elimination of DC energy storage elements, and compact structure. The modulation strategy for HLFMR is analyzed, and based on this, an improved commutation strategy is proposed that addresses the specific characteristics of the three-phase bridge direct-cascade structure. This strategy solves the load open-circuit problem that occurs with conventional commutation and prevents instantaneous inter-phase short circuits when the converter operating state switches to the zero vector. Simulation results verify the correctness of the proposed topology and the effectiveness of the improved commutation strategy.

Keywords: Line-voltage-cascaded, high-frequency link matrix rectifier, space vector modulation, one-step commutation

1 Introduction

Three-phase cascaded power converters are multilevel converters constructed by cascading traditional two-level six-switch power converters through line voltage. They offer advantages including increased voltage level, low harmonic content, easy modularization, and strong scalability. Compared with three-phase cascaded converters based on single-phase H-bridges, this approach uses fewer switches, reduces required DC capacitors, and exhibits smaller DC-side voltage ripple, making it more suitable for high-voltage applications.

In 1999, scholars such as E. Cengelci proposed the line voltage cascade (LVC) topology for medium-voltage adjustable speed drive systems, demonstrating through simulation its advantages of low voltage change rate and low harmonic content. Jun Wen and Keyue Smedley proposed obtaining six-phase output by serially connecting the outputs of six three-phase two-level voltage source inverters through current-limiting inductors, applying this to adjustable-speed six-phase motors. Reference [1] presented a three-phase line-voltage-cascaded structure formed by directly cascading the three-phase bridge arms of three three-phase full-bridge inverters, where the output line voltage is the superposition of submodule line voltages. Reference [2] proposed a novel line-voltage-cascaded structure by altering the connection method of three-phase bridge arms to facilitate easier expansion to higher cascade numbers. Most of these studies focused on three-phase cascaded converters based on traditional two-level six-switch power converters, whose DC capacitors in the intermediate stage not only reduce system reliability but also increase system volume and cost.

For reasons such as voltage level transformation, safety, and isolation, converters often require isolated structures. The high-frequency link matrix rectifier (HFLMR) consists of a reduced matrix converter (RMC), high-frequency transformer, and single-phase rectifier circuit. This structure simplifies the three-stage architecture of traditional isolated rectifiers into a two-stage configuration, eliminating the intermediate DC stage while maintaining good input-output characteristics. Building upon this, this paper proposes the line-voltage-cascaded high-frequency link matrix rectifier (LVC-HLFMR) structure, which uses HFLMR as unit modules cascaded through line voltage to form a multi-module cascaded converter for high-voltage, high-power applications. Its features include: (1) compact structure without DC energy storage elements; (2) good input characteristics with four-quadrant operation capability; (3) high-frequency transformers replacing line-frequency transformers, reducing transformer volume and weight; (4) direct three-phase line voltage cascading, saving switch count.

Commutation strategy is one of the key technologies for LVC-HLFMR practical implementation. Current research on HFLMR commutation strategies is relatively mature, with common methods including two-step commutation, four-step commutation, and semi-natural one-step commutation. Compared with two-step or four-step commutation, semi-natural one-step commutation is more promising for practical applications because the polarity of voltage across each switch and direction of current can be determined in every switching cycle, making the method simple and requiring no device detection. The three modules of LVC-HLFMR use identical switching signals, and simply applying HFLMR commutation strategies would result in load open-circuit conditions in individual modules during commutation. Therefore, this paper proposes a one-step commutation strategy suitable for LVC-HLFMR based on its structural characteristics, avoiding potential load open-circuit and instantaneous inter-phase short-circuit problems during commutation. A simulation model of the LVC-HFLMR system was established, and simulation results verify the correctness and feasibility of the proposed topology and its commutation strategy.

2 LVC-HFLMR Topology Structure

[Figure 1: see original paper] shows the LVC-HFLMR topology, which consists mainly of three high-frequency link matrix rectifier modules. The AC side is formed by line-voltage cascading of three reduced matrix converters. The RMC converts input line-frequency AC into positive and negative alternating high-frequency pulse electricity. After voltage level transformation and electrical isolation through high-frequency transformers, diode full-bridge rectification converts it to DC, and the outputs of the three rectifier circuits are paralleled to supply the load.

The midpoints of the three-phase bridge arms in LVC-HFLMR are denoted as a1, b1, c1, a2, b2, c2, and a3, b3, c3. For simplified analysis, based on the connection method shown in [Figure 1: see original paper] and Kirchhoff' s current law, when selecting switches, only the phase with maximum current in the three-phase input needs to be considered.

Let the currents flowing into each bridge arm be iki (k = a, b, c; i = 1, 2, 3). Assuming symmetrical three-phase input currents with RMS value I, we have:

$$i_a = i_{a1} = \sqrt{2}I \sin \omega t \tag{1}$$
$$i_b = i_{b2} = \sqrt{2}I \sin(\omega t - 120^\circ) \tag{2}$$
$$i_c = i_{c3} = \sqrt{2}I \sin(\omega t + 120^\circ) \tag{3}$$

Considering that each submodule employs synchronous control and based on the connection characteristics, during space vector modulation, taking Sector 1 as an example, only two line voltages uab and uac act, with current relationships:

$$i_{b1} = i_b \tag{4}$$
$$i_{a3} = -i_c \tag{5}$$
$$i_{c2} = 0 \tag{6}$$

The average line voltage in Sector 1 is uab = uac, with symmetric and equal action times for the two line voltages, yielding ia3 = ib1. In Sector 1, the fundamental component satisfies ia3 + ib1 + ic2 = 0. Similarly, equation (5) holds in every sector. Combining equations (2)-(5), the three bridge arm currents for each module are:

$$i_{a1} = \sqrt{2}I \sin \omega t \tag{7}$$
$$i_{b1} = \sqrt{2}I \sin(\omega t - 150^\circ) \tag{8}$$
$$i_{c1} = \sqrt{2}I \sin(\omega t + 150^\circ) \tag{9}$$
$$i_{a2} = \sqrt{2}I \sin(\omega t + 30^\circ) \tag{10}$$
$$i_{b2} = \sqrt{2}I \sin(\omega t - 120^\circ) \tag{11}$$
$$i_{c2} = \sqrt{2}I \sin(\omega t + 90^\circ) \tag{12}$$
$$i_{a3} = \sqrt{2}I \sin(\omega t - 30^\circ) \tag{13}$$
$$i_{b3} = \sqrt{2}I \sin(\omega t - 90^\circ) \tag{14}$$
$$i_{c3} = \sqrt{2}I \sin(\omega t + 120^\circ) \tag{15}$$

Although the three bridge arm currents in each submodule are asymmetric, the input phase currents drawn from each module have the same amplitude as the module currents. Considering synchronous switching action, the three RMC modules can be equivalently simplified for analysis.

Neglecting switching losses, the simplified equivalent circuit of the high-frequency transformer is shown in [Figure 2: see original paper] [5], where Ls is the equivalent leakage inductance; Cp is the primary-side distributed capacitance; Cs is the secondary-side circuit capacitance referred to the primary side; R1 is the internal resistance of the source; and R2 is the referred load winding resistance.

In the equivalent circuit of [Figure 2: see original paper], the high-frequency transformer input side is the high-frequency output of the RMC without DC capacitors, while the output side has DC capacitors. Considering that the DC capacitor value is much larger than the transformer distributed capacitance, and the secondary resistance is negligible compared to the load resistance, the equivalent circuit of the isolation stage in operating state is obtained as shown in [Figure 3: see original paper].

In each operating state, current flows through only two of the three modules. The high-frequency pulse electricity on the transformer secondary side is rectified and output in parallel, with an equivalent ideal transformer voltage ratio of n/2. Assuming balanced three-phase sources with zero internal resistance, La = Lb = Lc = L, identical device parameters for each module, and transformer turns ratio n, we can derive the following.

From [Figure 1: see original paper], the LVC-HFLMR AC-side line voltages are:

$$u_{ab} = u_{a1b1} + u_{a2b2} \tag{16}$$

$$u_{bc} = u_{b2c2} + u_{b3c3} \tag{17}$$

$$u_{ca} = u_{c3a3} + u_{c1a1} \tag{18}$$

The equivalent circuit of LVC-HFLMR is shown in [Figure 4: see original paper]. The functional structure is identical to the high-frequency matrix rectifier. Although cascading more components inevitably introduces additional device losses, the voltage stress sharing among cascaded devices is highly significant for meeting high-voltage-level system requirements.

3 LVC-HFLMR Modulation Strategy

Considering that the three modules employ identical switching signals, the analysis here focuses on the modulation strategy for a single HFLMR module. Bipolar-Current-Space Vector Modulation (B-C-SVM) can achieve sinusoidal input current, adjustable power factor, low output voltage/current ripple, and low switching losses, making it currently the most suitable modulation strategy for HFLMR. Unlike traditional current space vector modulation, to obtain positive and negative alternating high-frequency pulse electricity, the input current is synthesized using two groups of basic vectors with opposite polarities and a zero vector, resulting in both positive and negative output polarities—hence the name bipolar current space vector modulation.

Using the sector division shown in [Figure 5: see original paper], which differs from the traditional 6-sector division of B-C-SVM, the HFLMR input current space vector complex plane is divided into 12 sectors. In each sector, the relative magnitudes of the three-phase input voltages are determined. For example, in Sector 1, ua > uc > ub, and in Sector 2, ua > ub > uc. During vector synthesis, the vector corresponding to the lower line voltage is selected to act first. As shown in [Figure 5a: see original paper], when the required synthesized vector Ir is located in Sector 1, vectors Iab and Iac are selected for synthesis. The corresponding line voltages are uab and uac, and in Sector 1, uab > uac. In this case, Iac is selected to act first to ensure that during vector switching, the operating voltage always switches from uac to uab, enabling natural commutation. Since the matrix rectifier output is high-frequency electricity, the required synthesized input current vector is composed of five vectors: two active vectors adjacent to the reference input phase current sector (for obtaining positive output current Im), two active vectors with opposite polarity (for obtaining negative output current -Im), and a zero vector. Taking Sector 1 as an example, the input phase current is synthesized from Iab, Iac, Iba, Ica, and Iaa.

Let the three-phase input voltages be:

$$u_a = \sqrt{2}U \sin \omega t \tag{19}$$

$$u_b = \sqrt{2}U \sin(\omega t - 120^\circ) \tag{20}$$

$$u_c = \sqrt{2}U \sin(\omega t + 120^\circ) \tag{21}$$

Taking the vector synthesis sequence diagram for Sector 1 shown in [Figure 6: see original paper] as an example, when the reference current Ir is located in Sector 1, the first half of a switching period synthesizes Ir using two active vectors Iab, Iac adjacent to the sector and a zero vector. At this time, the RMC outputs forward current Im, and the transformer primary voltages are Uab, Uac. The corresponding vector action time calculations are:

$$T_1 = T_{ab} = T_{ba} = mT_s \sin(60^\circ - \theta_i) \tag{22}$$

$$T_2 = T_{ac} = T_{ca} = mT_s \sin(\theta_i) \tag{23}$$

$$T_0 = T_s - T_{ab} - T_{ac} \tag{24}$$

where Ts is the switching period, m is the modulation index, and i is the angle between the reference current vector and the I1 vector, with i = ωt - ϕ + 30°.

The vector synthesis method for the first half-period is shown in [Figure 7: see original paper].

The second half-period is similar to the first half-period. To obtain current with opposite polarity to the first half-period, vectors Iba and Ica adjacent to Sector 7 are used. The transformer primary voltages are Uba and Uca, with switching signals opposite to those in the first half-period. At this time, the RMC outputs reverse current -Im. The duty cycles of the basic vectors depend only on i and m, which remain constant within one period, so the basic vector duty cycles in the second half-period are identical to those in the first half-period, resulting in positive and negative alternating high-frequency electricity within one period.

Considering only the three-phase input phase currents, the average current for the first half-period is:

$$i_{a1} = i_{b2} = i_{c3} = \frac{(T_1 + T_2)I_m}{T_s} - \frac{T_{1I}m}{T_s} - \frac{T_{2I}m}{T_s} = \sqrt{2}I_m \cos(\omega t - \phi)$$

The vector action times in the second half-period are the same as those of the corresponding vectors in the first half-period, yielding identical average current values. Substituting i = ωt - ϕ + 30° gives:

$$i_a = i_{a1} = \sqrt{2}I_m \cos(\omega t - \phi) \tag{25}$$

$$i_b = i_{b2} = \sqrt{2}I_m \cos(\omega t - \phi - 120^\circ) \tag{26}$$

$$i_c = i_{c3} = \sqrt{2}I_m \cos(\omega t - \phi + 120^\circ) \tag{27}$$

These equations demonstrate that the three-phase input currents are sinusoidal and symmetrical. Adjusting the angle ϕ between the reference vector and input voltage vector can regulate the input power factor.

4 LVC-HFLMR One-Step Commutation Strategy

In the defined 12 sectors, the relative magnitudes of the three-phase voltages in each sector remain stable. In the modulation strategy described above, to increase voltage utilization and minimize switching losses, the phase with the maximum absolute voltage remains continuously conducting, while commutation occurs between the other two phases with the same polarity. For example, in Sector 1, ua > 0, uc < 0, ub < 0, and commutation occurs between phases b and c. By selecting an appropriate vector action sequence, one-step natural commutation can be achieved for the proposed topology.

The commutation process is illustrated for the first PWM period half-cycle in Sector 1, where "1" indicates the upper bridge arm is conducting, "0" indicates the lower bridge arm is conducting, "X" indicates both upper and lower bridge arms are off, and "S" indicates both upper and lower bridge arms are conducting, putting the bridge arm in a shoot-through state.

(1) During the transition from switching state 1X0 to 10X, the transformer primary voltage changes from uac to uab. While turning on Sbl (both IGBTs of the bidirectional switch receive turn-on signals simultaneously) and turning off Scl, because the IGBT turn-on time is much shorter than its turn-off time, the transformer primary side does not experience an open circuit. Moreover, since uc > ub, no inter-phase short circuit occurs between phases B and C. The operating current switches from iac to iab, a process of natural commutation where the switch achieves soft turn-off.

At this moment, the current changes from flowing through modules 1 and 3 to flowing through modules 1 and 2. The current paths before and after commutation are shown in [Figure 8: see original paper] and [Figure 9: see original paper]. Since the C-phase bridge arms of each module are not conducting, the transformer primary side of the third module becomes open-circuited, as shown in [Figure 10: see original paper]. In this case, turning on Sal in the third module to make the A-phase bridge arm shoot-through provides an energy discharge path for the transformer leakage inductance.

The switching actions during this commutation process are shown in [Figure 11: see original paper]. Here, S3al represents the lower switch of the A-phase bridge arm in the third module. S3al is turned off by changing its switching signal to low level after the leakage inductance current of the third module drops to zero.

Similarly, in the defined 12 sectors, the relative magnitudes of the three-phase inputs in each sector are determined. By arranging a reasonable active vector action sequence, one-step natural commutation can be achieved during active vector switching.

(2) During the transition from switching state 10X to SXX, the transformer primary voltage changes from uab to zero. The converter transitions from conducting Sah and Sbl to shoot-through of Sah and Sal to provide a discharge path for transformer leakage inductance. At this point, if direct one-step commutation is applied—turning off Sbl while turning on Sal—since phase A voltage is maximum, Sal+ carries the current shown in [Figure 12: see original paper]. The current through Sbl does not drop immediately due to turn-off delay; instead, it experiences a transient overshoot because the current flowing through Sal+ and the gradually increasing transformer primary current both flow through Sbl- before beginning to decline until turn-off is complete. This process creates a brief inter-phase short circuit between phases A and B, causing a current transient overshoot in switch Sbl-, which is detrimental to safe switch operation.

To avoid the inter-phase short circuit during commutation, a two-step commutation concept is adopted when the transformer primary voltage transitions from uab to zero. Only Sal- is turned on initially. Similar to the previous analysis, current continues to flow through Sbl. Then Sbl is turned off, and current is forcibly commutated to Sal-.

The switching actions during this commutation process are shown in [Figure 13: see original paper]. The commutation process in other sectors is similar to Sector 1: natural commutation occurs during working vector switching with soft turn-off of switches, while forced commutation occurs when switching to the zero vector. Since switch turn-off time is much longer than turn-on time, switching signals can still be applied simultaneously to both switch groups to achieve one-step commutation.

5 Simulation Study

Based on the theoretical analysis above, a simulation model of LVC-HFLMR and its control system was built in Matlab/Simulink. The simulation parameters are as follows: rated grid-side input phase voltage 220 V, rated frequency 50 Hz, DC inductance L0 = 10 mH, DC capacitance C0 = 1 F, load resistance R = 2 Ω, and switching frequency 10 kHz. The system simulation waveforms are shown in [Figure 14: see original paper].

[Figure 14a: see original paper] through [Figure 14c: see original paper] demonstrate that LVC-HLFMR can achieve near-unity power factor operation with stable DC output voltage. [Figure 14d: see original paper] shows the transformer primary voltage waveform; in each switching period, the vector corresponding to the lower line voltage acts first during vector synthesis to ensure natural commutation. Comparing [Figure 14e: see original paper] and [Figure 14f: see original paper] reveals that only two modules operate in each working state. The improved commutation strategy provides an energy discharge path for transformer leakage inductance in non-operating modules, preventing primary-side open circuits in non-operating transformers. Moreover, each transformer experiences non-operating status for only 1/3 of a period, reducing peak voltage and lowering primary voltage, thereby improving system safety.

6 Conclusion

(1) This paper proposes an LVC-HLFMR topology with direct three-phase cascading on the input side and parallel connection on the output side. Compared with three-phase cascaded structures based on single-phase H-bridges, this topology reduces switch count, eliminates DC-side capacitors, effectively increases switch voltage rating, and uses high-frequency transformers instead of traditional transformers, resulting in smaller system volume, more compact structure, lower cost, and good application prospects in three-phase high-voltage systems.

(2) Based on the one-step commutation strategy for HFLMR, the input phase currents are divided into 12 sectors. According to the relative magnitude relationships of the three-phase input voltages in each sector, the vector

switching sequence for each sector is determined, and appropriate switching sequences are selected to achieve safe commutation for LVC-HLFMR, simplifying commutation logic and improving commutation reliability.

(3) For modules that may experience load short circuits during LVC-HLFMR commutation, a bridge arm is shoot-through to provide an energy discharge path for transformer leakage inductance. Using the concept of two-step commutation avoids instantaneous short-circuit problems when switching to the zero vector, enhancing the safety and reliability of the commutation strategy.

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