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

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**Date:** 2018-06-15T00:00:00+00:00

## Abstract

A three-phase line voltage cascaded high-frequency link matrix rectifier (LVC-HLFMR) topology for high-voltage applications is proposed. The topology comprises 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 features advantages including a reduced switch count, elimination of DC energy storage elements, and a compact structure. The modulation strategy of HLFMR is analyzed, and an improved commutation strategy for HFLMR is subsequently proposed to address the characteristics of the three-phase bridge direct cascaded configuration. This strategy resolves the load open-circuit issue encountered with conventional commutation and the instantaneous inter-phase short-circuit problem during converter 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

DOI: 10.11985/2018.02.001

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

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## Abstract

A three-phase line-voltage-cascaded high-frequency link matrix rectifier (LVC-HLFMR) topology for high-voltage applications is proposed. 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 a three-phase system and offers advantages such as reduced switch count, elimination of DC energy storage elements, and compact structure. The HLFMR modulation strategy is analyzed, and based on this analysis, an improved commutation strategy is proposed that addresses the characteristics of the three-phase bridge direct-cascade structure. This strategy solves the load open-circuit problem that occurs with conventional commutation and the instantaneous inter-phase short-circuit problem 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 series connection. They offer advantages of increased voltage level, low harmonic content, easy modularization, and strong scalability. Compared with three-phase cascaded converters based on single-phase H-bridges, they require fewer switches, reduce the needed DC capacitors, and exhibit smaller DC-side voltage ripple, making them 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, verifying through simulation its advantages of low voltage change rate and low harmonic content. Jun Wen and Keyue Smedley proposed obtaining six-phase output by series connection of six three-phase two-level voltage source inverters through current-limiting inductors, applying it to adjustable speed six-phase motors. Reference [1] proposed a three-phase line-voltage-cascaded structure where three three-phase full-bridge inverters are directly cascaded through their bridge arms, with output line voltage formed by superposition of submodule line voltages. Reference [2] proposed a novel line-voltage-cascaded structure by changing the connection method of three-phase bridge arms to facilitate easier expansion to higher cascade numbers. Most of the above research focuses on three-phase cascaded converters based on traditional two-level six-switch power converters. The DC capacitors in the intermediate stage of traditional power converters not only reduce system reliability but also increase system volume and cost.

For reasons of voltage level transformation, safety, and isolation, converters often need to employ 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 traditional three-stage isolated rectifier into a two-stage structure, 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 transformer replacing line-frequency transformer, 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. Currently, 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 has better application prospects because the voltage polarity on each switch and current direction can be determined in every switching cycle, offering simplicity without requiring device detection. The three modules of LVC-HLFMR use identical switching signals. If the HFLMR commutation strategy is simply applied, load open-circuit in individual modules occurs during commutation. Therefore, this paper proposes a one-step commutation strategy suitable for LVC-HLFMR based on its structural characteristics, avoiding possible load open-circuit and instantaneous inter-phase short-circuit problems during commutation. A simulation model of the LVC-HLFMR system is established, and simulation results verify the correctness and feasibility of the proposed topology and its commutation strategy.

## 2 LVC-HLFMR Topology Structure

[Figure 1: see original paper] shows the LVC-HLFMR topology structure, which mainly consists 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 voltage, which after voltage level transformation and electrical isolation through the high-frequency transformer, is converted to DC through a diode full-bridge rectifier. The outputs of the three rectifier circuits are paralleled to provide DC output to the load.

The midpoints of the three-phase bridge arms in LVC-HLFMR 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, we have:

$$ia = ia1 = 2I\sin!t \tag{1}$$

$$ib = ib2 = 2I\sin(!t!120!) \tag{2}$$

$$ic = ic3 = 2I\sin(!t + 120!) \tag{3}$$

$$ia1 + ib1 + ic1 = 0 \tag{4}$$

$$ia2 + ib2 + ic2 = 0 \tag{5}$$

$$ia3 + ib3 + ic3 = 0 \tag{6}$$

$$ia2 =!ib1 \tag{7}$$

$$ib3 =!ic2 \tag{8}$$

$$ic1 =!ia3 \tag{9}$$

Considering that each submodule employs synchronous control and based on the connection characteristics, during space vector modulation and taking sector 1 as an example, only line voltages uab and uac are active. The current relationships are:

$$ib1 = ib \tag{10}$$

$$ia3 =!ic \tag{11}$$

$$ic2 = 0 \tag{12}$$

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:

$$ia1 = 2I\sin!t \tag{13}$$

$$ib1 = 2I\sin(!t!150!) \tag{14}$$

$$ic1 = 2I\sin(!t + 150!) \tag{15}$$

$$ia2 = 2I\sin(!t + 30!) \tag{16}$$

$$ib2 = 2I\sin(!t!120!) \tag{17}$$

$$ic2 = 2I\sin(!t + 90!) \tag{18}$$

$$ia3 = 2I\sin(!t!30!) \tag{19}$$

$$ib3 = 2I\sin(!t!90!) \tag{20}$$

$$ic3 = 2I\sin(!t + 120!) \tag{21}$$

Although the three bridge arm currents of each submodule are asymmetric, the input phase currents drawn from each module have the same amplitude as the module currents. Considering that the switches operate synchronously, 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 source internal resistance; 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 with the load resistance, the equivalent circuit of the isolation stage in operating state is shown in [Figure 3: see original paper].

In each operating state, current flows through only two of the three modules. After rectification, the high-frequency pulse voltages on the transformer secondary side are paralleled at the output, yielding 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, the LVC-HFLMR equivalent circuit is shown in [Figure 4: see original paper].

From the equivalent circuit, the LVC-HFLMR structure functions the same as a high-frequency matrix rectifier. Although cascading more components inevitably introduces additional device losses, the voltage stress sharing among cascaded devices is significant for meeting high-voltage-level system requirements.

## 3 LVC-HFLMR Modulation Strategy

Considering that the three modules employ identical switching signals, the modulation strategy analysis focuses on 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 a suitable modulation strategy for HFLMR. Different from traditional current space vector modulation, to obtain positive and negative alternating high-frequency pulse voltage, 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], the HFLMR input current space vector complex plane is divided into 12 sectors, 不同于传统

B-C-SVM 的不同于传统 B-C-SVM 的不同于传统 B-C-SVM 的不同于传统 B-C-SVM 的不同于传统 B-C-SVM 的不同于传统 B-C-SVM 的. 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 applied first. As shown in [Figure 5a: see original paper], when the reference vector Ir is located in sector 1, vectors Iab and Iac are selected for synthesis. The corresponding line voltages are uab and uac, with uab > uac in sector 1. In this case, Iac is applied first to ensure that during vector switching, the operating voltage always transitions from uac to uab, enabling natural commutation. Since the matrix rectifier output is high-frequency voltage, the required input current vector is synthesized from five vectors: two active vectors adjacent to the reference input phase current sector (for positive output current Im), two active vectors with opposite polarity (for negative output current -Im), and a zero vector. Taking sector 1 as an example, the input phase current is synthesized from vectors Iab, Iac, Iba, Ica, and Iaa.

[Figure 6: see original paper] shows the B-C-SVM output voltage and vector synthesis sequence. Let the three-phase input voltages be:

$$ua = 2U \sin !t \tag{22}$$

$$ub = 2U \sin(!t!120!) \tag{23}$$

$$uc = 2U \sin(!t + 120!) \tag{24}$$

Taking the vector synthesis sequence in 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 adjacent to the sector, Iab and Iac, plus a zero vector. The RMC outputs forward current Im, and the transformer primary voltages are Uab and Uac. The corresponding vector action times are calculated as:

$$T1 = Tab = Tba = m \sin(60° - \theta i)Ts \tag{25}$$

$$T2 = Tac = Tca = m \sin(\theta i)Ts \tag{26}$$

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 - + 30°. The first half-period vector synthesis method is shown in [Figure 7: see original paper].

The second half-period is similar to the first. 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. 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. Therefore, the basic vector duty cycles in the second half-period are identical to those in the first half-period, yielding positive and negative alternating high-frequency voltage within one period.

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

$$ia1 = ib2 = ic3 = (T1 + T2)Im - T1Im - T2Im = \sqrt{2}I\sin(60° - \theta i)$$

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

$$ia = ia1 = \sqrt{2}I_m\cos(!t - \phi) \tag{27}$$

$$ib = ib2 = \sqrt{2}I_m\cos(!t - \phi - 120°) \tag{28}$$

$$ic = ic3 = \sqrt{2}I_m\cos(!t - \phi + 120°) \tag{29}$$

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

## 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 above modulation strategy, 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 where ua > 0, uc < 0, and ub < 0, 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.

Taking the first PWM period half-cycle in sector 1 as an example, the commutation process is explained, 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 driving Sbl (both IGBTs of the bidirectional switch receive turn-on signals simultaneously), Scl is turned off. Since IGBT turn-on time is much shorter than turn-off time,

the transformer primary side does not experience open-circuit conditions. Moreover, because 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 with soft turn-off of the switching devices.

At this time, the current flows through modules 1 and 3 instead of 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-circuit, as shown in [Figure 10: see original paper]. To address this, Sal of the third module is turned on to create a shoot-through in the A-phase bridge arm, providing an energy discharge path for the transformer leakage inductance.

The switching actions during this commutation process are shown in [Figure 11: see original paper], where S3al represents the lower switch of the A-phase bridge arm in the third module. S3al is turned off 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 proper active vector action sequence, one-step natural commutation during active vector switching can be achieved.

(2) During the transition from switching state 10X to SXX, the transformer primary voltage changes from uab to zero. The converter transitions from having Sah and Sbl conducting to having Sah and Sal in shoot-through state to provide a discharge path for transformer leakage inductance.

If direct one-step commutation is applied here—turning off Sbl while turning on Sal—since phase A voltage is maximum, Sal+ carries current as shown in [Figure 12: see original paper]. Due to turn-off delay of Sbl, the current through Sbl does not decrease immediately. Instead, an instantaneous current surge occurs through Sbl- because both the current through Sal+ and the gradually increasing transformer primary current flow through Sbl-, before decreasing and eventually turning off. This process creates a brief inter-phase short-circuit between phases A and B, causing an instantaneous current surge in switch Sbl-, which is detrimental to safe device operation.

To avoid this inter-phase short-circuit during commutation, a two-step commutation concept is applied 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, forcing the current to commutate 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. Switching between operating vectors involves natural commutation with soft turn-off of devices. Switching to the zero vector involves forced commutation.

Since device turn-off time is much longer than turn-on time, switching signals can still be applied simultaneously to both sets of devices to achieve one-step commutation.

## 5 Simulation Study

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

[Figure 14a: see original paper]–[Figure 14c: see original paper] demonstrate that LVC-HLFMR can operate at near-unity power factor 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 is applied 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 operating state. The improved commutation strategy provides an energy discharge path for transformer leakage inductance in non-operating modules, preventing primary-side open-circuit in non-operating transformers. Since each transformer is in non-operating state for only 1/3 of a period, peak voltage is reduced, resulting in lower primary voltage and improved system safety.

## 6 Conclusion

(1) The LVC-HLFMR topology with direct three-phase cascading on the input side and parallel connection on the output side is proposed. 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 conventional transformers, resulting in smaller system volume, more compact structure, and lower cost, showing 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-circuit during LVC-HFLMR commutation, a bridge arm is placed in shoot-through state to provide an energy discharge path for transformer leakage inductance. Using the two-

step commutation concept avoids instantaneous short-circuit problems when switching to the zero vector, enhancing the safety and reliability of the commutation strategy.

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*Note: Figure translations are in progress. See original paper for figures.*