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L. Wei, Y. Matsushita, T.A. Lipo

Wisconsin Power Electronics Research Center
University of Wisconsin-Madison
Madison WI 53706-1691

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Wisconsin Electric Machines & Power Electronics Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

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A Compensation Method for Dual-bridge Matrix Converters Operating Under Distorted Source Voltages

Lixiang Wei, Yoichi Matsushita and Thomas A. Lipo

Department of Electrical and Computer Engineering
The University of Wisconsin-Madison,
Madison, WI, 53705, USA

Abstract- This paper investigates the performance of a dual-bridge matrix converter (DBMC) operating with distorted source voltages. A direct feed-forward unbalance control scheme is developed to reduce the influence of input voltage distortion to the load. The line side source voltages and its fundamental component are first detected. Then, appropriate distorted switching functions of the line side converter are applied to reduce the harmonic content of the load. The proposed method has several advantages: First, it can effectively reduce the harmonic content of the load side current with either unbalanced or distorted source voltage. Second, this control method requires only calculation of the fundamental components of the input line voltages. Third, the input power factor of the fundamental component can be adjusted readily without any difficulty. Lastly, the harmonic content of the line side current can also be easily approximated. Theoretical analysis and simulation results are presented in the paper to verify the effectiveness of the approach.

I. INTRODUCTION

The 9-switch dual-bridge matrix converter (DBMC) is a relatively newly developed concept [3][4][5][9][10][11][12]. Compared to the conventional matrix converter, it realizes the same high quality performance features, such as near sinusoidal input/output waveforms, adjustable input power factor, and compact system design due to absence of large energy storage components. Moreover, it has several other advantages over the conventional matrix converter, including easier and safer commutation, reduced number of switches, simple clamp circuit, etc. The operation of this converter under distorted source voltages will be discussed in detail.

The DBMC and the conventional matrix converter have the same input/output characteristics operating under the space vector PWM method. Thus, most of the control methods of the conventional matrix converter can also be applied to the DBMC. Like the conventional matrix converter, the DBMC is a direct frequency conversion device without any energy storage components. As a result, the distortion at the utility side can immediately be reflected to the load side and generate unwanted input/output harmonics to the system. Several techniques that reduce the influence of source voltage distortions for the conventional matrix converter have been reported [5][6][7][8][9][10]. Among them, [5][6] synthesize the performance of two available unbalance control strategies when the source voltage contains only positive and negative sequence components. It is concluded that by appropriately selecting the switching function, it is possible to generate balanced output voltage with optimized input current waveforms. In ref. [7], a generalized approach is proposed to analyze the matrix converter with distorted voltages. In this paper, an optimal input current modulation strategy was proposed and some analytical results were presented. However, the harmonic content of the output load remained distorted and no detailed implementation of the method was proposed. In [8][9][10], unbalance issues with distorted source voltage were investigated. Several strategies were proposed and tested to eliminate the unbalances of the load side voltage, but issues related to the distortion of line side current were not mentioned.

Because the DBMC has an AC/DC/AC structure, some of these methods mentioned above can be further simplified. One approach to simplify these controls is to decompose unbalanced control switching function into line side and load side converters individually [11][12]. For example, if the line side voltage is unbalanced, only the switching function corresponding to the line side converter is adjusted to allow the average DC side voltage \( V_{dc} \) to remain constant. As a result, the switching functions of the bad side converter remain balanced. On the other hand, if the three-phase output load is unbalanced, only the load side switching function need be adjusted to keep the average DC side current constant. The switching functions of the line side converter are still balanced. This scheme has two advantages. First, it eliminates the influence of unbalance from one side to the other side. For example, while the line side voltage is unbalanced, because the average DC side voltage is adjusted to be constant, if sinusoidal switching function is applied to the load side converter, the output voltage/current does not have any low order harmonics. Secondly, it can simplify the unbalance control of the DBMC to one used for the current source rectifier as discussed in [11][12]

A generalized feed forward unbalance control method is developed in this paper to enhance the performance of the nine switch DBMC (as shown in fig.1) under distorted source voltage. The line side source voltage is first detected and its fundamental component calculated. Then, by applying appropriate distorted switching functions of the line side converter, the harmonics contents of the load can be largely reduced even in the presence of adjustable input power factor. Moreover, the harmonic content of the input current can also be easily approximated.
The paper is organized as follows. After a brief discussion of the relationship between the source voltage and the switching functions, the unbalanced switching function is derived. The implementation of this control method is then described in detail. Finally, simulation results are presented to demonstrate the feasibility of the proposed method.

Fig. 1. Configuration of the 9-switch DBMC

II. CONTROL PRINCIPLE

In order to simplify the analysis, the instantaneous space vector representation of the line side converter is defined as

\[
\bar{\alpha} = x_α + j \cdot x_β = \sqrt{\frac{2}{3}}(x_u + x_b \cdot e^{\frac{j 2\pi}{3}} + x_c \cdot e^{\frac{j 4\pi}{3}})
\]

where, \(x\) can be a voltage, current or switching function vector.

Similarly, the instantaneous space vector representation of the load side converter is defined as

\[
\bar{\alpha} = x_α + j \cdot x_β = \sqrt{\frac{2}{3}}(x_u + x_v \cdot e^{\frac{j 2\pi}{3}} + x_w \cdot e^{\frac{j 4\pi}{3}})
\]

where, \(x\) can be a voltage, current or switching function vector.

Suppose the line side voltage is distorted and has multiple orders of harmonics, the input voltage vector can be illustrated as

\[
\bar{V}_{in} = \bar{V}_p + \sum_{i=0}^{\infty} \bar{V}_{2i+1} \quad \|\bar{V}_{2i+1}\| << \|\bar{V}_p\| \quad \text{for all} \quad i \neq 0
\]

where, \(\bar{V}_p\) is the fundamental component of the input source voltage; \(\bar{V}_{2i+1}\) is the \(2i+1\) order voltage harmonics. Here it is assumed that the amplitude of the fundamental component is much greater than that of the harmonics.

Assuming that the expected output voltage vector is \(\bar{V}_{out}\) and the vectors of line and load side switching functions are represented as \(\bar{S}_{rec}\) and \(\bar{S}_{inv}\) respectively, then

\[
\bar{V}_{dc} = \bar{V}_{in} \cdot \bar{S}_{rec} ; \quad \bar{V}_{out} = \bar{V}_{dc} \cdot \bar{S}_{inv}
\]

Equation (4) shows that the output voltage can be balanced automatically by setting the balanced output switching functions if the average DC line voltage \(\bar{V}_{dc}\) is a constant.

Similarly, assuming that the three-phase output current vector is \(\bar{i}_{out}\), the following relations can be obtained

\[
\bar{i}_{dc} = \bar{i}_{out} \cdot \bar{S}_{inv} ; \quad \bar{i}_{in} = \bar{i}_{dc} \cdot \bar{S}_{rec} = \bar{i}_{out} \cdot \bar{S}_{inv} \cdot \bar{S}_{rec}
\]

where, \(\bar{i}_{dc}\) is the average DC line current.

From equation (5), it can also be determined that if the average DC line current \(\bar{i}_{dc}\) is a constant, the input current vector is proportional to the switching function vector of the line side converter.

Combining equations (4) and (5), the relationship of the input, DC link, and output power can be illustrated as

\[
P_{in} = \bar{P}_{in} \cdot \bar{S}_{in} = \bar{V}_{dc} \cdot \bar{i}_{dc} = \bar{V}_{in} \cdot \bar{i}_{in} = P_{out}
\]

This result demonstrates that, over any given time, the input power must be the same as the output power as well as the DC link power regardless of the input voltage unbalance. In order to obtain harmonic-free output power, the DC link power as well as the input power of the converter must also be harmonic-free. Since the line side voltage is distorted, the line side current and the switching functions should also be distorted if the quality of output waveforms is to be improved.

It can be assumed that the unbalanced line side switching function is also distorted and can be expressed as:

\[
\bar{S}_{rec} = \bar{S}_p - \sum_{i=0}^{\infty} \bar{S}_{2i+1} \quad \|\bar{S}_{j+1}\| << \|\bar{S}_p\| \quad \text{for all} \quad j \neq 1
\]

where, \(\bar{S}_p\) is the fundamental component of the input source voltage; \(\bar{S}_{2i+1}\) is the \(2i+1\) order voltage harmonics; Again, supposing that the amplitude of its fundamental component is much higher than that of the harmonics.

Combining eqs (3), (4), and (7), the DC side voltage can be expressed as

\[
\bar{V}_{dc} = \bar{S}_p \cdot \bar{V}_p + \sum_{i=0}^{\infty} (\bar{S}_p \cdot \bar{V}_{2i+1} - \bar{S}_{2i+1} \cdot \bar{V}_p)
\]

The third part of equation (8) can be omitted since it is much smaller than the first two parts. Consequently, in order to obtain a constant value of \(\bar{V}_{dc}\), the switching functions of
the line side converter can be appropriately selected by
canceling the second part of equation (8) as
\[ \tilde{S}_p \cdot \tilde{V}_{2i+1} = \tilde{S}_p \cdot \tilde{V}_p = 0 \quad \text{for all } i \neq 0 \quad (9) \]

Thus, the relationship between harmonic components of the
switching function in line side converter can be expressed as
\[ S_{2i+1} = \frac{V_{2i+1}}{V_p} \cdot S_p \quad (10) \]
\[ \angle S_p + \angle S_{2i+1} = \angle V_p + \angle V_{2i+1} \quad (11) \]

Based on (10) and (11), assuming that the fundamental
component of line side switching function can be expressed as
\[ \tilde{S}_p = k \tilde{V}_p e^{-j\psi_{in}} \quad (12) \]
where, \( k \) is a constant value that can be proportional to the
DC link voltage, \( \psi_{in} \) is the power factor angle between the
line side fundamental voltage and fundamental current.

In this case, the \( 2i+1 \) order harmonics of the switching
function can be derived from equations (10), (11), and (12) as
\[ \tilde{S}_{2i+1} = k \tilde{V}_p e^{-j\psi_{in}} \quad (13) \]

Combining equations (13) and (7), the following equation can be derived
\[ \tilde{S}_{rec} = S_p e^{-j\psi_{in}} - \sum_{i=0}^{\infty} \frac{V_{2i+1}}{V_p} e^{j\psi_{in}} \tilde{V}_p \quad (14) \]

Combining equations (14) and (3), Eq. (14) can be simplified to be
\[ \tilde{S}_{rec} = S_p (e^{-j\psi_{in}} - \frac{(\tilde{V}_{in} - \tilde{V}_p)}{V_p} e^{j\psi_{in}}) \tilde{V}_p \]

or
\[ \tilde{S}_{rec} = \frac{S_p}{V_p} (2V_p \cos \psi_{in} - \tilde{V}_{in} e^{j\psi_{in}}) \quad (15) \]

Equation (15) suggests that one need only detect the line
side voltage vector and its fundamental component to implement the proposed unbalance control method.

The average DC side voltage can also be calculated from
(8) as
\[ V_{dc} = \tilde{S}_p \cdot \tilde{V}_p \quad (16) \]

From (16), it can be concluded that the average DC side
voltage has a constant value with only small amounts of low
order harmonic components.

The actual output voltage vector can be approximated by
\[ \tilde{V}_{out} = V_{dc} \tilde{S}_{inv} = V_p S_{rec} S_{inv} \cos \psi_{in} \tilde{S}_{inv} \quad (17) \]

Since the load side converter is balanced, if the switching
functions of the load side converter are balanced, the
harmonic contents of the load side current can also be largely
reduced and be neglected. As a result, the line side current
vector can be obtained from equation (5) as
\[ \tilde{i}_{2i+1} = i_{dc} (\tilde{S}_p - \sum_{i=0}^{\infty} \tilde{S}_{2i+1}) \quad (18) \]

The average DC link current \( i_{dc} \) is also approximately
a constant. By combining (18) with equations (12) and (13), it

can be found that
\[ \tilde{i}_{2i+1} = k i_{dc} \tilde{V}_p e^{-j\psi_{in}} \quad (19) \]

This equation demonstrates that the input current has the
same order of harmonics as that of the input voltage. Moreover, the input power factor angle of fundamental component at the line side inherently becomes the desired value \( \psi_{in} \).

From (19), it can also be concluded that the total harmonic
distortion (THD) factor of the input current.
\[ \text{ITHD} = \sqrt{\sum_{i=0}^{\infty} \left( \frac{V_{2i+1}}{V_p} \right)^2} = \text{VTHD} \quad (20) \]

The THD of the input current is approximately the same as
the THD of the input source voltage.

The method described is similar to scheme B in [7].
However, one advantage of this method is that the input
power factor can be adjusted without difficulty. The scheme
B in paper [7] is only effective when the input power factor is unity.

One special case of this derivation is that the input source
voltage has only positive and negative sequences. Under this
condition, the switching function of line side converter becomes
\[ \tilde{S}_{rec} = S_p (e^{-j\psi_{in}} - \frac{\tilde{V}_{n}}{V_p} e^{j\psi_{in}}) \tilde{V}_p \quad (21) \]

where \( \tilde{V}_n \) is the negative sequence of the line side voltage.

With equations (21) and (8), the average DC side voltage
equals to following equations
\[ V_{dc} = \tilde{S}_p \cdot \tilde{V}_p + \tilde{S}_n \tilde{V}_n = V_p S_p \cos \psi_{in} (1 - \frac{V_n^2}{V_p^2}) \quad (22) \]
Thus, the output voltage becomes
\[ V_{\text{out}} = V_p \cos \omega_{\text{in}} \left( 1 - \frac{V_n^2}{V_p^2} \right) S_p S_{\text{inv}} \tilde{S}_{\text{inv}} \quad (23) \]

Also, the input current vector becomes
\[ I_{\text{in}} = I_{\text{dc}} S_{\text{rec}} = I_{\text{dc}} S_p \left( e^{j\omega_{\text{in}}} - \frac{V_n}{V_p} e^{j\omega_{\text{in}}} \right) \quad (24) \]

From equation (21) to (24), it can be found that, this method can be simplified as the similar control method mentioned in paper $^{[5]}$.$^{[6]}$.$^{[9]}$.$^{[13]}$.

Because this unbalance control method requires only that fundamental component of the input voltage vector be calculated, the complexity of this unbalance compensation method for input source voltage with harmonic content is an extension to algorithms concerned only with negative sequence harmonics $^{[5]}$.$^{[6]}$.$^{[9]}$.$^{[13]}$.

III. CONTROL IMPLEMENTATION

The control block diagram of the DBMC with unbalance compensation is shown in fig. 2. It consists of several functional blocks. Among them, the voltage decomposition block computes the input line side voltage vector and its fundamental component, the switching function block calculates the input current angle, output voltage vector angle and amplitude that are necessary for space vector PWM control, and the PWM control logic block calculates the duty cycles and the appropriate PWM sequences to the converter.

![Control block diagram](image)

**A. Voltage decomposition block**

This block calculates the fundamental component of the line side voltage vector by using a fourier transformation. With this transformation, the sample frequency is N times that of the fundamental input frequency.

\[ N = f_s / f_{\text{in}} \quad (25) \]

\[ V_{\text{in}}(n,t) = V_{\text{in}}(t - n \cdot t_s) \quad (26) \]

\[ V_p(t) = V_p(1,t) e^{ \frac{2\pi i n}{N} } + \frac{1}{N} (V_{\text{in}}(0,t) - V_{\text{in}}(N,t)) \quad (27) \]

where $f_s$ is the sampling frequency of the system, $f_{\text{in}}$ is fundamental frequency of input voltage, $V_{\text{in}}(n,t)$ is the nth sampled input voltage vector before time t, and $V_p(1,t)$ is the previously calculated fundamental component of the input voltage vector.

From (25), (26) and (27), the fundamental component can be developed after one input time period under any type of distorted input.

**B. Unbalanced control block**

The unbalanced control block calculates the necessary information for the space vector PWM block from the input voltage vectors and its fundamental component.

Previously, assuming that the expected output voltage
\[ V_{\text{oref}} = k_u V_p \angle \theta_0 \quad (28) \]

To simplify the space vector PWM control, the amplitude of the line side converter can be set to unity. Thus
\[ S_{\text{rec}} = 1 \]

\[ \angle S_{\text{rec}} = \angle (e^{-j\omega_{\text{in}}} - \frac{V_{\text{in}} - V_p}{V_p} e^{j\omega_{\text{in}}}) + \angle V_p \quad (29) \]

The amplitude of the load side converter must be adjusted to realize the expected output voltage vector by combining equations (8) and (15)

\[ S_{\text{inv}} = \frac{k_u V_p}{V_p e^{j\omega_{\text{in}}} - (V_{\text{in}} - V_p) e^{j\omega_{\text{in}}}} \quad (30) \]

The phase of the load side converter is the same phase as the expected output voltage. That is
\[ \angle S_{\text{inv}} = \theta_0 \quad (31) \]

Fig. 3 demonstrates the simulated amplitude of the load side converter $S_{\text{inv}}$ and the phase angle of the line side switching function $\angle S_{\text{rec}}$ while $k_u = 0.8$ under distorted line voltage conditions. From this figure, it can be found that the switching functions of both sides have large amount of harmonics.

**C. PWM control logic block**

The PWM control logic block calculates the duty cycles of different vectors and finally provides the gate signals of each switch. The input of this block is the angle of the line side
switching function $\angle S_{\text{rec}}$, power factor angle $\psi_{\text{in}}$, modulation level $S_{\text{in}}$, and the angle of output voltage vector $\theta_0$. Both the calculation and switching sequences are the same as that of the balanced space vector PWM illustrated in refs [1][2].

Fig. 3. Amplitude of the load side switching function and the phase of the line side switching function under a distorted input voltage condition

IV. SIMULATION RESULTS

The proposed distortion control scheme has been studied thoroughly on a 9-switch DBMC with three phase R-L load by the simulation. The parameter of the system is

Input frequency: 60Hz; Output frequency: 35Hz
Filter inductor: 200uH; Filter capacitor: 30uF
Modulation level: 0.8; Load resistance: 8Ω
Load inductance: 5mH

The line voltage of the harmonic components of the input voltage is listed below

Fundamental: 191V Negative sequence: 30V
Positive fifth order: 19V Negative fifth order: 3V
Positive seventh order: 19V Negative seventh order: 3V

Figs. 4 and 5 illustrate the simulation results of the converter without and with the proposed control method. The waveforms shown in these figures are input voltage and input current, DC side voltage $V_{\text{dc}}$ and output currents respectively. Figs.6 and 7 illustrate the simulation results of the converter while the input source voltage has only fundamental and negative sequence components illustrate above. The waveforms in these four figures portray the DC link voltage $V_{\text{dc}}$ and the input/output current.

The following conclusions can be obtained from these four figures.

- If no unbalance control is applied, the load side current is obviously distorted. Moreover, the harmonics of the output voltage are also distorted.

Fig. 4. Simulation result without unbalanced control (With multiple order of harmonics in the source voltage)

Fig. 5. Simulation result with unbalance control (With a multiple order of harmonics in the source voltage)
V. CONCLUSIONS

In this paper, a direct feed forward unbalance control scheme is developed for the 9-switch DBMC operating under distorted source voltages. Theoretical analysis and simulation results are provided to verify its effectiveness. The proposed control method has the following characteristics:

- The proposed control method can largely reduce the harmonic contents of the load side under distorted source voltage and can simultaneously adjust the input power factor of fundamental component without difficulty;
- This control method needs only to detect the input voltage vector and its fundamental component;
- Since the DBMC has the same input/output characteristics as the conventional matrix converter, this unbalanced control is also applicable to the conventional matrix converter topology.

VI. REFERENCES

[10] Sedat Sunter, Huseyin Altun, and Jon C. Clare, "A control technique for compensating the effects of input voltage variations on

