# Modified Venturini Modulation Method for Matrix Converter Under Unbalanced Input Voltage Conditions

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## ABSTRACT

A Venturini method is one of the popular modulation techniques for controlling the matrix converter due to its simplicity of gating signal generation and a maximum voltage ratio of 0.866 between fundamental output magnitude and fundamental input magnitude. However, even with simple modulation method and achieving maximum fundamental output magnitude, the possible unbalanced conditions of the three-phase input voltages affect the reduction and distortion of the output performances. Thus, a control strategy based on Venturini method is presented in this paper, in order to solve the impacts of unbalanced input voltage conditions on the matrix converter performance. Conceptually, this strategy is done by modifying the mathematical model for controlling the modulating waves as generated in the event of normal situation. Up to this approach, it can support either singlephase condition or two-phase condition. Performance of the proposed control strategy was verified by a simplified simulation model in the MATLAB/Simulink software. It is shown that the matrix converter can be controlled by the proposed algorithm without the energy storage devices for regulating the output voltages, which results in a good steady-state and dynamic operation.


**Keywords**: Matrix Converter, Venturini Method, Carrier-based Pulse Width Modulation (PWM), Unbalanced Voltage Conditions

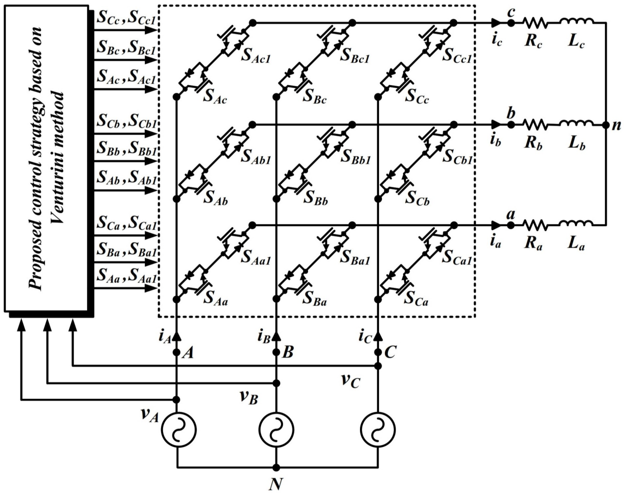


***Fig.1:*** *Matrix converter with the proposed control strategy.*

## 1. INTRODUCTION

Matrix converters having direct ac-ac power conversion were originally evolved by Venturini and Alesina [1, 2] in 1980. Based on its typical structure of nine bidirectional switches, as shown in Fig. 1, the attractive expediencies of this converter compared with the indirect matrix converter are such as lacking large dc-link energy storage elements and therefore having compact and lightweight package, bidirectional energy-flow ability, and reduction in the voltage stress on individual switches. Moreover, due to its included capabilities of adjustable output magnitude and fundamental frequency, it has been considered a popular alternative and has been continuously developed to use in various ac electrical utility applications for any industry, such as adjustable speed drives for an ac induction motor [3–5], uninterruptible power supplies along with improved control strategies for enhancing the power quality [6, 7], grid interfacing converter in the renewable energy conversion system [8, 9], etc.

Regarding modulation methods to satisfy the switching operation of the matrix converter, it is well known that the most relevant and powerful method is the Venturini method proposed in [1] and this has been employed up to now [10–15]. With this method, which is used as the direct transfer function, it can flexibly be used to generate the variable-frequency and -amplitude sinusoidal output voltages from fixed-frequency and amplitude sinusoidal input voltages with the maximally desirable voltage ratio, in terms of output voltage magnitude versus input voltage magnitude, reaching to 0.866, which is the maximum gain at this time. In addition, its lowcomplexity and good dynamic performance, as reported in [16], lead to a very convenient modulation method for the matrix converter in this paper with the scope of fixed-frequency output voltage contribution.

One important problem in the control of the ma-

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trix converter is the imbalance of the three-phase input voltages. This causes incorrect waveforms (reduction and/or distortion) in output voltages (and thereby currents) from the analytical theory. To remedy such consequences, the modified input current modulation strategies based on the space vector modulation (SVM) algorithm were proposed in [17–19] to improve the input current quality under unbalanced conditions. However, the strategies unavoidably need extreme and complicated real-timing vector calculations, which depend on all the switching configurations. Meanwhile, the feedback compensation strategies via closed-loop control of output currents based on Venturini modulation method were presented in [20, 21]. Among these algorithms, it is difficult to design the feedback system due to elaborate mathematical functions, and it also depended on the delay ability of each technical system. Another solution is the additional clamp circuit between input side and output side of the matrix converter, as introduced in [22, 23]. This leads to more complexity of the control method and cumulative hardware components.

This paper presents a control strategy for the matrix converter based on Venturini method under unbalanced input voltage conditions, which is drawn in Fig. 1. The first proposed viewpoint was exposed in [24]. The relevant features of the proposed control strategy are as follows: i) It modifies the modulation strategy based on Venturini method to maintain constant duty cycles despite experiencing unbalanced input voltage conditions, as it is operated under the normal condition. ii) It simplifies the complexity of the analytical mathematic model. That means it does not rely on the SVM algorithm and the feedback closed-loop control. iii) It does not need any additional hardware to handle the issue of interest. The remainder of this paper are organized as follows. Section 2 briefly addresses the basics of the Venturini method along with its effects under the unbalanced input voltage condition. The theory-based solution of the proposed control strategy is subsequently presented in Section 3. Simulation results testifying the performance of the proposed strategy are demonstrated in Section 4. Finally, this paper is summarized in Section 5..

## 2. OVERVIEW OF VENTURINI METHOD

### 2.1 Structure and Switching Operation of Matrix Converter

As shown in Fig. 1, the structure of the matrix converter is consisted of eighteen IGBTs in total, where there are two constraints [1, 2] of the switching operation per leg as follows.

1. No two bidirectional switches are turned on in the same horizontal leg. This leads to the short through in a converter leg.
2. Not all the switches are turned off in the same horizontal leg. This might destroy the switches in a converter leg due to the overvoltage.

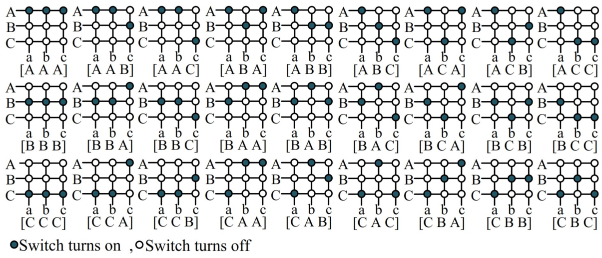



***Fig.2:*** *Matrix converter with the proposed control strategy.*

***Table 1:*** *Switching States per Leg (Leg a) of the Matrix Converter.*

| Switching states | Switching for Leg a | | | $v_a$ |
|---|---|---|---|---|
| | $S_{Aa}$ | $S_{Ba}$ | $S_{Ca}$ | |
| A | ON | OFF | OFF | $v_A$ |
| B | OFF | ON | OFF | $v_B$ |
| C | OFF | OFF | ON | $v_C$ |

According to these two constraints, there are thus 3 switching states that can be allowed to operate in one leg of this converter, as listed in Table 1. With these switching states, the switching states of leg b and leg c are also similar to leg a, but they are shifted by rad and rad, respectively. Hence, the switching modes in three phases of the matrix converter are 27 modes in total, as shown in Fig. 2.

From which, the relationship between input voltage ($v_i(t)$) and output voltage ($v_o(t)$) can be expressed in point of view of the switching function as follow:

$$v_i(t) = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} v_o(t) \tag{1}$$

Based on Eq. (1), it is further an algorithm, which is used to initially find out the modulating function in Venturini modulation method for controlling the matrix converter, as discussed in the next subsection.

### 2.2 Principle of Venturini Modulation

In Venturini method, the approach of the attainable gating pulse generation for each of nine bidirectional switches is initially synthesized from the instantaneous input voltages , as given by

$$v_i(t) = \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} V_i \sin(\omega_i t) \\ V_i \sin(\omega_i t - 2\pi/3) \\ V_i \sin(\omega_i t + 2\pi/3) \end{bmatrix} \tag{2}$$

where $V_i$ is the amplitude of the input voltages, $\omega = 2\pi f_i$ is the fundamental angular frequency of the input voltages. Following Eq. (2), it is supposed that the input voltages are balanced at the normal condition.

According to this strategy, the output voltages ($v_o(t)$) related to the input voltages with the direct transfer function can be derived as

$$v_o(t) = M(t)v_i(t) \tag{3}$$

where $M(t)$ is the transfer matrix of the matrix converter, and also can be defined as

$$M(t) = \begin{bmatrix} m_{Aa} & m_{Ba} & m_{Ca} \\ m_{Ab} & m_{Bb} & m_{Cb} \\ m_{Ac} & m_{Bc} & m_{Cc} \end{bmatrix} \tag{4}$$

Using Eq. (4), the transfer matrix is consisted of the duty cycles for generating the gating pulses of the switches. Wherewith, the comprehensive formula form for all the duty cycles can be expressed as

$$m_{jk} = \frac{1}{3}\left(1 + 2q_c\frac{v_j v_k}{V_i^2} + \frac{2q}{3q_m}\sin(\omega_j t + \theta_j)\sin(3\omega_j t)\right) \tag{5}$$

where $j = A, B, C$ and $k = a, b, c$. $v_j$ is the phase-to-neutral input voltage. $v_k$ is the phase-to-neutral output voltage. $q$ is the gain of 0.5. $q_m$ is the gain of $\sqrt{3}/2 \approx 0.866$. $q_c$ is the modulation voltage ratio, which is in the range of $0 \leq q_c \leq 1$.

Based on Eq. (5), for a given $q_c = 1$, the fundamental magnitude of the output voltage can achieve the maximum utility of 0.866 of the input voltage. For extending the clarification of the physical Venturini method, much more detail can be found from [1, 2].

### 2.3 Statement of Drawbacks

In fact, the derivation of Venturini algorithm for the matrix converter is realized with the well balanced input voltage condition. For this reason, it is known that the existing abnormal input voltage from the utility three-phase system is directly responsible for the reduction in magnitude and addition of distortion in output voltage waveforms, as it is formed by the low-order harmonic components. Among these, the families of unbalanced input voltage conditions can be distinguished into three different cases: i) unbalanced voltage magnitudes, ii) unbalanced phase angle deviation, iii) unbalanced levels of harmonic distortion. Out of these cases, the case of the voltage sag (case i) is found to be the most common event for the power quality disturbance, as agreed with IEEE 1159 standard [25], and is therefore discussed in this paper.

As can be seen in Fig. 3(a), the instance of responses for both balanced and unbalanced input voltage conditions with the Venturini method at the modulation voltage ratio $q_c$ of 1 is presented, where the parameters listed in Table 2 are used. Before 0.2 s, the balanced input voltage condition affects the symmetrical waveforms of pole voltages $v_{aN}$, $v_{bN}$ , and $v_{cN}$ along with the line-to-line output voltage $v_{ab}$ and currents $i_a$, $i_b$, and $i_c$. Therefore, referring to Figs. 4(a) and 5(a), the output voltages can numerically approach to around 0.866 of input voltages. On the other hand, it can again be seen from Fig. 3(a) that when the unbalanced input voltage condition (on phase A) is occurred after 0.2 s, the duty cycles in only the first column of Eq. (4), i.e., $M_{Aa}$ in this figure, are reduced from the normal operation. For this reason, it produces asymmetrical waveforms, as shown within the purple dashed-line borders. This consequently leads to further reduction and distortion in output currents and voltages, as investigated in Figs. 4(b) and 5(b), respectively. Besides, when the proposed control strategy is applied, as shown in Fig. 3(b) at 0.2 s, the duty cycle $M_{Aa}$ is obviously increased and equal to that of the period of the balanced input voltage condition (see Fig. 3(a), before 0.2 s). This leads to the reduction of the problems caused by the unbalanced input voltage condition, as can be seen by the increased magnitudes of the fundamental currents and voltages along with the reduced magnitudes of their harmonics in Figs. 4(c) and 5(c), respectively.

## 3. PROPOSED CONTROL STRATEGY FOR MATRIX CONVERTER

Overcoming the effect of unbalanced input voltage conditions discussed above, Therefore, in order to make an analysis with regard to balanced and unbalanced input voltage conditions, the desired reference voltages of three-phase input voltages are given initially as

$$v^*_{j,ref} = V_{j,ref}\sin(\omega_j t + \theta_j) \tag{6}$$

where $v^*_{j,ref}$ is used instead of the desired reference voltages of three-phase input voltages in the normal situation.

Subsequently, the mean function ($v_{mean}$) of three-phase input voltages can be determined as

$$v_{mean} = \frac{v_A + v_B + v_C}{3} \tag{7}$$

Considering Eq. (7), it can be seen that the mean function vmean becomes 0, when the three-phase input voltages are balanced. Otherwise, it will lead to the tangible appearance. Then, the error function ($e_j$) can be calculated by

$$e_j = v^*_{j,ref} - v_{mean} \tag{8}$$

Using Eqs. (6) to (8), the modified duty cycle calculation based on Venturini method can be formulated as

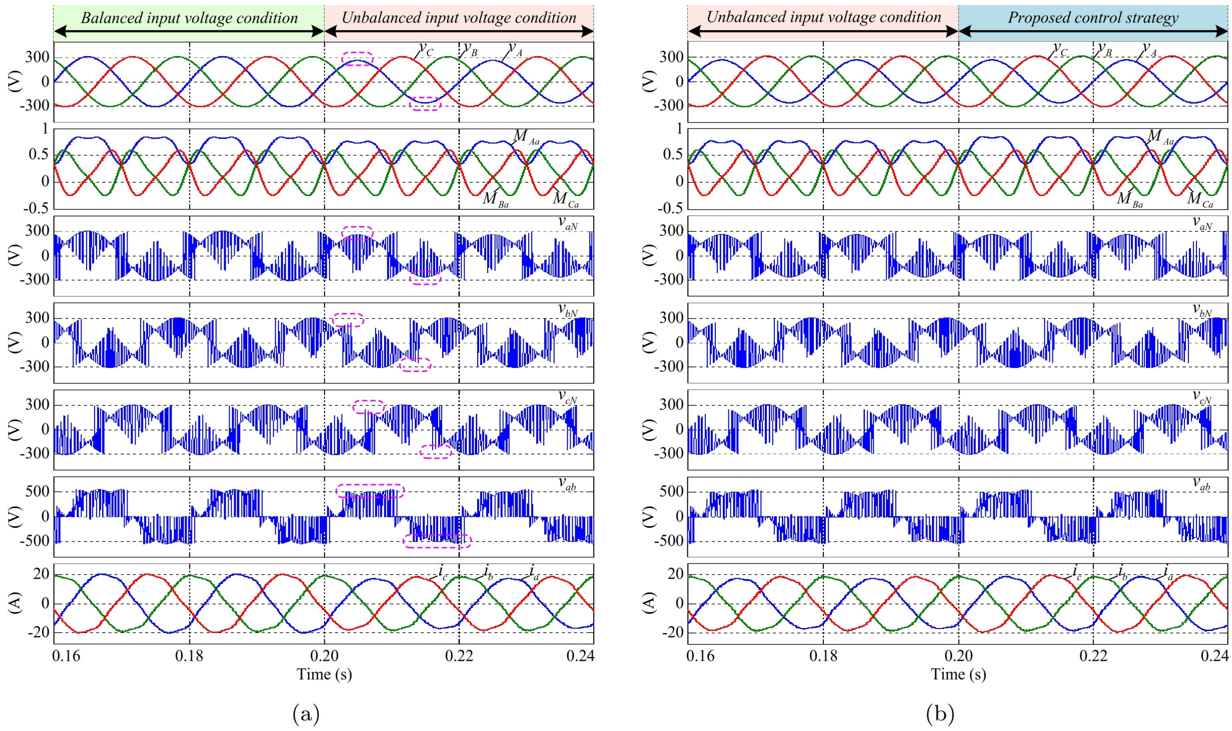



***Fig.3:*** *A transition from (a) balanced input voltage condition to unbalanced input voltage condition with Venturini method and (b) unbalanced input voltage condition with Venturini method to unbalanced input voltage condition with the proposed control strategy. (Top to bottom) Waveforms of input voltages $v_A$, $v_B$, $v_C$, duty cycles $M_{Aa}$, $M_{Ba}$, $M_{Ca}$, pole voltages $v_{aN}$, $v_{bN}$, $v_{cN}$ , line-to-line output voltage vab, and output currents $i_a$, $i_b$, $i_c$.*

$$M_{jk} = \frac{1}{3}\left(1 + 2q_c\frac{(v_{mean} + e_j)v_k}{V_i^2} + \frac{2q}{3q_m}\sin(\omega_j t + \theta_j)\sin(3\omega_j t)\right) \tag{9}$$

According to Eq. (9), the modification based on Venturini method is in terms of the input voltages of the duty cycle calculation to be not varied following unbalanced input voltages. Later on, these attainable duty cycles are used for the process of gating pulse generation for driving all the switches of the matrix converter, referring to Fig. 6.

## 4. SIMULATION RESULTS

Using the proposed control strategy presented in the prior Section for the matrix converter, as shown in Fig. 1, it has been verified by simulation using a MATLAB/Simulink environment under single-phase and two-phase unbalanced input voltage conditions. The parameters indicated in Table 2 are also employed.

***Table 2:*** *Parameters Used for Simulation.*

| Parameters | Symbol | Value |
|---|---|---|
| Three-phase input voltages | $v_A$, $v_B$, $v_C$ | 220 V |
| Input frequency | $f_s$ | 50 Hz |
| Output frequency | $f_o$ | 50 Hz |
| Three-phase resistive loads | $R_a$, $R_b$, $R_c$ | 10 Ω |
| Three-phase inductive loads | $L_a$, $L_b$, $L_c$ | 30 mH |
| Switching frequency | $f_{sw}$ | 2 kHz |
| Modulation voltage ratio | $q_c$ | 0.5 |

### 4.1 Results

Fig. 7 shows the results of the proposed control strategy with the modulation voltage ratio $q_c$ of 0.5 under the 10% step-sag command for single-phase unbalanced input voltage condition on phase A. As shown in Fig. 7(a), it can be observed that the mean function $v_{mean}$ results in 0 V for the period of the balanced input voltage condition, as theoretically calculated from Eq. (7). Hence, the modulation for the matrix converter is directly carried out according to the Venturini principle. On the other hand, since the phase-A input voltage reduces to around 280 V, the proposed control strategy is responsible for regulating the duty cycles to be constant at the desirable mod-

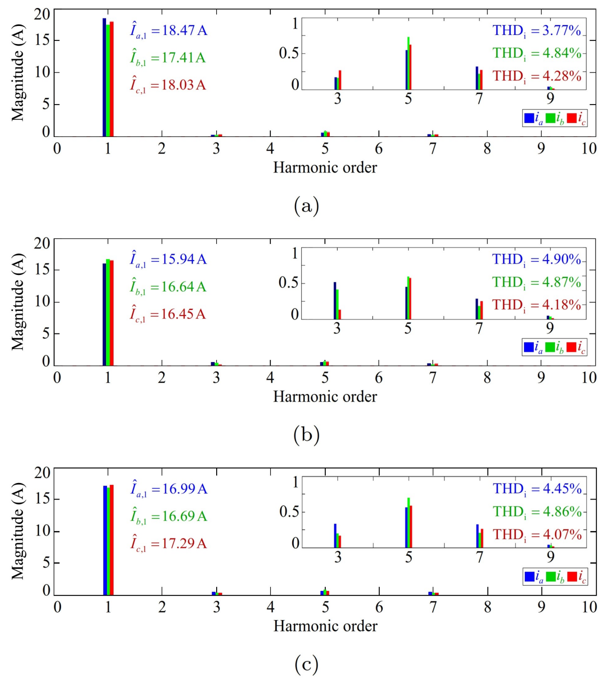



***Fig.4:*** *Harmonic spectrum of output currents for the period of (a) balanced input voltage condition, (b) unbalanced input voltage condition with Venturini method, and (c) unbalanced input voltage condition with the proposed control strategy.*

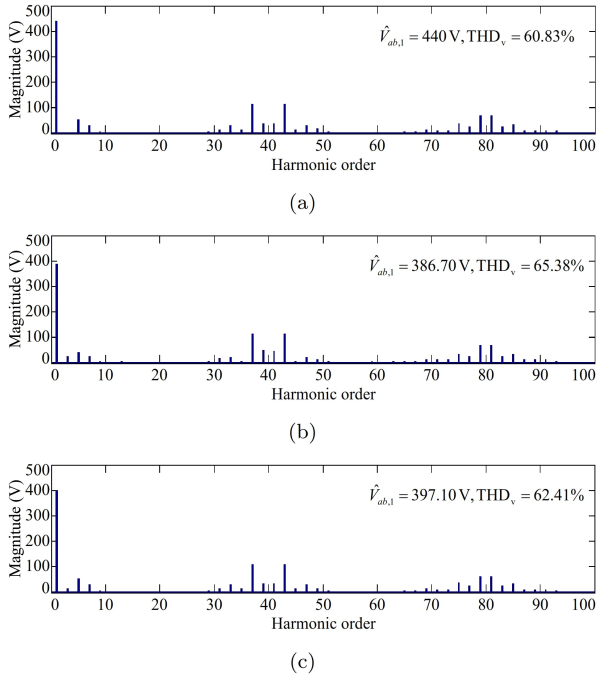



***Fig.5:*** *Harmonic spectrum of line-to-line output voltage for the period of (a) balanced input voltage condition, (b) unbalanced input voltage condition with Venturini method, and (c) unbalanced input voltage condition with the proposed control strategy.*

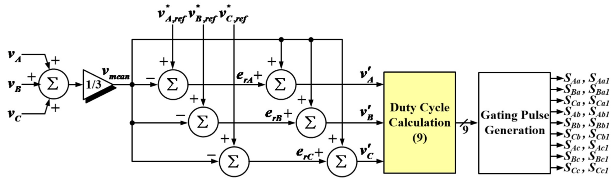
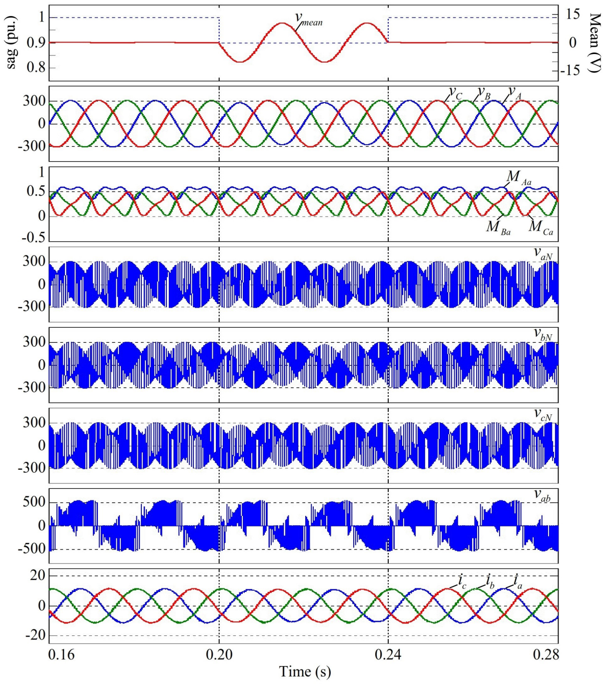



***Fig.6:*** *Block diagram of the proposed control strategy.*

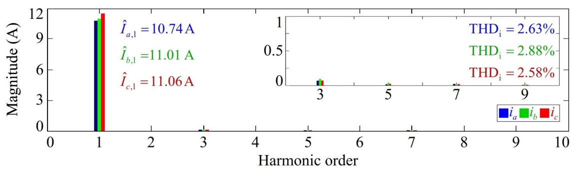
ulation voltage ratio $q_c$ of 0.5 with the magnitude of the mean function around 10.33 V. As a consequence, the arrangements of pole voltages $v_{aN}$, $v_{bN}$, and $v_{cN}$ obtained from this strategy provide the stability and balance for line-to-line output voltages ($v_{ab}$ for the figure) and output currents $i_a$, $i_b$, and $i_c$, as confirmed by the harmonic spectrum of output currents demonstrated in Fig. 7(b). As shown by this harmonic spectrum, it is evident that the three-phase output voltages can be calculated such that their fundamental components are equivalent to around 50% of the input voltages, which is based on the Venturini method, along with having low magnitudes of the loworder harmonic components.

This is similar to the earlier test, except that the operating condition of the 15% step-sag command is provided in Fig. 8. With Fig. 8(a), the appearance of the mean function $v_{mean}$ in the event of sag duration resembles that of Fig. 7(a), whereas its magnitude further reaches to around 15.55 V. That means the disturbance of unbalanced input voltages occurred. Methodically, the duty cycles keeping with the constant modulation voltage ratio $q_c$ of 0.5 lead to the good qualities of the output voltages and currents. As can be seen in Fig. 8(b), it is also distinctly shown that the harmonic spectrum of output currents provides acceptable results without the reduction in the magnitudes of their fundamental components, including the distortion of the waveforms. This can authenticate the theoretical validity and the reliability of the proposed control strategy performance. As for the case study of the two-phase unbalanced input voltage condition, a set of the simulated results for the 10% step-sag command on phases A and B are shown in Fig. 9. Considering 0.2 s to 0.24 s (see Fig. 9(a)), based on the proposed control strategy, the mean function $v_{mean}$ has the same magnitude as that of the single-phase unbalanced input voltage condition (see Fig. 7(a)), whereas its phase angle is led by 90°. As expected, although both phase-A and phase-B input voltages involuntarily fall to around 280 V, the output voltages and currents can achieve the recognizable magnitudes and qualities for the entire duration. In Fig. 9(b), it is obvious that the three-phase output voltages and currents are still kept balancedthrough utilisation of the proposed strategy.

In addition to investigate the performance of the proposed control strategy under the two-phase un-

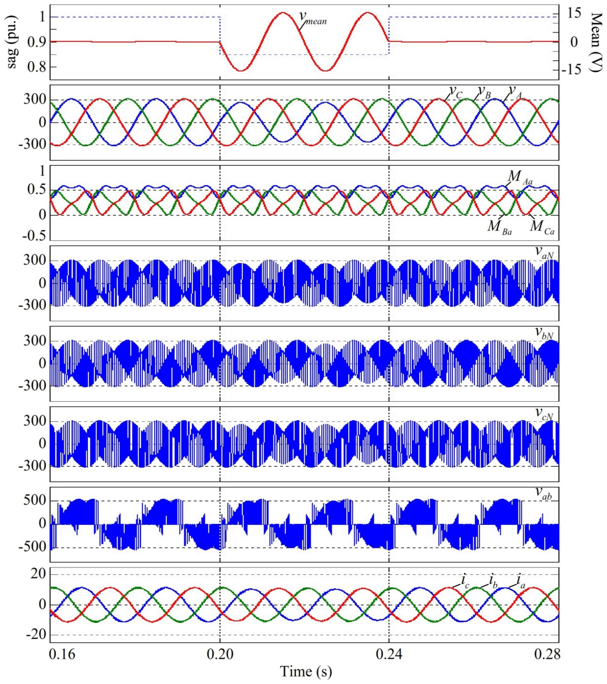



(a)

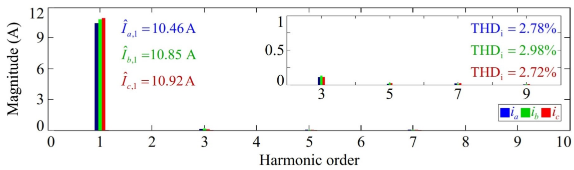



(b)

***Fig. 7:*** *Simulated results under the 10% step-sag command for single-phase unbalanced input voltage condition on phase A compensated with the proposed control strategy. (a) Waveforms of step-sag command and error, input voltages, duty cycles, pole voltages, line-to-line output voltage, and output currents. (b) Harmonic spectrum of output currents for the period of unbalanced input voltage condition.*




(a)




(b)

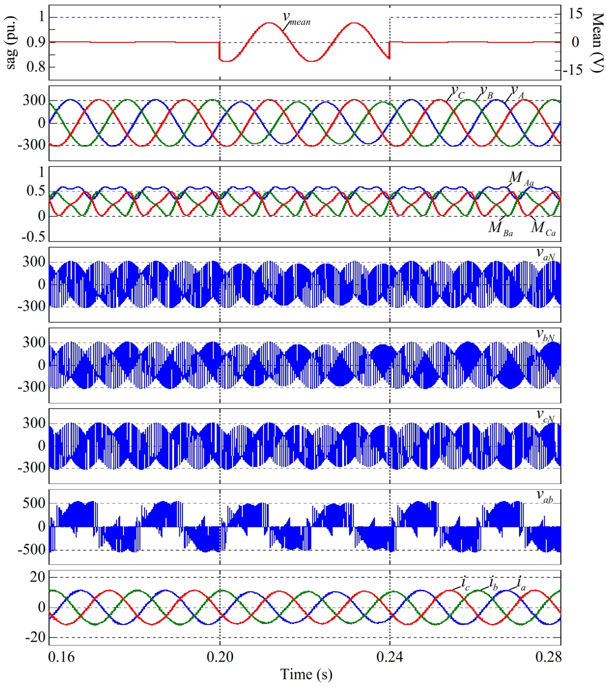
***Fig. 8:*** *Simulated results under the 15% step-sag command for single-phase unbalanced input voltage condition on phase A compensated with the proposed control strategy. (a) Waveforms of step-sag command and error, input voltages, duty cycles, pole voltages, line-to-line output voltage, and output currents. (b) Harmonic spectrum of output currents for the period of unbalanced input voltage condition.*

balanced input voltage condition, the applying of the 15% step-sag command is also tested in Fig. 10. As can be seen in the sag period of the input voltages, the mean function $v_{mean}$ of this case is found to be around 15.55 V (see Fig. 10(a)), as it has the same magnitude as that of Fig. 8(a). However, a change in the dualphase (A and B) input voltages does not affect the duty cycles. This is why there are not more distortions in the output voltages and currents, as can be viewed from the corresponding harmonic spectrum in Fig. 10(b). It can be seen that the magnitudes of fundamental components of output voltages and currents in phases A and B are slightly reduced to be around 44% of the input voltages, which is inconsistent with the theoretical principle, and they almost appear as unbalanced three-phase waveforms, whereas the acceptable waveform quality is maintained for each of the individual output phases.

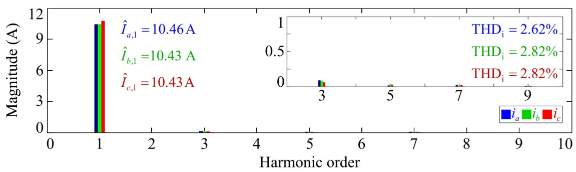
As stated previously, it should be noted that the proposed control strategy is not suitable for cases of much more than 15% two-phase unbalanced input voltage condition. Unfortunately, this is the involuntary limitation of the proposed control strategy. That means it is unserviceable for the extreme single-phase and two-phase unbalanced input voltage conditions, including the three-phase unbalanced input voltage condition.

## 4.2 Performance Evaluation

According to disagreeable output profiles under 15%-sag unbalanced input voltage condition of the proposed control strategy, as investigated in the previous section, it is consequently evaluated with only 10% sag of single-phase unbalanced input voltage condition. To confirm the performance of the proposed

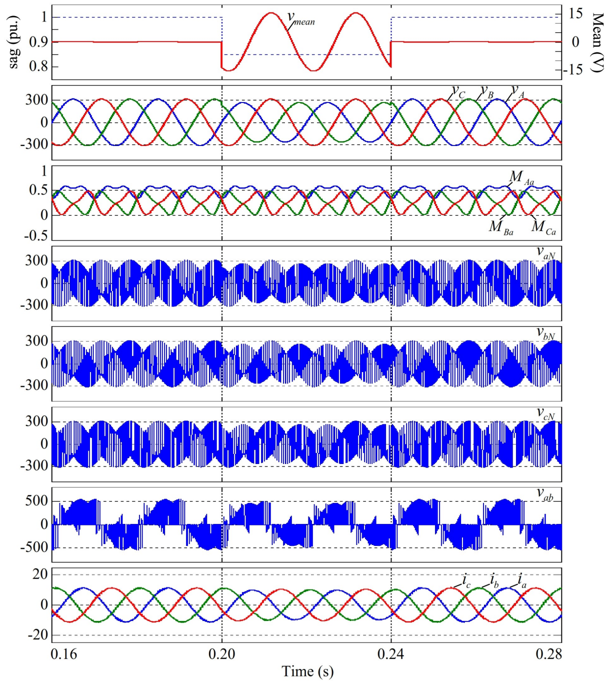



(a)

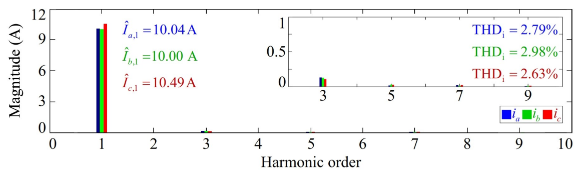



(b)

***Fig.9:*** *Simulated results under the 10% step-sag command for two-phase unbalanced input voltage condition on phases A and B compensated with the proposed control strategy. (a) Waveforms of step-sag command and error, input voltages, duty cycles, pole voltages, line-to-line output voltage, and output currents. (b) Harmonic spectrum of output currents for the period of unbalanced input voltage condition.*




(a)




(b)

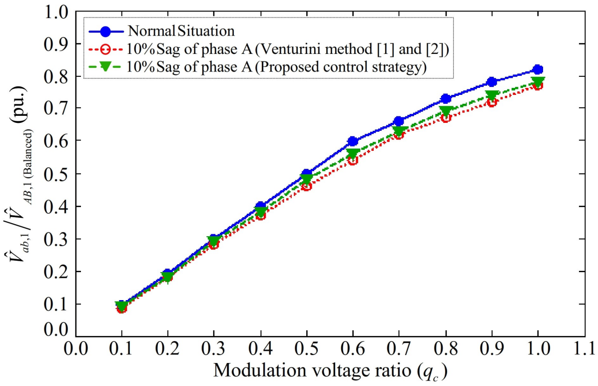
***Fig.10:*** *Simulated results under the 15% step-sag command for two-phase unbalanced input voltage condition on phases A and B compensated with the proposed control strategy. (a) Waveforms of step-sag command and error, input voltages, duty cycles, pole voltages, line-to-line output voltage, and output currents. (b) Harmonic spectrum of output currents for the period of unbalanced input voltage condition.*

control strategy, it is also compared with the conventional Venturini method in terms of the fundamental output magnitude and the output current quality, as shown in Figs. 11(a) and 11(b), respectively. The evaluation of Fig. 11(a) shows that the proposed control strategy can improve the output magnitude of the matrix converter from the conventional Venturini method under the same condition of unbalanced input voltages although it produces the lower output magnitude, when compared to that of the normal situation, with the modulation index of greater than 0.5.

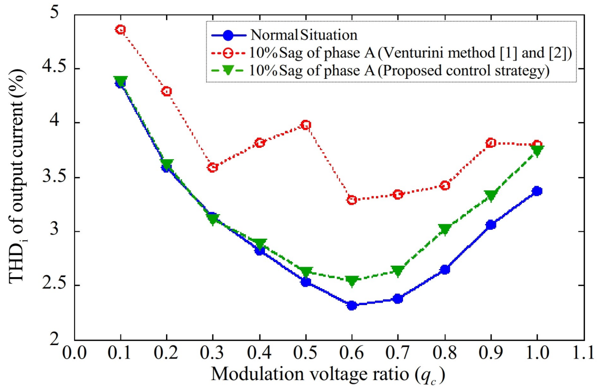
As the $THD_i$ have been illustrated in Fig. 11(b), it is pointed out that the proposed control strategy not only can improve the output magnitude of the matrix converter, but also can improve the output current quality from the conventional Venturini method, when it is operated under unbalanced input voltage condition. Moreover, it also provides the same $THD_i$ tendency, as operated under the non-unbalanced input voltage condition (normal situation). This could well confirm the performance of the proposed control strategy for the matrix converter under unbalanced input voltage condition.

## 5. CONCLUSION

A developed control strategy applying for the matrix converter under unbalanced input voltage conditions has been proposed in this paper without additional energy storages, hardware devices, and complicated control algorithms. With this strategy, the duty cycle calculation based on Venturini method is modified by mathematical analysis on the average and error calculations from the measured input voltages in




(a)




(b)

***Fig.11:*** *Performance evaluation of the proposed control strategy for the matrix converter compared with the conventional Venturini method ([1, 2]).*

order to achieve the sinusoidal and balanced output voltages along with the desirable magnitudes of fundamental components. From the results, it is shown that the proposed control strategy is able to eliminate the low-order harmonic components of the output voltages and provide balanced waveforms under single- and two-phase unbalanced input voltage conditions. Again, the results can confirm the theoretical validity and authenticity of the proposed strategy as well. However, this strategy is unworkable for the sag condition of more than 15% and the three-phase unbalanced input voltage condition.

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