Modeling, Simulation and Analysis of Matrix Converter Using Matlab&Simulink

Hulusi Karaca and Ramazan Akkaya

***Abstract*— In this paper, a matrix converter (MC) which makes directly AC-AC power conversion is modeled using Matlab&Simulink and its working principles are analyzed. The gate signals of the power switches of MC are produced using Optimum Amplitude-Venturini Modulation (OAVM) method. This method provides the amplitude of output voltage up to 86.6% of input voltage, and unity fundamental displacement factor at the input regardless of the load displacement factor. The simulation results obtained from the model at various operating conditions are presented. These results prove effectiveness of the proposed matrix converter model with a unity input power factor. Consequently, the designed Matlab&Simulink model can be confidently used in the construction stage of the OAVM method based matrix converter.**

***Index Terms*—Matrix converter, AC-AC converter, modeling and simulation, OAVM method.**

I. Introduction

One of the most important processes in power electronics is to convert electric power to different forms. In controlling of the electric energy, the great advances are provided together with fast improvements in semiconductor power elements and power electronics converters.

The matrix converter providing directly ac-ac power conversion is one of the most interesting members of the power converter family. Matrix converter firstly introduced in 1976 started to improving after papers of Venturini and Alesina in 1980 [1, 2]. The proposed method by these authors is known as the Venturini method or the direct transfer function approach. In this method, gate-drive signals for the nine bidirectional switches are calculated to generate variable-frequency and/or variable-amplitude sinusoidal output voltages from the fixed-frequency and the fixed-amplitude input voltages.

The MC has some advantages as follows according to traditional converter.

- Generation of output voltages with the desirable amplitude and frequency;
- Energy regeneration aptitude to the mains;
- Sinusoidal input and output currents;
- Controllable of input displacement factor regardless of the load;
- Compact design due to the lack of dc-link components for energy storage.

These fascinating properties have motivated researchers to study about the MC [3, 4].

But, the physical realization of the MC is very difficult, and the number of the devices in the power circuit is higher than that of the inverter. Therefore, it is crucial to obtain an effective model and to test it before constructing a working prototype of the MC. However, popular circuit-oriented simulation software packages such as PSPICE, PSIM and Matlab&Simulink have not got the model of an MC as a standard block in their libraries [5].

In this work, an effective model of the MC is developed by using Matlab&Simulink in order to compensate mentioned necessity. The basic concepts of matrix converter are explained and the mathematical model of matrix converter is briefly given in a clear form. Optimum Amplitude-Venturini Modulation (OAVM) method is used to produce the gate signals driving bidirectional power semiconductors, and a maximum voltage transfer ratio (0.866) was obtained. An input filter is used at input side of converter. It smoothes distortion of the input current around the switching frequency and eliminates the generation of overvoltage produced during commutation of currents due to the presence of the short-circuit reactance of any real power supply. The working principles of MC producing the output voltages at various amplitude and frequency are analyzed. Also, simulation results of OAVM method based matrix converter are given.

II. The Basic Topology of Matrix Converter

The matrix converter is a single-stage converter, which has an array of m x n bidirectional power switches. Each bidirectional switch is composed of two IGBTs and two fast diodes connected anti-parallel. Theoretically, the number of input phases, m must be at least three, and the number of output phases, n can be chosen from one to infinity. The basic matrix converter topology which connects a three-phase voltage source to a three-phase load is shown in Fig. 1. This is the most important matrix converter topology from a practical point of view. A matrix converter is an unlimited frequency changer, which can generate both smaller and bigger output frequency than input frequency of the converter. The output voltage waveforms are constructed by piecing together selected segments of the input voltage waveforms.

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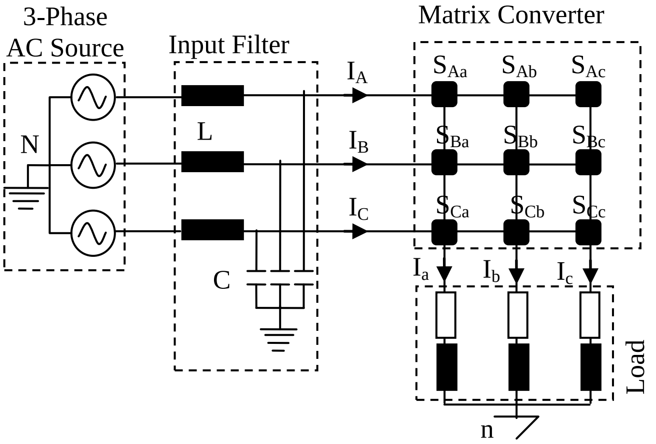


Fig. 1. Circuit of a 3 x 3 matrix converter

Each switch is characterized by a switching function, defined as follows and can connect or disconnect phase *K* of the input stage to phase *j* of the load.

$$S_{Kj}(t)=\begin{cases}0 & Switch, S_{Kj} \text{ is open}\\ 1 & Switch, S_{Kj} \text{ is closed}\end{cases} \qquad (1)$$
$$K=\{A,B,C\},\ j=\{a,b,c\}$$

Output voltages can be synthesized by switching according to a proper combination of these switches.

Control of the matrix converter must comply with the following basic two rules. Firstly, any two input terminals should never be connected to the same output line to prevent short-circuit, because the MC is fed by a voltage source. The other is that, an output phase must never be open-circuited, owing to the absence of a path for the inductive load current which leads to the over-voltages. The above two constraints can be expressed by (2).

$$\begin{aligned} m_{Aa}(t)+m_{Ba}(t)+m_{Ca}(t)=1\\ m_{Ab}(t)+m_{Bb}(t)+m_{Cb}(t)=1\\ m_{Ac}(t)+m_{Bc}(t)+m_{Cc}(t)=1 \end{aligned} \qquad (2)$$

When these rules are provided, the 3 x 3 matrix converter can allow only 27 different switching states among the possible 512 switching combinations.

III. Modeling of OAVM Method Based Matrix Converter

In this paper, V_{sK} are the source voltages, i_{sK} are the source currents, v_{jn} are the load voltages with respect to the neutral point n of the star connected load, and i_j are the load currents. Also, other variables have been defined to be used as a basis of the modulation and control strategies: v_{KN} are the MC input voltages, i_K are the MC input currents, and v_{jN} are the load voltages with respect to the neutral point *N* of the grid.

If t_{Kj} is defined as the time during switch S_{Kj} is on and T_s the switching period, duty cycle of switch S_{Kj} can be given as follows.

$$m_{Kj}(t)=\frac{t_{Kj}}{T_s} \qquad (3)$$

So, modulation matrix can be given as in (4).

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

Under ideal input voltage conditions, the three-phase sinusoidal input voltages of the MC will be as follows,

$$[v_{sK}(t)]=V_{sKm}\begin{bmatrix} cos(\omega_i t)\\ cos(\omega_i t+2\pi/3)\\ cos(\omega_i t+4\pi/3)\end{bmatrix} \qquad (5)$$

In accordance with this, each output phase voltages with respect to the neutral point N of the grid can be expressed by (6).

$$[v_{jN}(t)]=[M(t)][v_{KN}(t)] \qquad (6)$$

In the same way, the input currents are also shown by the following expression.

$$[i_K(t)]=[M(t)]^T[i_j(t)] \qquad (7)$$

Where, $[M(t)]^T$ is the transpose matrix of $[M(t)]$.

The amplitude of the output voltage is limited to 50 percent of the input voltage in the initial approach of Venturini Modulation method. To obtain a maximum voltage transfer ratio, third harmonics of the input frequencies are added to the target output phase voltages and third harmonics of the output frequencies are subtracted from it as given in (8). A Matlab&Simulink model is illustrated to compute the reference output phase voltage in Fig. 2. In this figure, only model of target voltage of the output phase a (V_{a_ref}) is clearly given. Also, models of target voltages of the output phase b and c are like this model.

$$[v_{jN}(t)]=qV_{KNm}\begin{bmatrix} cos(\omega_o t)-\frac{1}{6}cos(3\omega_o t)+\frac{1}{2\sqrt{3}}cos(3\omega_i t)\\ cos(\omega_o t+\frac{2\pi}{3})-\frac{1}{6}cos(3\omega_o t)+\frac{1}{2\sqrt{3}}cos(3\omega_i t)\\ cos(\omega_o t+\frac{4\pi}{3})-\frac{1}{6}cos(3\omega_o t)+\frac{1}{2\sqrt{3}}cos(3\omega_i t)\end{bmatrix} \qquad (8)$$

Where, q is the voltage gain or voltage transfer ratio. By this way, a voltage transfer ratio of 0.866 which is maximum value can be obtained. The third-harmonic injection of the input and output frequencies into the target output voltages has no effect on the output line-to-line voltages [4, 6]. The target output voltage equals the average output voltage during each switching sequence.

If unity input displacement factor is required in the OAVM method [6-8], the algorithm can be simpler in the form of (9) [3, 4, 8].

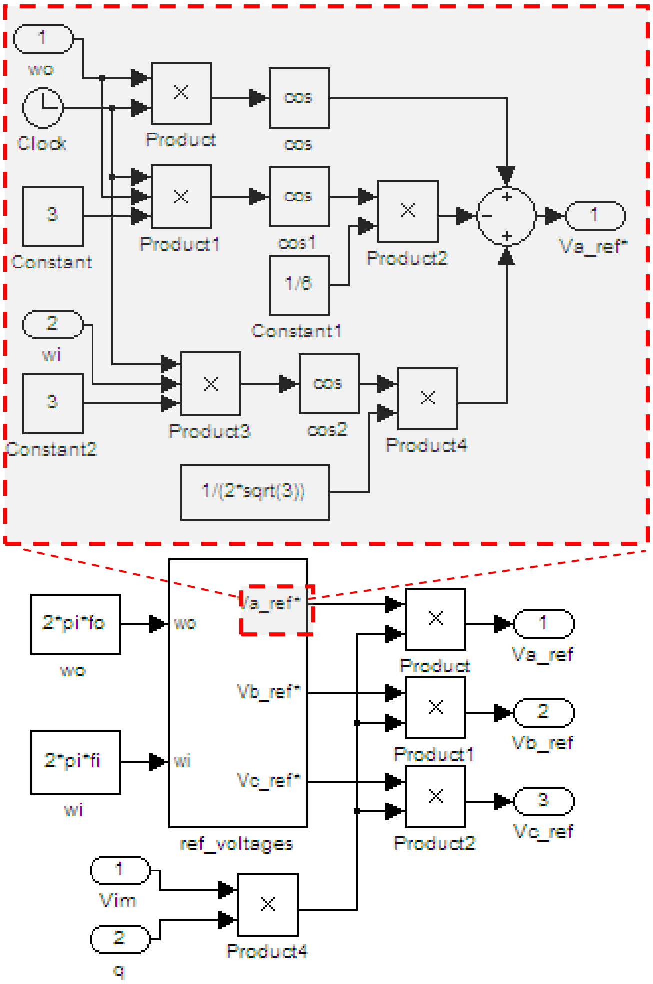


Fig. 2. Third-harmonic injection of the input and output frequencies into the output phase voltages

$$m_{Kj}=\frac{1}{3}\left[1+\frac{2v_{KN}v_{jN}}{V_{KNm}^{2}}+\frac{2q}{3q_{m}}\sin(\omega_i t+\beta_K)\sin(3\omega_i t)\right] \quad (9)$$

$$K=\{A,B,C\},\quad j=\{a,b,c\} \text{ and } \beta_K=0,\frac{2\pi}{3},\frac{4\pi}{3}$$

Then, duty cycles of bidirectional switches are calculated according to (10).

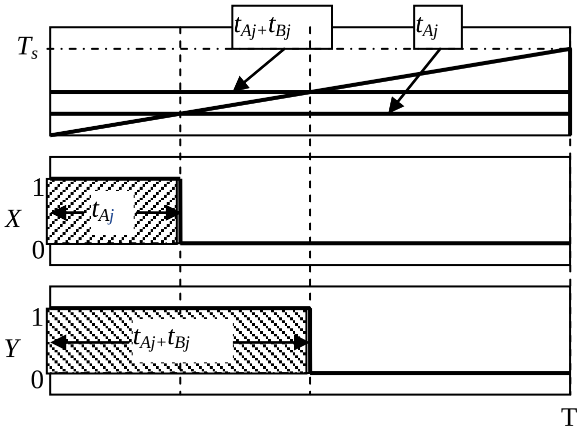


Fig.3. Gate signals of the power switches connected to the same output phase

$$t_{Kj}=T_s\left[\frac{1}{3}+\frac{2v_{KN}v_{jN}}{3V_{KNm}^{2}}+\frac{2q}{9q_{m}}\sin(\omega_i t+\beta_K)\sin(3\omega_i t)\right] \quad (10)$$

As shown in Fig. 3, signals, X and Y are obtained by comparing saw tooth signal with switching frequency and these calculated duty cycles.

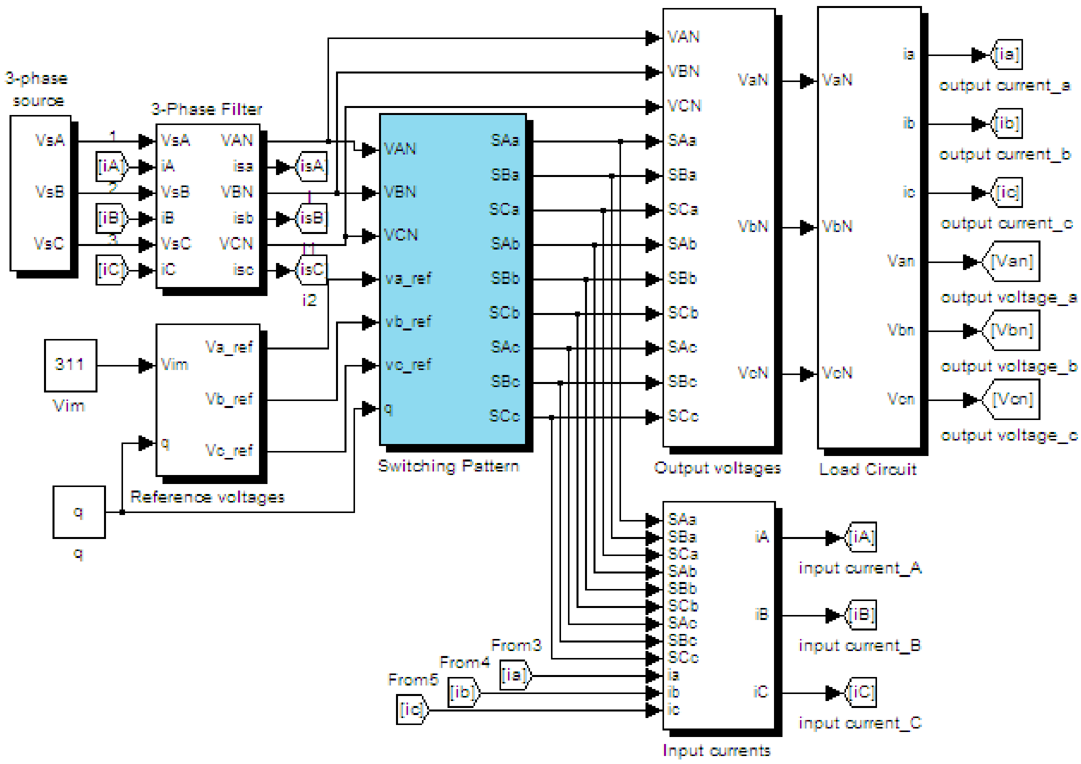


Fig.4. Matlab&Simulink model of the 3 x 3 matrix converter

Final gate drive signals ($SKj(t)$), determining turn-on-time of the power switches can be obtained according to the logic statements in (11) by using duty cycles [5]. Consequently, only duty cycles of six switches are sufficient to calculate the gate signals for all of the power switches

$$\left.\begin{array}{l} X = t_{Aj} \\ Y = t_{Aj} + t_{Bj} \end{array}\right\} \Rightarrow \begin{array}{l} S_{Aj} = (X) \\ S_{Bj} = not\,(X) \;\; and \;\; (Y) \\ S_{Cj} = not\,(X) \;\; and \;\; not\,(Y) \end{array} \qquad (11)$$

A global Matlab&Simulink model of matrix converter which includes models of three-phase source, filter, reference voltage, load, and especially the switching pattern is given in Fig. 4. As a result, input and output currents, output phase voltages with respect to N (v_{aN}, v_{bN}, v_{cN}) and n ($\mathrm{v_{an}}$, $\mathrm{v_{bn}}$, $\mathrm{v_{cn}}$), output line-to-line voltages (v_{ab}, v_{bc}, v_{ca}) of matrix converter controlled with OAVM method are attained using this model.

IV. Simulation Results and Discussion

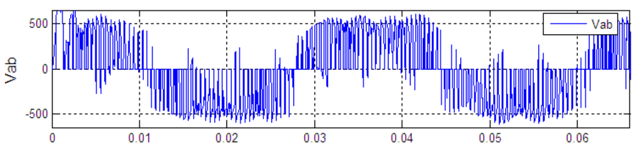
Parameters used in the developed simulation model have been given in Table I.

TABLE I . SIMULATION PARAMETERS

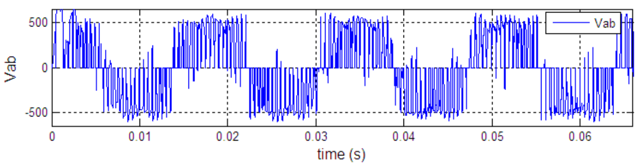
Source voltage amplitude,	*311 V*
Filter inductance,	*3 mH*
Filter capacitance,	*25 μF*
Filter resistance,	*1 Ω*
Load inductance,	*30 mH*
Load resistance,	*10 Ω*
Input frequency,	*50 Hz*
Voltage transfer ratio,	*0.8*
Output frequency,	*30 and 60 Hz*

Simulation of matrix converter has been performed to produce output with variable frequency from input with fixed frequency. In this paper, simulation results have been presented for only output frequencies of 30 and 60 Hz from an input of 50 Hz.

In Fig. 5(a) and Fig. 5(b), output line-to-line voltages for 30 and 60 Hz have been respectively given. As shown, these voltages have pulses with switching frequency but their averages constitute a sinusoidal waveform. That is, third-harmonic injection does not have a negative effect on the output line-to-line voltages.

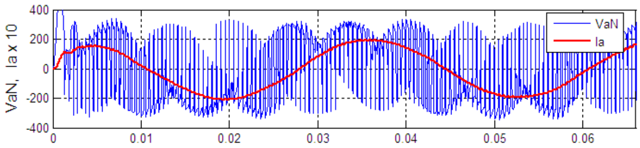


(a)

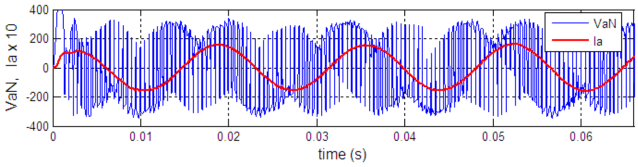


(b)

Fig. 5. Output line-to-line voltage: (a) in 30 Hz (b) in 60 Hz

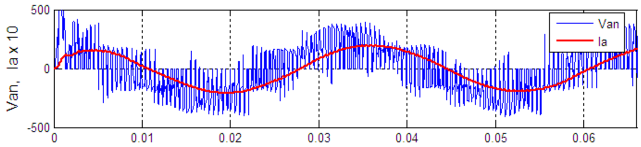


(a)

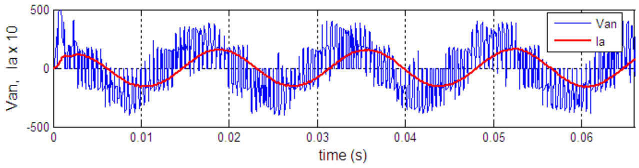


(b)

Fig. 6. Output phase voltage with respect to star point of source and output current: (a) in 30 Hz (b) in 60 Hz

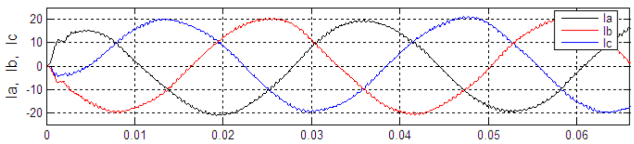


(a)

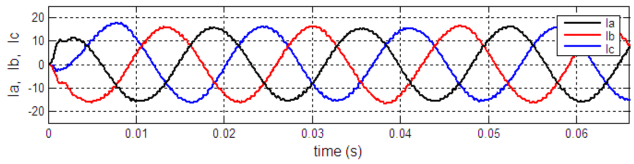


(b)

Fig. 7. Output phase voltage with respect to star point of load and output current: (a) in 30 Hz (b) in 60 Hz



(a)



(b)

Fig. 8. Three phase output current: (a) in 30 Hz (b) in 60 Hz

In Fig. 6(a) and Fig. 6(b), output phase voltage with respect to neutral of source and output current have been shown at output frequencies of 30 and 60 Hz, respectively.

In Fig 7(a) and Fig. 7(b), output phase voltage with respect to neutral of load and output current have been shown. As understood from these figures, output phase voltages have pulses with 2 kHz frequency and average of its waveform is sinusoidal. Besides, output current is lag from output phase voltage due to inductive load.

Three phase output currents have been illustrated at outputs of 30 Hz in Fig 8(a) and 60 Hz in Fig. 8(b). As shown, load currents are nearly a pure sinusoidal in the two-frequency and there is a phase difference of 120 °among the currents.

In Fig. 9, waveforms of source voltage, current drawn from source and load current which are obtained using by the implemented matrix converter model are given on the same axis. As understood from Fig. 9(a) and Fig. 9(b), both frequency of input voltage and input current is 50 Hz, even if frequency of output current is 30 Hz or 60 Hz.

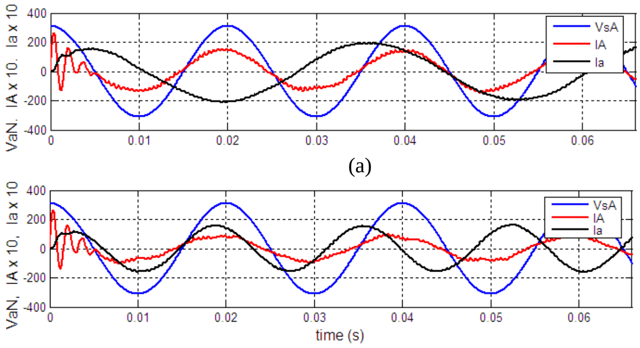


Fig. 9. Input voltage, input current and output current: (a) in 30 Hz (b) in 60 Hz

Input voltage and input current are at the same phase, while output current of matrix converter is lag from output phase voltage due to inductive load. These results prove that the matrix converter can draw current in the unity displacement factor from mains at any load. In addition to, pulses with the switching frequency which are occurred on input current during commutation have been smoothed using a small three input filter.

V. Conclusion

The working principle and analysis of the MC that connects direct three-phase source to three-phase load and controlled with the OAVM method has been presented. Modulation strategies and fundamental mathematical equations of the MC have been presented clearly. Also, modeling and simulation of the OAVM method, which can give an output voltage with maximum amplitude, has been implemented. The designed model has satisfactorily given the behavior of the MC including the impact of the input filter. The simulation results show that the modulation algorithm provides a unity input displacement factor even if the load has an inductive characteristic. As a result, the Matlab&Simulink model presented can be confidently used in the construction stage of the matrix converter.

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