Analysis of Non-ideal Step Down Matrix Converter Based on Circuit DQ Transformation

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Abstract

This paper analyzes non-ideal step down matrix converter (MC) under the control strategy proposed by Venturini [1] using circuit DQ transformation (CDQT) technique [2]. The non-ideal step down MC consists of L, C and switches where L and C act as current and voltage sources, respectively. Closed form solutions for the voltage gain and the input phase angle are obtained from the DQ transformed equivalent circuit.

I. INTRODUCTION

New type of AC to AC converter so called generalized transformer was proposed by Venturini. This converter can be used to reduce or boost the output voltage simultaneously varying the output frequency and the input power factor. Sinusoidal input and output waveforms can also be produced with this converter using small size reactive components. However such a conversion technique was not used widely because number of practical implementation problems existed such as synchronization, protection, slow switching speed and bidirectional capabilities of the power devices.

In recent years the progress of power device and the development of large power integrated circuits have attracted growing interests for the applications of matrix converter (MC) and practical implementations have been considered. However the research about MC is only limited to ideal cases, so far, which contains ideal voltage and current sources and switches. The analysis of practical MC is far beyond that of the ideal MC because of its complexity due to the non-ideal sources such as L and C reactive components.

In this paper we obtained the analytic expressions for the voltage gain, input power factor and so on with ease using the circuit DQ transformation technique (CDQT) [2]. Since it converts rotationary circuit variables to stationary ones through partial fractions and equivalent conversion circuits, the cumbersome nine switches of MC are substituted by equivalent ideal transformers and thereby non-ideal step down MC is analyzed using simple circuit theory. Both the analytic expression and digital computer simulation results are compared in the paper.

II. CDQT OF STEP DOWN NINE SWITCH MC

A. Step Down Nine Switch MC

The AC to AC nine switch matrix converter topology was firstly introduced in 1976 and recently improved significantly using generalized high frequency switching strategy. Fig. 1 shows the power circuit of the AC to AC step down nine switch MC.

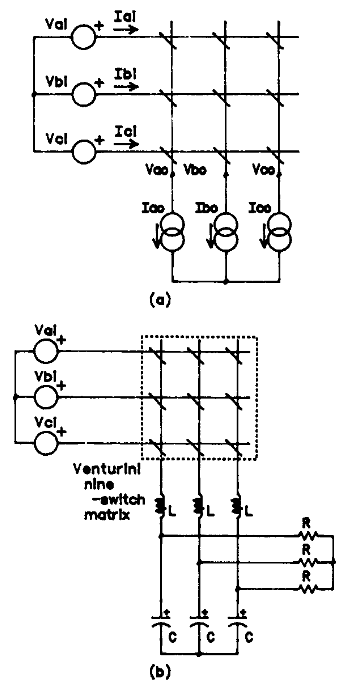

Fig. 1 Step down nine switch MC (a) ideal (b) non-ideal.

Venturini's modulation function M for the control of output voltage, frequency and input power factor is given by

$$[M] = a_1 M_s + a_2 M_a \quad (1)$$

where,

$$M_s = \frac{1}{3}\begin{bmatrix} d_1 & d_2 & d_3 \\ d_3 & d_1 & d_2 \\ d_2 & d_3 & d_1 \end{bmatrix}, \quad M_a = \frac{1}{3}\begin{bmatrix} Ad_1 & Ad_2 & Ad_3 \\ Ad_2 & Ad_3 & Ad_1 \\ Ad_3 & Ad_1 & Ad_2 \end{bmatrix}$$

$d_i = 1 + 2q\cos(\omega_m t-(i-1)a)$, $i = 1,2,3$, $\omega_m = \omega_o - \omega_i$

$Ad_i = 1 + 2q\cos(\omega_a t+(i-1)a)$, $i = 1,2,3$, $\omega_a = \omega_o + \omega_i$

q : voltage control variable, $0 \le q \le 0.5$

a_1, a_2 : forward, reverse power factor control variable

$0 \le a_1, a_2$, $a_1 + a_2 = 1$, $a_1 - a_2 = a$, $a_1 + a_2 = 1$

In this equation, a_1, a_2 and q are the variables for the controls of the output voltage and the input displacement factor. Therefore the elementary switches are modeled based on the relations given by

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$$[V_o] = [M]\,[V_i]$$
$$[I_i] = [M]\,[I_o] \qquad (2)$$

where,

$$V_i = \begin{bmatrix} V_{ai} \\ V_{bi} \\ V_{ci} \end{bmatrix}, \qquad V_o = \begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix}$$

$$I_i = \begin{bmatrix} i_{ai} \\ i_{bi} \\ i_{ci} \end{bmatrix}, \qquad I_o = \begin{bmatrix} i_{ao} \\ i_{bo} \\ i_{co} \end{bmatrix}$$

From eq. (2), applying the control strategy proposed by Venturini, the ideal step down nine switch matrix acts as generalized transformer. But it is nearly impossible to analyze the non-ideal nine switch MC such as shown in Fig.1(b), because it is composed of non-ideal sources and switch elements. The analysis of MC was previously tried with the equational DQ transform method which is conventional 3-ϕ circuit analysis method. This method is useful for the case of ideal sources, but it is very complicated for the non-ideal MC due to L and C reactive elements and switches. This is why the CDQT technique is introduced for the analysis of non-ideal MC. The basic principle of the CDQT is to find out the equivalent circuits for the fundamental frequency whose circuit variables are the filtered stationary variables from the rotationary variables of the converter.

B. CDQT of Step Down Nine Switch Matrix

In this section, let's find out the equivalent stationary circuit for the nine switch set which is the key step to apply the CDQT technique to the matrix converter. The DQ transform of the nine switch matrix is given as follows:

$$\begin{aligned} V_{qdoo} &= K_{wo}\, V_{abco} \\ &= K_{wo}\, M_{abc}\, V_{abci} \\ &= K_{wo}\, M_{abc}\, K_{wi}^{-1}\, V_{qdoi} \\ &= M_{qdo}\, V_{qdoi} \end{aligned} \qquad (3)$$

In the above equation K_{wi} and K_{wo} indicate the DQ transform matrices for the input and output sides, respectively. Therefore, the modulation fouction M for the CDQT is given as follows:

$$M_{qdo} = K_{wo}\, M\, K_{wi}^{-1} = \begin{bmatrix} q & 0 & 0 \\ 0 & \alpha q & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

where,

$$\alpha = \alpha_1 - \alpha_2$$

Equation (4) shows that the DQ transformed equivalent circuit can be represented by two ideal transformers with turn ratios 1 : q and 1 : αq, respectively, as shown in Fig. 2. It is assumed that all switching harmonics are negligible.

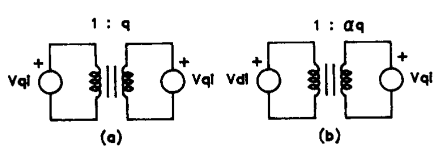


Fig. 2 CDQT of nine switch matrix (a)q-axis (b)d-axis.

C. Circuit Partitioning and CDQT

First step for partitioning is to divide the original circuit into several fundamental sub circuits along the dotted lines indicated in Fig.3. The independent partitioned circuits are obtained regarding the voltages or currents adjacent to the dotted line before partitioning as the external sources. Then the equivalent DQ transformed circuits are obtained respectively as shown in Fig. 4 assuming all elements are balanced.

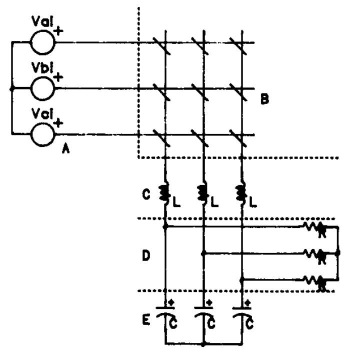


Fig. 3 Partitioning of MC for DQ transform.

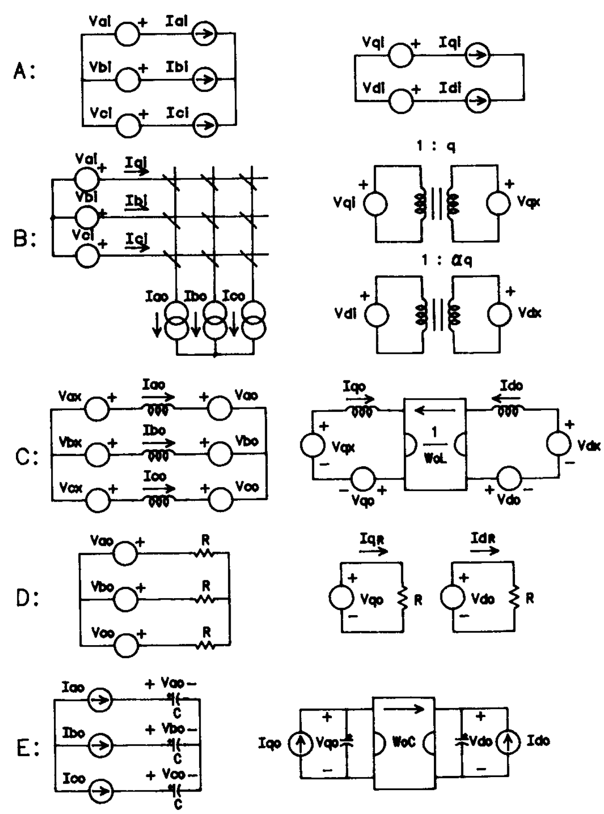


Fig. 4 Partitioned subcircuits(left sides) and there equivalent CDQTs(right sides).

D. Circuit Reconstruction

The reconstructions of the DQ transformed subcircuits in Fig. 4 are done by matching the external sources and connecting the adjacent subcircuits as shown in Fig. 5. Therefore the DQ transformed circuit of Fig. 1(b) can be simply drawn as shown in Fig. 5. In this case, the switching frequency is assumed much higher than the cut off frequency of the circuit LC filter so that the switching harmonics are negligible compared with the fundamental component.

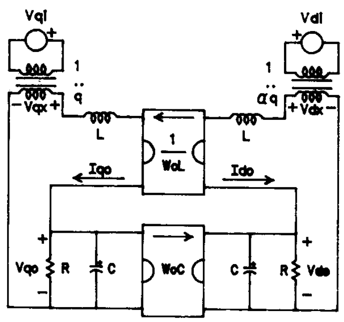


Fig. 5 Equivalent circuit for step down nine switch MC.

III. ANALYSIS OF STEP DOWN NINE SWITCH MC

A. Steady State Analysis

The analysis of the step down nine switch MC can be divided into steady state and transient state cases from Fig. 5. The steady state model is obtained simply by eliminating the reactive elements. Therefore the equivalent circuit and signal flow graph for the non-ideal MC at steady state are shown in Fig. 6.

For convenience, let the initial phase of input voltage source equal to q-axis, then the DQ transformed value of input voltage has only q-axis component. The transfer function G_{vd} between input and output is obtained by Mason's gain formula as

$$G_{vd} = \frac{1}{\Delta}\left[\left(\frac{V_{qo}}{V_{qi}}\right)^2 + \left(\frac{V_{do}}{V_{qi}}\right)^2\right]^{1/2} \tag{5}$$

where,

$$\Delta = 1 - \left\{\frac{1}{\omega_o^2LC} + \frac{1}{\omega_o^2LC} - \left[\frac{1}{\omega_oR_2C}\right]^2\right\} + \left[\frac{1}{\omega_o^2LC}\right]^2$$

$$= \left\{1 - \frac{1}{\omega_o^2LC}\right\}^2 + \left\{\frac{1}{\omega_oR_2C}\right\}$$

$$\frac{V_{qo}}{V_{qi}} = q\cdot\left(\frac{-1}{\omega_o^2LC}\right)\cdot\left(1 - \frac{1}{\omega_o^2LC}\right)$$

$$\frac{V_{do}}{V_{di}} = q\cdot\left(\frac{-1}{\omega_o^2LC}\right)\cdot\left(\frac{-1}{\omega_o^2LC}\right)$$

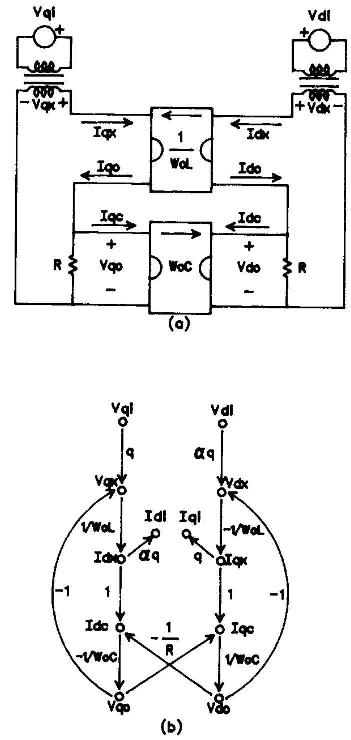


Fig. 6 Steady state (a) equivalent circuit (b) signal flow graph.

Therefore we obtain

$$G_{vd} = \frac{q}{\sqrt{(1-\omega_o^2LC)^2 + (\omega_oL/R_2)^2}} \tag{6}$$

This equation shows that the non-ideal step down MC is directly proportional to gain control variable q as in the case of ideal MC and it is also under the influence of output frequency and circuit component values.

The input displacement angle which is used for the input power factor is obtained as follows:

$$\phi_i = -\tan^{-1}\left(\frac{I_{di}}{I_{qi}}\right)$$
$$= -\tan^{-1}\{\alpha\omega_o(\omega_o^2C^2R^2L + L - R^2C)/R\} \tag{7}$$

In the above equation, it is shown that the input displacement angle is directly proportional to the phase control variable α and is a function of output frequency and circuit values as in the case of G_{vd}.

Therefore in spite of their complexity in structure, G_{vd} and ϕ_i of non-ideal step down MC are given by very simple closed form expressions and the equations show that they can be controlled independently as in the case of ideal MC by gain control variable q and phase control variable α of the modulation function **M**, respectively.

B. Transient State Analysis

The equivalent circuit and signal flow graph of transient state are obtained as shown in Fig. 7.

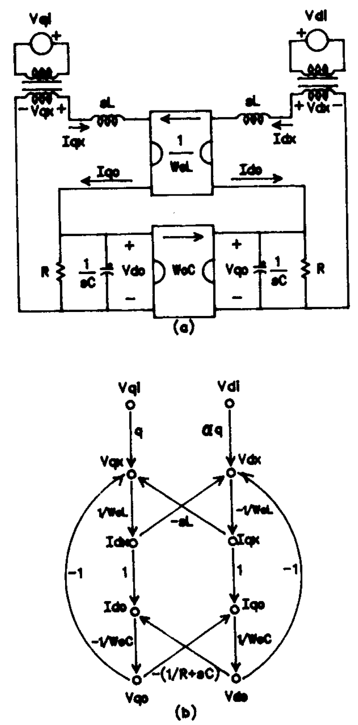


Fig. 7 Transient state (a) equivalent circuit (b) signal flow graph.

From the signal flow graph, the transfer function G_{vt} is obtained as

$$G_{vt} = \frac{\sqrt{P_q^2 + P_d^2}}{\Delta} \tag{8}$$

where,

$$P_q = \frac{V_{qo}}{V_{qi}} = q \cdot \left(\frac{1}{\omega_o^2 LC}\right)^2 \cdot \left\{(1 - \omega_o^2 LC) + s^2 LC + s\frac{L}{R_2}\right\}$$

$$P_d = \frac{V_{do}}{V_{qi}} = q \cdot \left(\frac{1}{\omega_o^2 LC}\right)^2 \cdot \left\{2s\,\omega_o LC + \frac{\omega_o L}{R_2}\right\}$$

$$\Delta = s^4 \cdot \frac{1}{\omega_o^4} + s^3 \cdot \frac{2}{\omega_o^4 R_2 C} + s^2 \cdot \left\{\left(\frac{1}{\omega_o^2 R_2 C}\right)^2 + \frac{2}{\omega_o^2} + \frac{2}{\omega_o^2 LC}\right\} + s \cdot \frac{2}{\omega_o^2 LC} \cdot \left\{1 + \frac{1}{\omega_o^2 LC}\right\} + \left\{1 - \frac{1}{\omega_o^2 LC}\right\}^2 + \left\{\frac{1}{\omega_o^2 R_2 C}\right\}$$

The result showns that the non-ideal step down nine switch MC can be modeled as fourth order system.

IV. SIMULATION RESULTS

The analysis results using CDQT and digital computer simulations are compared as shown in Fig. 8. The difference between CDQT and digital computer simulation increases as the output frequency increases. This phenomenon is due to the influence of the switching harmonics since the ratio of switching frequency to the fundamental frequency decreases relatively as the output frequency increases. The dynamic characteristics can similarly be evaluated from Fig. 5 as in the steady state case. Fig. 9 represents that G_v and power factor of non-ideal step down MC are independently controllable by gain control variable q and phase angle control variable α. Fig. 10 and 11 represent the transient responses for three different output frequencies and two different switching frequencies respectively. They show that the higher the switching frequency increases, the smaller the error between CDQT and simulation becomes.

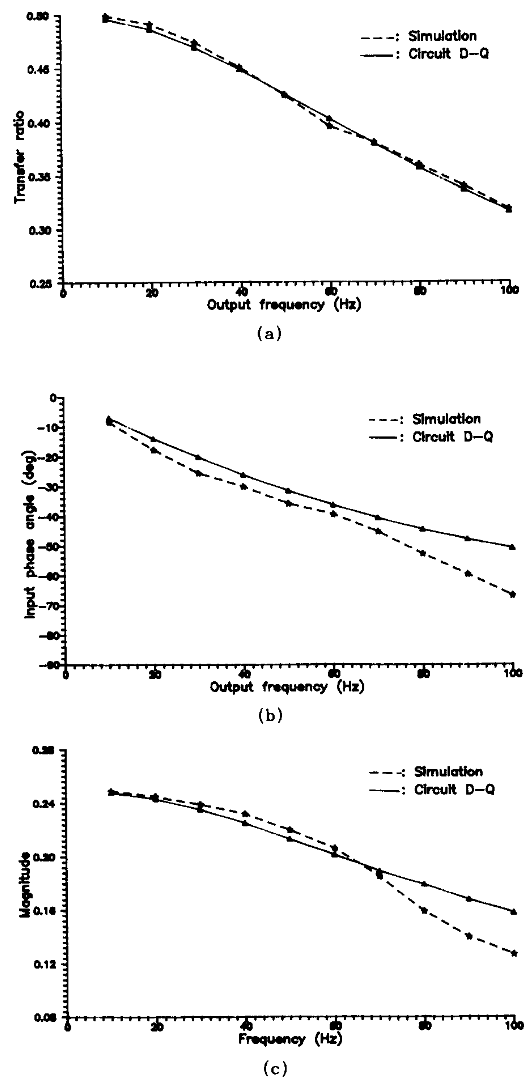
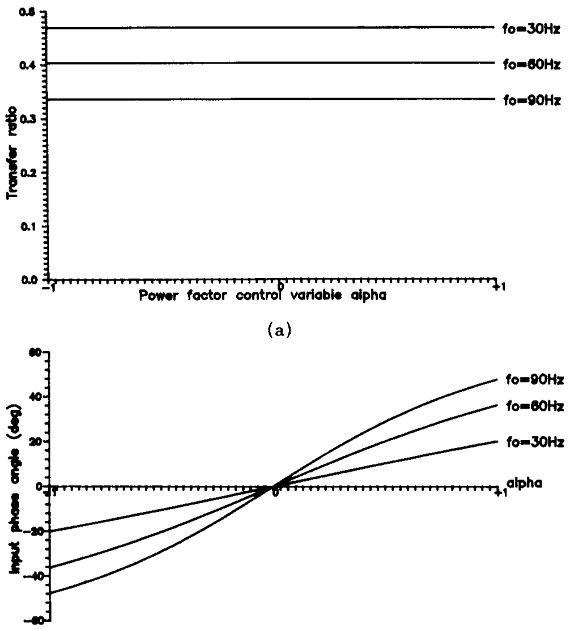


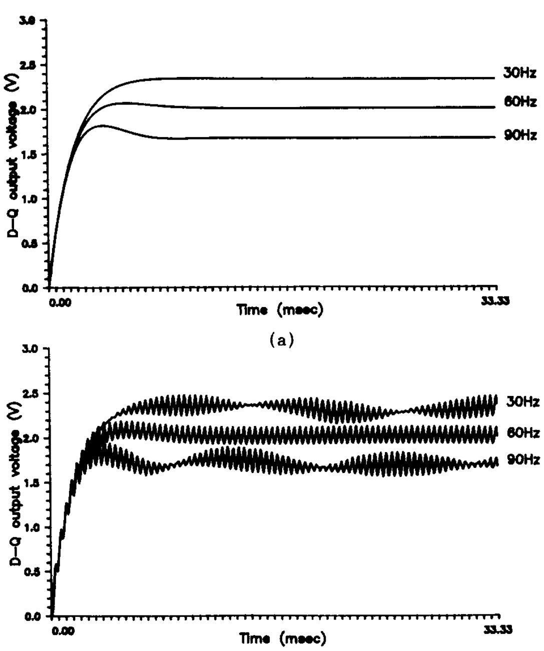
Fig. 8 Steady state response for variable output frequency varying at L=10mH, C=10μF, R_2=5Ω and q=0.5 : (a) transfer ratio (b) input phase angle (c) input current.



(a)

(b)

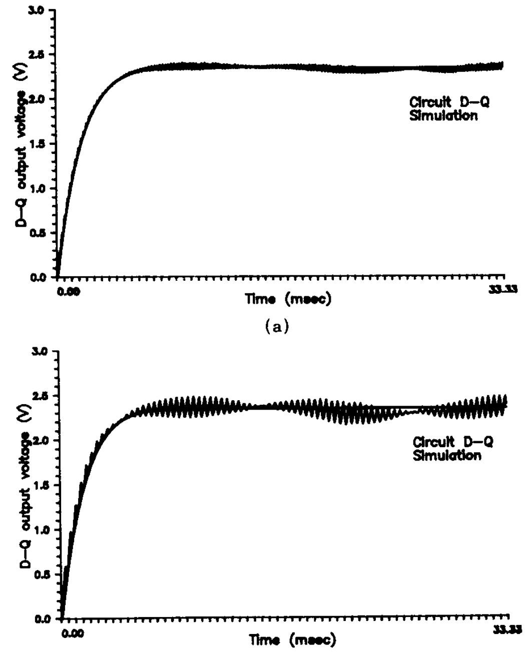
Fig. 9 Steady state response for power factor control at L=10mH, C=10μF, R_2=5Ω and q=0.5 : (a) transfer ratio (b) input phase angle.



(a)

(b)

Fig. 10 Transient DQ output response for three different output frequencies at L=10mH, C=10μF, R_2=5Ω : (a) circuit DQ output (b) time simulation.



(a)

(b)

Fig. 11 Transient DQ output response for two different switching frequencies at L=10mH, C=10μF, R_2=5Ω : (a) switching freq. = 4.8 kHz (b) switching freq. = 2.4kHz.

V. CONCLUSION

Non-ideal step down matrix converter (MC) is analyzed by applying the circuit DQ transformation technique. CDQT allows us to model the circuit including switches and reactive elements as a simple RLC circuit with ideal transformers. By doing so analytic solutions are obtained in closed forms. It is also shown that G_V and power factor of non-ideal step down MC are functions of converter circuit parameters and output frequency and they are independently controllable like the ideal step down MC by gain control variable q and phase angle control variable α of the Venturini's modulation function. Therefore non-ideal step down MC can be controlled to preserve the unity power factor over the full range of output voltage and frequency irrelevant to the load variation. In spite of the switching harmonics, the fundamental behavior closely coincides with the result of CDQT analysis.

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