An Analysis of Power Quality of Matrix Converters when using a Fryze reference

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Abstract— **Static power converters produce harmonics due to the nature of the conversion process. This paper will investigate the effect on the power factor of a sinusoidal and Fryze current reference on Matrix Converters. It has been shown in previous papers that a Fryze current ref is best. This paper will develop a mathematical model, based on the single sided Fourier expansion. Using this mathematical model it will be shown that even though a high harmonic content could be present in a Fryze controlled Matrix Converter; the power factor will have been improved**

Index Terms-- **Matrix converter model power quality**

I. INTRODUCTION

A 3x3 matrix converter is a direct AC-to-AC forced commutated converter (see figure 1)). The topology of a 3x3 matrix converter does not have an intermediate energy storing dc-link capacitor. This specific topology provides for both voltage and/or infinite frequency modification, through a single stage converter, directly connecting the input source to the output load. The specific switching elements of the matrix converter consist of a controlled bi-directional four quadrant switch. A matrix converter can provide an output of varying frequency and amplitude.

Matrix converters are growing in popularity from an interesting power electronic converter to a viable industrialised direct AC-AC converter.

The term 'matrix converter' was coined by Venturini and Alensia when they presented their work on direct AC-AC converters in [1] and [2].

The authors developed and formalized the analysis and design of a 3x3 matrix converter in [3]. The paper mathematically defined the output amplitude limitations of the matrix converter. It was shown that, depending on the modulation technique, the output voltage can be either 50% or 86.6% of the maximum input voltage. This control method was later referred to as the direct transfer function approach [4]. Although [4] is a review, the discussion is limited to brief summaries of the various aspects of matrix converters. This paper places an emphasis on present modulation and control techniques.

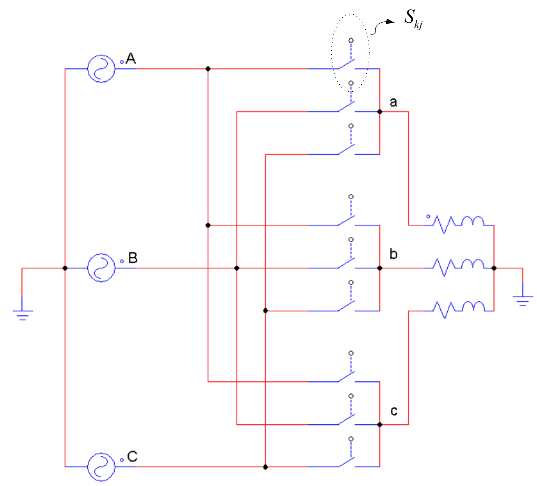

Figure 1 Matrix Converter

The theory and modulation of a 3x3 matrix converter was further researched. A novel control method was introduced by Rodriguez [5]. This method has been termed the indirect transfer function. Rodriguez proposed that the switching pattern should resemble that of a Voltage Source Inverter (VSI): the output line/load is switched between the most positive and most negative rail of the input using a pulse width modulation technique. This method implies the use of a virtual DC-link capacitor in the control methodology.

Research topics progressed further with the focus shifting from a theoretical approach to more practical applications for variable speed drives for electrical motors [6], [7], [8], [9], [10] and [11]. The direct frequency conversion functionality of the matrix converter is practically useful as a variable frequency drive; due to the smaller form factor and lack of bulky energy storage capacitors. This is evidenced and documented in [12], [13] and [14].

Naturally for development of industrial applications, other operational aspects of the matrix converter were covered. Protection, commutation and operation under abnormal conditions are discussed in [15], [16], [17] and [18].

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II. FUNDEMENTAL DEFINITIONS

The fundamentals of matrix converters are described in [1], [2] and [4] and are summarized below. The switching function of the bi-directional switch may be defined as [19]:

$$S_{Kj} = \begin{cases} 1 & switch\, S_{Kj}\, closed \quad K = \{A, B, C\} \\ 0 & switch\, S_{Kj}\, open \quad j = \{a, b, c\} \end{cases} \tag{1}$$

Subject to the constraint

$$S_{Aj} + S_{Bj} + S_{Cj} = 1 \tag{2}$$

The input and output voltages, expressed as vectors, are referenced the neutral of the supply:

$$\mathbf{v_o} = \left[v_a(t) \quad v_b(t) \quad v_c(t) \right]^T \tag{3}$$

And

$$\mathbf{v_i} = \left[v_A(t) \quad v_B(t) \quad v_C(t) \right]^T \tag{4}$$

Where $v_{a,b,c}$ *(t)* is the respective output voltage and $v_{A,B,C}$ *(t)* is the respective input voltage. The relationship between the input and output voltage may be expressed as the instantaneous transfer matrix

$$\mathbf{v_o} = \mathbf{S} \cdot \mathbf{v_i} \tag{5}$$

Where $\mathbf{S}$ is the switch state

$$\mathbf{S} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Bc}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \tag{6}$$

In the same fashion the input and output current may be expressed as:

$$\mathbf{i_o} = \left[i_A(t) \quad i_B(t) \quad i_C(t) \right]^T \tag{7}$$

And

$$\mathbf{i_i} = \left[i_a(t) \quad i_b(t) \quad i_c(t) \right]^T \tag{8}$$

Where $i_{a,b,c}$ *(t)* is the respective input currents and $i_{A,B,C}$ *(t)* is the respective output current. The relationship between the input and output current may be expressed as the transpose of the instantaneous transfer matrix

$$\mathbf{i_i} = \mathbf{S}^T \cdot \mathbf{i_o} \tag{9}$$

III. HARMONIC DEFINATIONS USING A SINGLE SIDED FOURIER EXPANSION

When a linear circuit is subjected to a forcing function, the complete circuit response will consist of a transient response and a forced response. Steady state linear AC circuit theory is derived from the forced response of circuits when subjected to a sinusoidal forcing function.

This concept may be expanded to accommodate definitions for circuits subjected to multi-frequency forcing functions i.e. distortion.

For a sinusoidal single-frequency system, *v* and *i* are both time dependant functions and may be written as:

$$v(t) = \sqrt{2}V\cos(\omega t + \alpha) \tag{10}$$

$$i(t) = \sqrt{2}I\cos(\omega t + \alpha) \tag{11}$$

Equations (10) and (11) may be written in a more generalized complex function:

$$v(t) = \sqrt{2}Ve^{j\alpha}e^{j\omega t} \tag{12}$$

$$i(t) = \sqrt{2}Ie^{j\beta}e^{j\omega t} \tag{13}$$

The complex function is now expressed in two separate parts. The first is a complex constant and the second is a function of time that implies rotation in the complex plane. The complex phasor $\boldsymbol{V} = \sqrt{2}Ve^{j\alpha}$ is termed the transform of *v*(*t*). The same is valid for (27). Multi-frequency systems imply non-linearity and do not lend themselves to the definition of a phasor. If the multi-frequency forcing function is periodic then the Fourier analysis produces discrete responses in the frequency domain. Each of these responses is sinusoidal with unique phase and magnitude. Each of these discrete responses may be defined with a phasor. The single sided complex Fourier series of a distorted periodic voltage or current waveform may be expressed as:

$$v(t) = \sum_{n=0}^{\infty} \sqrt{2}V_n e^{jn\omega t} \tag{14}$$

$$i(t) = \sum_{n=0}^{\infty} \sqrt{2}I_n e^{jn\omega t} \tag{15}$$

A distorted voltage can be analyzed with Fourier to obtain the discrete sinusoidal components. The composite voltage or current profile may be obtained by summing the individual harmonic time dependent components.

$$v(t) = V_1 \sin\omega t + \sum_{n=3,5...}^{\infty} V_n \sin(n\omega t + \alpha_n) \tag{16}$$

$$i(t) = \sum_{n=1,3,5...}^{\infty} I_n[\sin(n\omega t + \beta_n) + \cos(n\omega t + \beta_n)] \tag{17}$$

The IEEE STD defines distortion factor (sometimes referred to as harmonic factor) as: The ratio of the root mean square of the harmonic content to the root mean square value of the fundamental quantity, expressed as a percent of the fundamental. *Total Harmonic Distortion* (THD) is a term which has come in to common usage to define either voltage or current 'distortion factor'[20]. The IEEE STD 519:1992 defines distortion factor (*DF*) and total harmonic distortion as one and the same. In other words it is a measure of the closeness in shape between a waveform and its fundamental component:

$$DF = \sqrt{\frac{\sum_{n=2}^{k} |V_n|^2}{|V_1|^2}} \tag{18}$$

Individual harmonic distortion is a measure of the contribution of an individual harmonic frequency contribution to the distortion and may be defined as:

$$IHF_n = \frac{|V_n|}{|V_1|} \tag{19}$$

Power factor is the measure of how effectively a load draws real power. Power factor is a dimensionless quantity. A power factor of 1.0 is ideal as the imaginary power component is zero. As defined by the IEEE STD, power factor is the ratio of the total power input, in watt, to the total Volt-Ampere input.

Displacement power factor is the ratio of the active power of the fundamental, in watt, to the apparent power of the fundamental.

IV. Reference Current

Ideally the Matrix Converter should generally draw a sinusoidal current that is in phase with the input voltage. The current reference for the Matrix Converter may be either sinusoidal (20) or a Fryze type (21):

$$i_{ref\_s}(t) = K_i V_1 \sin(\omega t) \tag{20}$$

$$i_{ref\_F}(t) = K_i \sum_{n=1,3,5...}^{\infty} V_n \sin(n\omega t + \varphi_n) \tag{21}$$

where *Ki* is a conversion constant.

The choice for the reference current between sinusoidal or Fryze is further analyzed using the power factor (*PFs*) defined as the ratio of active power (*P*) over apparent power (*S*).

The active power in case of distorted input voltage (16) with sinusoidal reference (20) can be written as:

$$P_s = \frac{1}{2\pi} \int_0^{2\pi} \left[\sum_{n=1,3}^{\infty} V_n \sin(n\omega t + \varphi_n) \right] \cdot [K_i V_1 \sin(\omega t)] d(\omega t) \tag{22}$$

The active power may be simplified to

$$P_s = K_i \frac{V_1^2}{2} \sum_{n=1,3}^{\infty} \frac{V_n}{V_1} \tag{23}$$

The power factor may be written as

$$PF_s = \frac{P_s}{V_{RMS} I_{RMS}} = \frac{V_{1-RMS}^2}{V_{RMS}^2} \sum_{n=1,3}^{\infty} \frac{V_n}{V_1} \tag{24}$$

Additionally, the active power in the case of distorted input voltage (16) and a Fryze reference (21) can be written as:

$$P_F = \frac{1}{2\pi} \int_0^{2\pi} \left\{ \left[\sum_{n=1,3,5}^{\infty} V_n \sin(n\omega t + \varphi_n) \right] \bullet \left[K_i \sum_{n=1,3,5}^{\infty} V_n \sin(n\omega t + \varphi_n) \right] \right\} d(\omega t) \tag{25}$$

$$P_F = K_i \sum_{n=1,3,5...}^{\infty} \left(\frac{V_n^2}{2} \right) = K_i V_{RMS}^2 \tag{26}$$

The current drawn using the Fryze reference has the RMS value different to the supply voltage by the same constant Ki and:

$$PF_F = \frac{P_F}{V_{RMS} I_{RMS}} = \frac{K_i V_{RMS}^2}{K_i V_{RMS}^2} = 1 \tag{27}$$

The observant reader will note that the power factor is UNITY when using the Fryze reference. For a sinusoidal reference, the power factor is dependent on the distortion of the supply voltage

V. Conclusion

When selecting a current reference for current mode control for a Matrix Converter the ideal current reference should be the Fryze current reference. With a Fryze current reference the power factor will have a higher value than any other method as per IEEE definition of power factor.

It is still not perfect unity because of the effect of switching frequency which can be seen as noise. A current which is proportional to the input voltage (Fryze reference) is better for the individual load and the power supply; it practically creates a "linear/resistive load". However, the harmonic content is higher than when using a sinusoidal reference.

Using the balanced sinusoidal reference, the current profile will be sinusoidal in nature, but the power factor is not optimally improved. A poor power factor will result in in-efficient use of the electrical capacity of the electrical device.

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