Using PSIM to Investigate Harmonic Control for Boost-type PWM Rectifiers

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***Abstract*-- Static power converters produce harmonics due to the nature of the conversion process. This paper will investigate two variations of current mode control for three-phase power converters ensuring reduced harmonic pollution and power factor improvement. The first method employed uses a Fryze current reference and the second method utilises a balanced three-phase sinusoidal reference. Both control techniques are simulated under unbalanced and distorted supply conditions using the PSIM simulation platform. The results are presented showing that using the Fryze current reference is the best choice.**

***Index Terms*—Control Systems, harmonics, power electronics, reactive power, simulation.**

I. Introduction

Control of harmonic pollution in electrical systems by power converters may be as simple as adding a simple filter [1] or dynamically controlling the current drawn [2]. The control strategy of the power converter is usually developed for ideal balanced supply conditions. As a result a balanced sinusoidal reference may be used. The effectiveness of the method and others will be discussed and simulated.

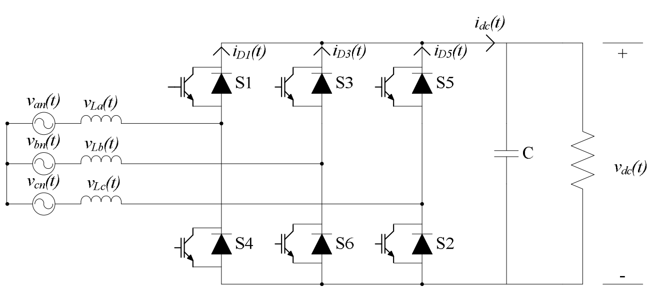

Figure 1 PWM Boost rectifier

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II. Background

Each combination of IGBT and anti-parallel diode will be considered as a single switch. If no switching occurs, the configuration of the anti-parallel diodes will function as an uncontrolled rectifier. The converter consists of three phase arms. The switch modules, S1 and S4, are connected to Phase A, switch modules S3 and S6, are connected to Phase B, and the switch modules S5 and S2, are connected to Phase C. It can be said that the converter consists of two halves. The upper half (S1, S3 and S5), which is connected to the positive rail and the lower half (S2, S4 and S6) is connected to the negative rail. Each switch module can conduct current in either direction but block voltage in one direction only. This converter is a two-quadrant converter.

Following the methods of [3] and [4]; to simplify the notation let the switches connected to phase A be designated S_a, the switches connected to phase B be designated S_b and the switches connected to phase C be designated S_c. The state of each switch may be further expressed in terms of a binary value, either a '1' or a '0'. Then if S_a=1 the upper switch (i.e. S1) is conducting and if S_a=0 (i.e. S4) then the lower switch is conducting. S_b and S_c keep to the same condition.

From three phase circuit theory the following may be written for a balanced system:

$$v_{an}(t)+v_{bn}(t)+v_{cn}(t)=0 \tag{1}$$

and

$$i_a(t)+i_b(t)+i_c(t)=0 \tag{2}$$

The following equations may be written for the three phase circuit in figure 1:

Phase A:

$$L\frac{di_a(t)}{dt}+Ri_a(t)=v_{an}(t)+\frac{v_{dc}(t)}{3}(S_b-2S_a+S_c) \tag{3}$$

Phase B:

$$L\frac{di_b(t)}{dt}+Ri_b(t)=v_{bn}(t)+\frac{v_{dc}(t)}{3}(S_c-2S_b+S_a) \tag{4}$$

Phase C:

$$L\frac{di_c(t)}{dt}+Ri_c(t)=v_{cn}(t)+\frac{v_{dc}(t)}{3}(S_a-2S_c+S_b) \tag{5}$$

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The inference of the binary definition of each bi-directional switch is that only one switch in each phase arm will conduct.

A. Control

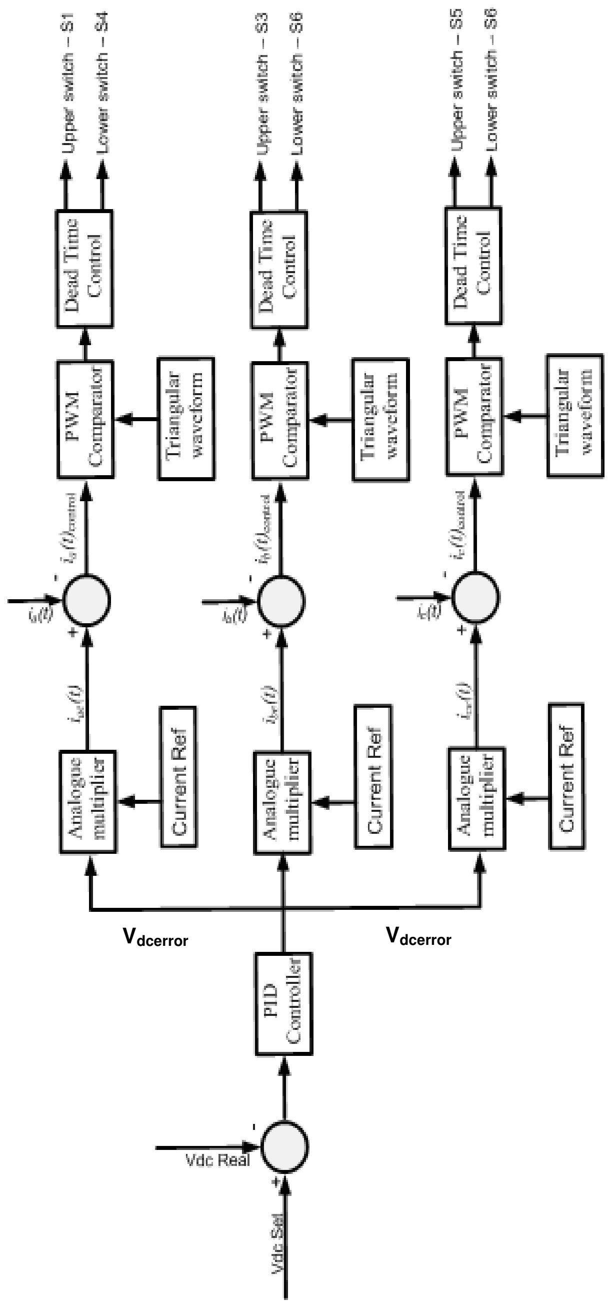

Fig. 2 Proposed Control

The control system must furnish a control signal to facilitate the switching of the converter to draw a near sinusoidal current at unity power factor as well as maintaining a constant DC supply. A potential control method is direct current control [2]. This method allows the amplitude and phase of the input current to be accurately controlled. This is done by measuring the instantaneous phase currents and forcing them to follow a predetermined template. This template may be either the Fryze current reference or a sinusoidal reference.

Current mode control can be implemented using either hysteresis or PWM.

From the equations (3), (4) and (5), each phase supply will see an effective DC voltage of $\pm\frac{2}{3}v_{dc}(t)$, $\pm\frac{1}{3}v_{dc}(t)$ or 0 depending on the switching pattern.

According to [3] if a hysteresis tolerance band controller is used the zero state gives no control of the line currents and periodically causes the line currents to exceed the hysteresis limit by a factor of 2. This zero state can cause unnecessary stress on the switching devices.

The switching frequency, which varies continuously, may be determined by considering (3). For simplicity the source and line resistance will be ignored. (3) can be re-arranged as:

$$\Delta t = \frac{L\Delta i_a(t)}{v_{an}(t) - V_{dc}(t)} \quad (6)$$

This varying switching frequency results in varying high-order current harmonics which can be difficult to filter from the line current. A PWM control method is thus more desirable. By operating the converter at a fixed switching frequency, the high order harmonics can easily be filtered out. The proposed control method will employ a PWM method, having a fast response time and eliminating the problem of a variable switching frequency. A PWM switching scheme does generate fixed high order harmonics, which may be filtered from the line, if required.

The object is to provide a constant DC voltage. In a closed loop control system, feedback is required to adjust the system parameters to bring the output in line with the desired set point. The signal conditioned by the PI controller may be expressed in the complex s plane as:

$$(V_{dc}set - V_{dc}real)\cdot(K_p + \frac{K_i}{s}) = V_{dc}error \quad (7)$$

This signal (7) is multiplied against a current reference template, to yield the current error, $i_{ne}(t)$. This value is subtracted from the actual current value to yield $i(t)_{control}$ which is compared against a triangular signal at a fixed frequency to produce a PWM signal.

Briefly, when the DC load-current increases, the capacitor voltage decreases, increasing the **'Vdc error'** signal. This increases the current error signal $i(t)_{control}$ increasing the input current drawn by the converter. A larger current injects more power to the DC capacitor, increasing the DC voltage. If the DC voltage is too large the procedure will be reversed.

In section III the simulation results, under unbalanced and distorted supply conditions, will be discussed.

B. Harmonic definitions

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:

$$v(t) = \sqrt{2}V\cos(\omega t + \alpha) \tag{8}$$

$$i(t) = \sqrt{2}I\cos(\omega t + \beta) \tag{9}$$

Equations (6) and (7) may be written in a generalised complex function:

$$v(t) = \sqrt{2}\boldsymbol{V}\mathrm{e}^{\mathrm{j}\alpha}.\mathrm{e}^{\mathrm{j}\omega t} \tag{10}$$

$$i(t) = \sqrt{2}\boldsymbol{I}\mathrm{e}^{\mathrm{j}\beta}.\mathrm{e}^{\mathrm{j}\omega t} \tag{11}$$

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 (11). 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:

$$\boldsymbol{v}(t) = \sum_{\mathrm{n}=0}^{\infty} \sqrt{2}\,\mathbf{V}_n\,\mathrm{e}^{\mathrm{j}nwt} \tag{12}$$

$$\boldsymbol{i}(t) = \sum_{\mathrm{n}=0}^{\infty} \sqrt{2}\,\mathbf{I}_n\,\mathrm{e}^{\mathrm{j}nwt} \tag{13}$$

The n^{th} order voltage and current time dependent complex quantities may be expressed as:

$$\boldsymbol{v_n}(t) = \sqrt{2}V_n\mathrm{e}^{\mathrm{j}\alpha}.\mathrm{e}^{\mathrm{j}nwt} \tag{14}$$

$$\boldsymbol{i_n}(t) = \sqrt{2}I_n\mathrm{e}^{\mathrm{j}\alpha}.\mathrm{e}^{\mathrm{j}nwt} \tag{15}$$

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'[5]. The IEEE STD defines distortion factor 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.

$$DF = \sqrt{\frac{\sum_{\mathrm{n}=2}^{\mathrm{k}} |V_n|^2}{|V_1|^2}} \tag{16}$$

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

$$IHF_{\mathrm{n}} = \frac{|V_n|}{|V_1|} \tag{17}$$

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.

A distorted voltage or current can be analysed 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.

III. Simulation Results

A boost-type PWM rectifier and the proposed control method were simulated in PSIM ver. 7.1. The supply was unbalanced and distorted. In the simulation, the amplitude unbalance and phase displacement values of the supply were:

$$\begin{bmatrix} v_r \\ v_w \\ v_b \end{bmatrix} = \begin{bmatrix} 310\cos(\omega t + 0^\circ) \\ 310\cos(\omega t + 115^\circ) \\ 300\cos(\omega t - 135^\circ) \end{bmatrix} \tag{18}$$

In the first instance a Fryze current reference was used. This is where the real, instantaneous magnitude and phase displacement of the phase voltage is used as a template for the current as mentioned before.

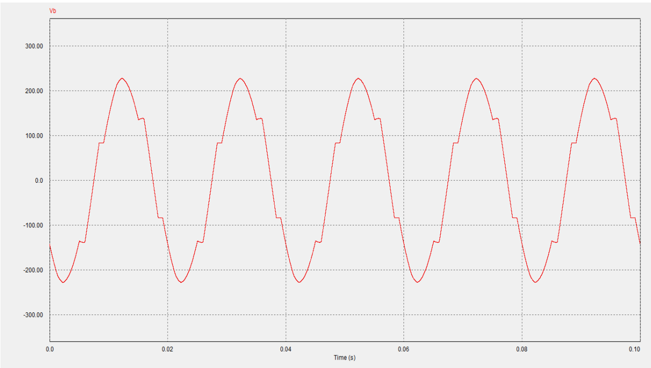

Fig. 3 Distorted Phase Voltage

Figure 3 shows the simulated distorted phase voltage of the blue phase. The voltage notching is clearly visible. This voltage profile will form the template for the phase current in the blue phase i.e. Fryze Current reference. In a similar fashion the red phase voltage profile and the white phase voltage profile will be the red and white phase currents templates respectively.

Figure 4 shows the phase currents as a result of the phase voltage templates. As a result, each phase current will be in phase with the respective phase voltage, improving the power factor. Figure 5 shows the improved power factor, despite the voltage distortion. However the trade-off is that the phase current will have a high content of harmonics. The FFT of the simulated phase current is shown in figure 6. The Y-axis has a log scale

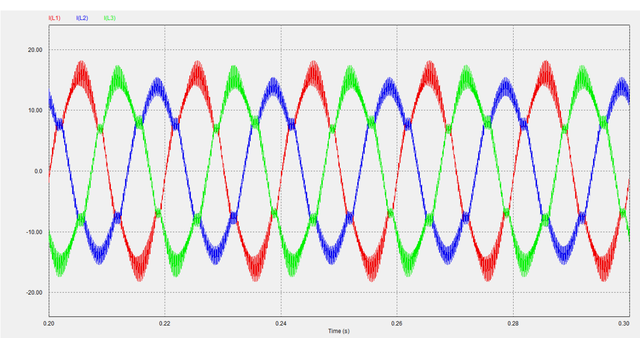

Fig. 4 Phase Currents

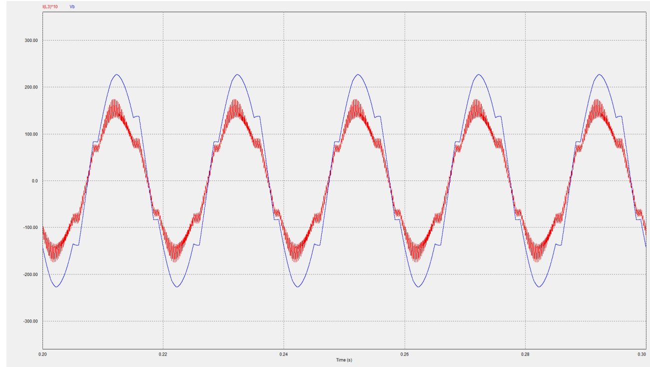

Fig. 5 Magnified current with Voltage profile

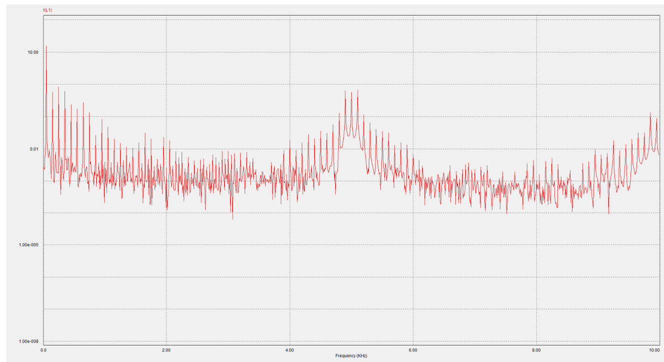

Fig. 6 FFT analysis of the Fryze Current

If the current reference in the control loop is replaced with a balanced three phase sinusoidal supply, the simulation results are as follows:

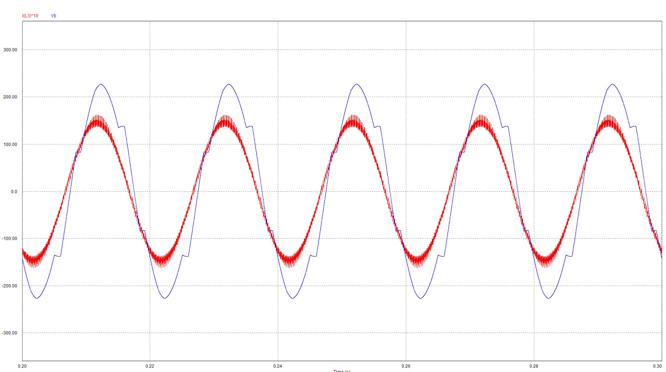

Fig. 7 Phase current using a sinusoidal current reference

The phase current, as expected, will be sinusoidal in nature with limited harmonic content; however the power factor has not been optimised.

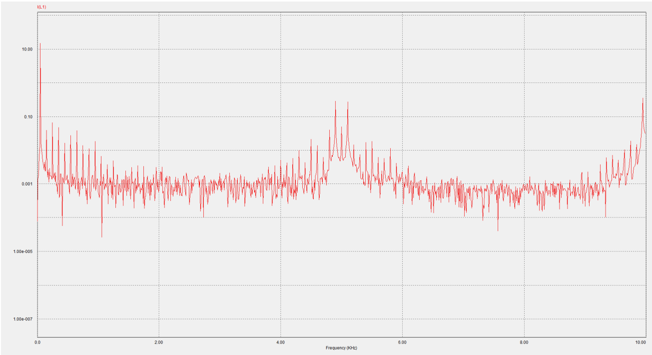

Figure 8 FFT of the Phase Current using a sinusoidal current reference

IV. Conclusions

In the paper two possible current references were compared for use in current mode control. The use of a sinusoidal reference resulted in the converter drawing a sinusoidal current. The drawback under unbalanced and distorted conditions is that the power factor will not be optimally improved.

The use of the Fryze reference current yields an improved power factor. Additionally the harmonic content can be filtered out.

A current which is proportional to the input voltage is better for the individual load and the power supply. When selecting a current reference for current mode control for boost-type PWM rectifiers, the ideal current reference must be the Fryze current reference.

II. References

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Appendix 1

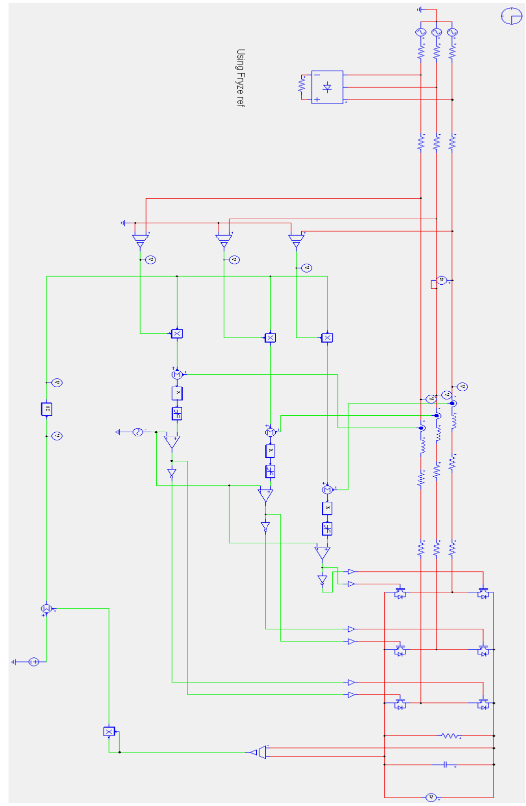

Fig. 9 PSIM layout when using a Fryze ref

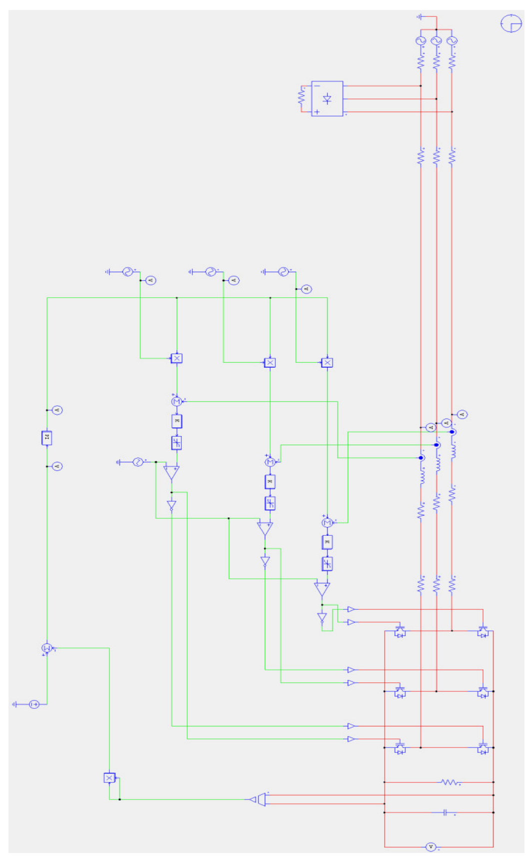

Fig. 10 PSIM layout when using a sinusoidal ref