Analysis of the PWM Boost Type Rectifier under Unbalanced Input Voltage Conditions

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Abstract – PWM Boost Type Rectifiers are ideal for the front-end converter of an Uninterruptible Power Supply (UPS) because they generate nearly sinusoidal input currents at a unity power factor. [1] [2] In the past, UPSs have solved, caused, and been affected by power quality problems. The PWM Rectifier now allows UPSs to stop causing power quality problems, even the compatibility problems when used in conjunction with a stand-by diesel generator. This paper analyzes how a UPS using a PWM Rectifier front-end can still be affected by power quality problems. Unbalanced input voltages can generate significant input current distortion, dc capacitor ripple current and voltage, and more importantly, the generation of sub-harmonic components in the inverter output voltages. [1] [2] Analytical results of an Open-Loop configuration are presented as well as a simulation of a 1-kVA PWM Rectifier under 3% and 22% voltage unbalance using SABER.

I. INTRODUCTION

In the past year, UPS manufactures have introduced new lines of UPSs featuring PWM Rectifier front-ends. The benefits include standby generator compatibility, low input current distortion, and unity input power factor. Other benefits of PWM rectifiers include controllability of the DC link voltage and instantaneous reversal of power flow. Unfortunately, these benefits are only fully realized when the input voltage is balanced. [1] [2] Unbalanced input voltages can occur for a variety of reasons: Utility/Customer unbalanced loads, unbalanced source impedance, and weak supplies such as a standby generator.

Under unbalanced input voltages large lower order harmonics appear at the input and output ports of the rectifier. In the open loop configuration, unbalanced input voltages cause a 2nd harmonic at the DC bus which reflects back to the input causing a 3rd harmonic input current to flow. [1] [2]

To avoid poor performance caused by unbalanced input voltages, PWM Rectifiers designers can increase the input filters [2] or use sophisticated closed loop control techniques such as Indirect Current Control, Hysteresis, or Feed-Forward. [1] These closed loop techniques are not presented in this paper.

This paper analyzes the following PWM Rectifier in the open-loop configuration for voltage unbalances of 2.9% and 22%:

Power Rating = 1kW
Vin = 70.71 Vrms at 50Hz
Vout = 316 Vdc
Filter Inductor = 1mH
Filter Capacitor = 100uF
Load = 100 ohm resistor

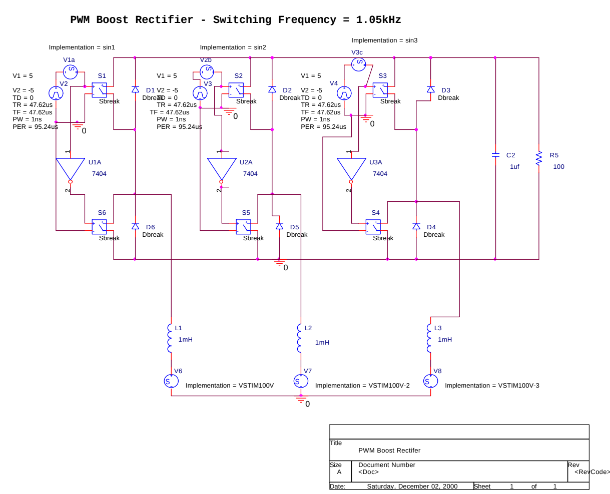


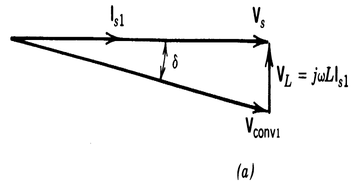
Fig. 1 Pspice rendering of PWM Boost Rectifier

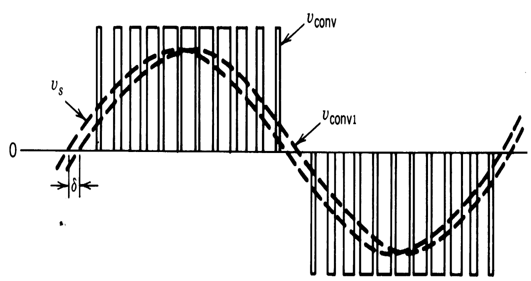
II. THEORETICAL APPROACH

Power flow in the PWM converter is controlled by adjusting the phase shift angle δ between the source voltage V_1 and the respective converter reflected input voltage V_{conv1} also known as V_{s1} (synthesized voltage). As shown below in the per phase equivalent circuit and phasor diagram.

This phase shift is accomplished in PWM control by adjusting phase shift angle δ between the control voltage, $V_{control}$, with respect to the source voltage V_1 since $V_{control}$ is related to V_{s1} by the following equation

$$V_{conv1} = ½ V_{dc} S1\sin(wt - \theta)$$



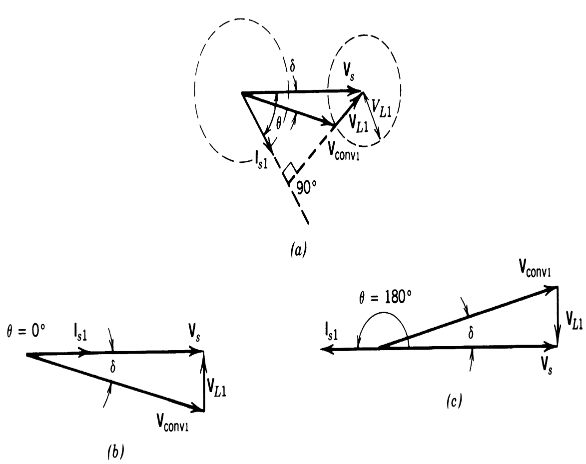


Where S1 the amplitude modulation ratio (ma) and θ is the phase angle shift of the balanced PWM switching function SW1.

When V_1 leads V_{conv1} the real power flows from the source in to the converter. Conversely, if V_1 lags V_{conv1}, real power flows from the converter's dc side into the ac source (inverter mode). [3]

The ac power factor is adjusted by controlling the power factor of $V_{conv1.}$ The phasor diagram on figure 3 shows that to achieve a unity power factor, V_{conv1} has to be

$$V_{conv1} = \sqrt{V_1^2 + (X_1 I_1)^2}$$



Rectification and inversion: (a) general phasor diagram; (b) rectification at unity power factor; (c) inversion at unity power factor.

Figure 3. Phasor Diagram.

The real power transferred is given by the equation

$$P = (V_1 * V_{conv1})/X_1 * \sin(\delta)$$

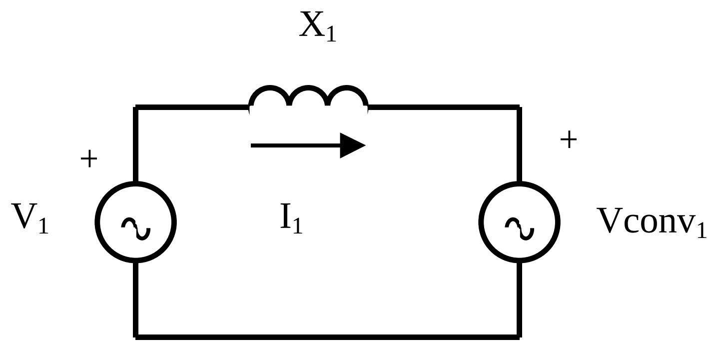


Figure 4. Per phase equivalent circuit.

The next step is to select controller parameters to so the rectifier delivers 1 kW to the load at unity power factor and 316Vdc.

- $1000\ W = Vdc^2 / R$, $Vdc = 316\ V$
- $X_L = 2 * \Pi * f * L = .314\ \Omega$
- $1000W = 3 * 70.71 * I_L * \cos(0)$, $I_L = 4.715\ A$
- At unity PF, solve for $V_{conv1} = \sqrt{V_1^2 + (X_1 I_1)^2}$ $V_{conv1} = 70.725\ V$
- Solving for δ in the per phase real power flow equation δ = sin-1((333.3 *.314) / (70.71 * 70.725) Yields: d **= 1.1976°**
- From the converter switch equation

  $S1 = m_a = (2 * V_{conv1}) / Vdc$, $\mathbf{m_a = .6329}$

III. SIMULATION AND EXPERIMENTAL RESULTS

The PWM Rectifier was modeled in SABER and simulations were run for the balanced and two unbalanced cases.

The simulation data includes:
1. Source Voltages
2. Reference Voltage Sources (Control Voltage)
3. Input Current and FFT
4. Output Voltage and FFT
5. Output Power and FFT

Using Vtri = 10V at 2 kHz and balanced control voltages $V_{conv1} = ½ V_{dc} S1\sin(wt - \theta)$ for the three simulations:

$V_{conv1a} = 6.329 \sin(314t – 1.1976)$
$V_{conv1b} = 6.329 \sin(314t – 121.1976)$
$V_{conv1c} = 6.329 \sin(314t + 118.8024)$

Input Voltage Sources
For three cases

	Case A Balanced		Case B 2.9% Unbalanced		Case C 22% Unbalanced	
	Mag.	Ph.	Mag.	Ph.	Mag.	Ph.
Vsa	100	0	100	0	90	0
Vsb	100	-120	105	-120	65	-120
Vsc	100	120	104	120	95	120

A. Simulated Results for the Balanced Case

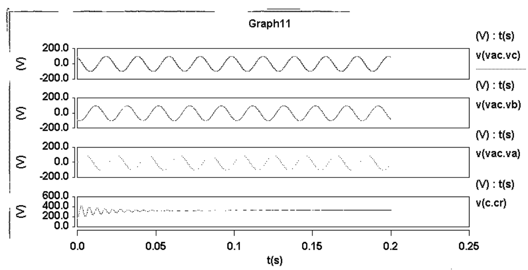


Fig. 5 Balance Input Voltages.

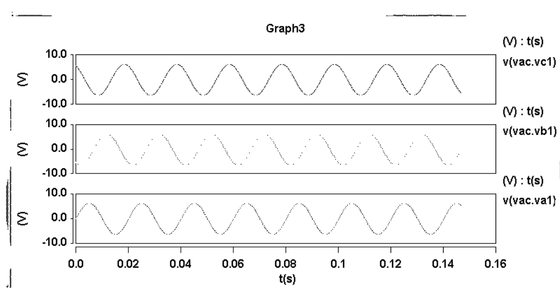


Fig. 6 Balanced Control Voltages.

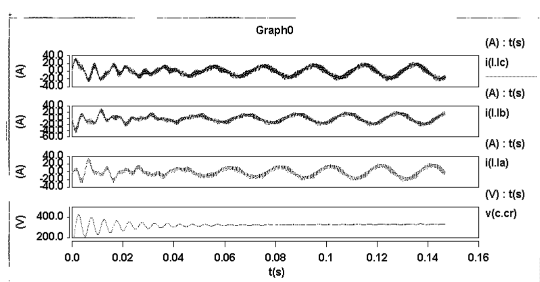


Fig. 7 Balanced Sinusoidal Input Currents.

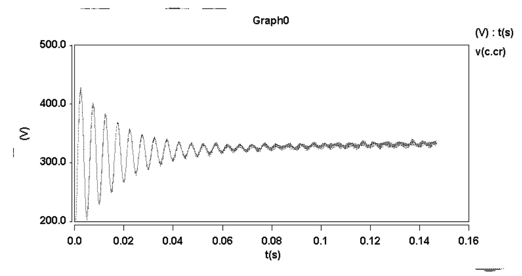


Fig. 8 Output Voltage = 316 Vdc.

B. Simulated Results for 2.9% Voltage Unbalance

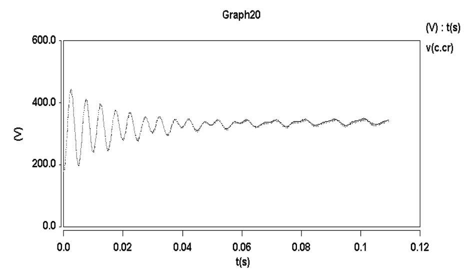


Fig. 9 Output Voltage with Ripple.

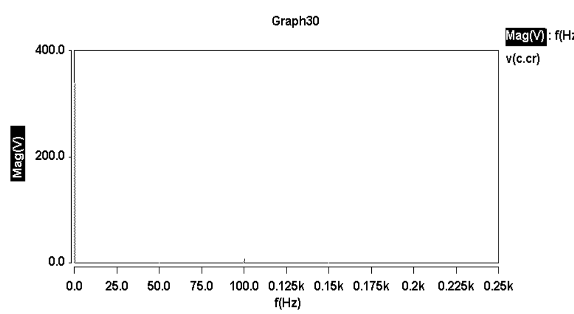


Fig. 10 Output Voltage has 2nd harmonic.

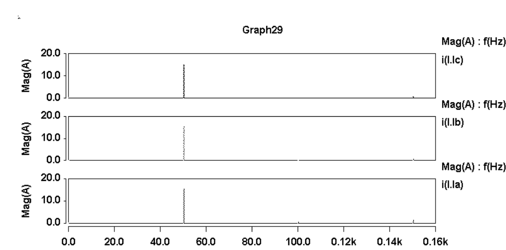


Fig. 11 Input Current has 3rd harmonic.

C. Simulated Results for 22% Voltage Unbalance

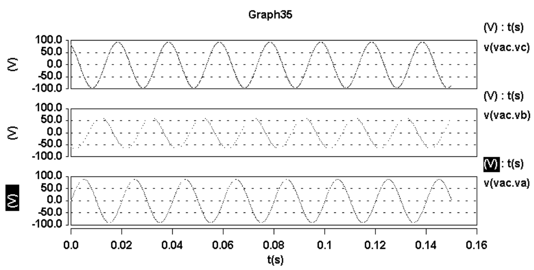


Fig. 12 Input Voltage 22% Unbalanced.

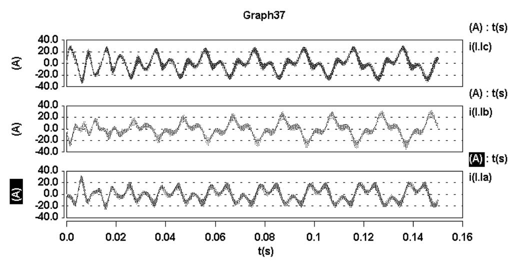


Fig. 13 Input Currents Severely Distorted.

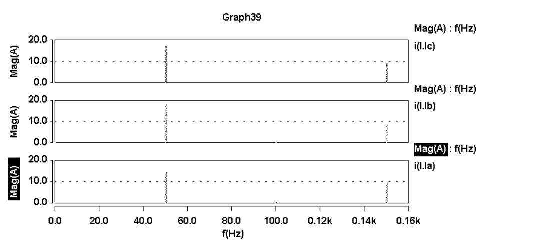


Fig. 14 Input Current has Severe 3rd harmonic.

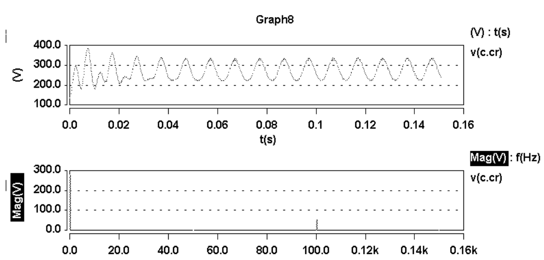


Fig. 15 Output Voltage has Severe Ripple and 2nd Harmonic.

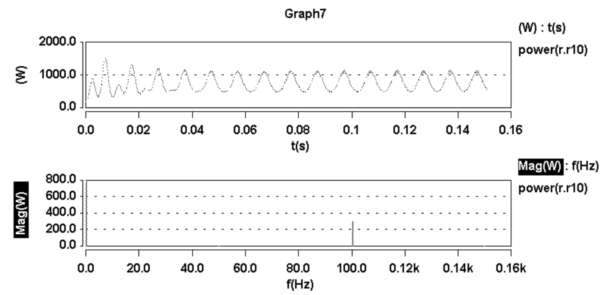


Fig. 16 Output Power has Severe Ripple and 2nd Harmonic Distortion.

IV. CONCLUSION

In this paper, the analysis of PWM Boost Type Rectifier under Unbalanced Input Voltage Conditions has been presented. The analysis has included the harmonic assessment of input/output current and voltage waveforms. It has been theoretically shown that the input voltage unbalance generates uncharacteristic low-frequency harmonic components in the input and output currents. Specifically, with unbalanced input voltages, even harmonics will flow at the output and odd harmonics will flow at the input. [1] [2]. The dominant even harmonic is the 2nd harmonic. The dominant odd harmonic is the 3rd harmonic. The output voltage ripple and output power ripple increases dramatically as well. Finally, the input power factor decreases and the input currents increase due to lower input voltage and the poor power factor.

REFERENCES

[1] A. V. Stankovic and T. A. Lipo, "A Novel Control Method for Input Output Harmonic Elimination of the PWM Boost Type Rectifier Under Unbalanced Operation Conditions," *IEEE APEC 2000*, pp. 413-418, Feb. 6-10, 2000.

[2] L. Moran, P. D. Ziogas, and G. Joos, "Design Aspects of Synchronous PWM Rectifier-Inverter System Under Unbalanced Input Voltage Conditions, "*IEEE Transactions on Industry Applications, vol. 28, no. 6, pp.1286-1293, Nov./Dec. 1992.*

[3] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc, New York, 1995.