Design and Experimental Results of a 6kW Single-Switch Three-Phase High Power Factor Rectifier Using Multi-Resonant Zero Current Switching

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Abstract - The design and breadboard implementation of a single-switch three-phase high power factor multi-resonant rectifier delivering 147 V (DC) at 6 kW from a 3φ 240 V (L-L, rms) AC input is described. This rectifier has continuous input and output currents. By the use of a multi-resonant scheme, the transistor operates with zero current switching and the diodes operate with zero voltage switching. This paper focuses on the design, implementation, and performance of the rectifier. High quality input current waveforms at nearly unity power factor, wide load range, and low stresses on the semiconductor devices are attained. The total harmonic distortion (THD) of the line current is less than 5% and the system efficiency is about 94% at full load.

I. Introduction

Numerous publications [1-8] have treated the power factor correction of three-phase ac-dc power supplies. Moreover, the resonant buck-type high power factor rectifiers have been introduced in [1,2,4,6]. It was shown in [1,2,4] that, even though a resonant circuit is used, the transistor currents are lower than those in an equivalent PWM 3φ-dc converter. In addition, the zero current switching property makes this approach well-suited for applications employing IGBTs. However, these buck-type rectifiers in [4] have pulsating input current hence require an extra input filter.

Recently, a new family of buck-type single-switch three-phase high power factor rectifiers have been introduced [1,2] which have continuous input current and constant output current. By the use of a multi-resonant scheme, the transistor operates with zero current switching, and the diodes operate with zero voltage switching. These rectifiers are capable of drawing a high quality input current waveform at nearly unity power factor with a single transistor. Moreover, these rectifiers have a wide load range with low voltage and current stress on the transistor.

In this paper, the design and breadboard implementation of a single-switch three-phase high power factor multi-resonant rectifier [1,2] delivering 147 V (DC) at 6 kW from a 3φ 240 V (L-L, rms) AC input is described. High quality input current waveforms at nearly unity power factor, wide load range, and low stresses on the semiconductor devices are attained. Experimental results demonstrate total harmonic distortion of less than 5% at the full output power, less than 3.5% THD at 50% output power, and less than 2% THD at 10% output power, in an open loop rectifier. The rectifier efficiency is about 94% at full load.

In Section II, the benefits and special characteristics of the 3φ single-switch high power factor multi-resonant buck-type rectifiers [1,2] are briefly reviewed.

In Section III, a design procedure for this rectifier is described. Extensive experimental results at 6 kW are reported in Section IV which verify the rectifier performance.

Fig. 1. The basic converter circuit and ideal waveforms of the new single transistor three-phase multi-resonant zero current switching high power factor rectifier.
II. Review of Single-Switch Three-Phase High Power Factor Rectifiers Using Multi-Resonant Zero Current Switching

A. Benefits and special characteristics

Figure 1 shows the basic circuit diagram and ideal waveforms of the single-switch 3\(\phi\) multi-resonant ZCS HPF rectifier. The inductance \(L_a\) and the capacitors \(C_{11}-C_{13}\) and \(C_d\) form the multi-resonant tank circuit and lead to zero current switching in the transistor and zero voltage switching in the diodes. Moreover, the voltage waveforms of the resonant tank capacitors \(C_{11}-C_{13}\) are pulsating sinusoidal with peaks proportional to the input line currents. From Fig. 1, the resonant voltage waveshapes of \(V_{C11}-V_{C3}\) can be divided by three different periods. During the first period \((t_0-t_1)\), \(V_{C11}-V_{C3}\) are increasing linearly with slope proportional to the respective input currents \(i_1-t_1\). During the second period \((t_1-t_4)\), the resonant capacitors \(C_{11}-C_{13}\) are ringing together with the resonant tank inductor \(L_v\), until \(V_{C11}-V_{C3}\) reach zero voltage. Finally during \((t_4-t_5)\), \(V_{C11}-V_{C3}\) remain at zero for the third period. Hence, if the first period is longer than the sum of second and third periods, then the input current waveform becomes more proportional to the input voltage waveform. Indeed, it is a good design, if the first period is longer than the second and third periods. This property yields an average or low frequency component in the phase voltage approximately proportional to the line current. The multi-resonant scheme significantly reduces the second and third periods. Hence, low harmonic rectification is obtained. Inductors \(L_a, L_v, L_c,\) and \(L_d\) are filter inductors with small current switching ripples. The converter is basically a buck topology, with output voltage controllable between zero and approximately the peak ac line-line voltage.

This rectifier has many advantages. These advantages include: (a) High power factor, low harmonic rectification is performed naturally. (b) Input and output currents are continuous. (c) Because of the buck-type rectifier property, the output voltage is lower than the peak input line-line voltage and hence the voltage stress on the transistor is lower than in the boost-type rectifier. (d) Wide range of the load power variation is achieved. (e) Use of a single controlled switch, such as an IGBT, operating at zero current switching with good switch utilization. (f) Simple control circuit. The transistor on-state time is almost constant for complete output load range, hence the control of the switch turn-off time is only required for frequency control.

B. Normalized control characteristic and stresses

Figure 2 shows the input characteristic of the converter, or normalized peak input current \(I_{ph}\) vs. normalized peak input voltage \(M_{ph}\) for a given \(F\). The normalized switching frequency \(F\) is the control variable for this rectifier. The converter equations are normalized with respect to the dc output voltage instead of the ac input voltage. This allows the system waveforms to be expressed as functions of the dc operating point. The normalizing base quantities are then described as,

- base voltage = \(V\), base current = \(V/R_0\),
- characteristic impedance \(R_0 = \sqrt{L_r/C_x}\),
- base frequency \(f_0 = 1/2\pi\sqrt{L_x/C_x}\),

where \(V\) is the output voltage of the rectifier. Hence, if the rectifier is an ideal loss free system, then the normalized

Fig. 3. The normalized stresses of the single transistor 3\(\phi\) multi-resonant ZCS HPF rectifier; (a) voltage stress of the switch \(S_1\), (b) voltage stress of the output diode \(D_d\), and (c) current stress of the switch \(S_1\).
values of the input and output quantities are described as:

\[ M_g = \frac{V_g}{V}, \quad J_g = \frac{I_g}{I}, \quad R_d = \frac{V}{I}, \quad J = \frac{I}{R_d} = M_g J_g. \]

The relations between the actual three phase input circuit and normalized quantities are described approximately; (a) \( C_x = \frac{C_1}{2} \times \frac{2}{3} \) where the input resonant capacitors \( C_1 \) to \( C_3 \) have the same values and are represented as \( \frac{C}{R} \), (b) \( I_g = peak \) phase current \( \frac{I}{I_{peak}} \) (c) \( V_g = 3/2 \) times peak phase voltage \( V_{peak} \) where \( V_g \) is also the same as the average voltage of \( V_{C_x} \) during one switching period, and (d) three-phase input power \( P_{in} = V_g \times I_g = 3/2 \times (V_{peak} \times I_{peak}). \)

The characteristics of Fig. 2 end, for large \( I_g \) at the zero current switching boundary. The zero current switching property is lost at large currents. Also, the characteristics are not plotted for \( M_g \) less than 1; the multi-resonant buck rectifier does not function when \( M_g < 1 \), i.e., when \( 3/2 \times V_{peak} \) is less than the dc output voltage \( V \).

Figure 2 is useful for determining the converter steady-state operating point.

III. Design of a Single Transistor 3φ Multi-Resonant ZCS HPF Buck-Type 6kW Rectifier

A. Design

The single-switch 3φ multi-resonant ZCS HPF rectifier as shown in Fig. 4 was designed for experiment.

**Specification**

- Input voltage: 3φ ac 240 V (L-L, rms)
- Output voltage: dc 147 V
- Output power: 6 kW = 600 W

From the specification, the effective input voltage
\[ V_g = \frac{3}{2} \times V_{peak} = \frac{3}{2} \times \frac{240 \sqrt{2}}{\sqrt{3}} = 294 \text{ V} \]
and hence, the normalized input voltage \( M_g = \frac{V_g}{V} = \frac{294}{147} = 2 \). From Fig. 2, the normalized input current \( J_g \) can be chosen to be as large as 1.36 for the maximum output power 6 kW and 0.136 for the 10% output power 600 W. The normalized frequency \( F \) is 0.99 at the maximum output power and 0.21 at the 10% load. The output current \( I \) \((P_{out}/V)\) becomes 40.8 A for the 6 kW output power, and hence the characteristic impedance is
\[ R_0 = \frac{M_g J_g V}{I} = \frac{2 \times 1.36 \times 147}{40.8} = 9.8 \Omega \]
and \( J \) is \( M_g J_g \). If the maximum switching frequency for the 6 kW is chosen to be 90 kHz, then the resonant frequency \( f_0 \) can be calculated as \( f_0 = \frac{f_x}{F} = \frac{90}{0.96} = 91 \text{ kHz} \), where the normalized frequency \( F \) is switching frequency \( f_0 \) divided by the resonant frequency \( f_0 \). Hence, the minimum switching frequency at 10% load becomes \( f = f_0 \times F = 91 \times 0.21 = 19.1 \text{ kHz} \). From the above results, characteristic impedance
\[ R_0 = \sqrt{L_x/C_x} = 9.8 \Omega \] and base frequency \( f_0 = \frac{1}{2\pi \sqrt{L_x C_x}} = \]

![Fig. 4. Diagram of the 6 kW multi-resonant buck-type high power factor rectifier.](image)

91 kHz. The effective capacitance \( C_x \) is calculated to be 178 nF and the resonant tank inductor \( L_x \) becomes 17 μH. Therefore, the input side resonant tank capacitors \( C_{11} - C_{13} \) are 268 nF and the value of the output side resonant tank capacitor \( C_d \) is chosen to be 178 nF.

From Fig. 3(a), the peak value of normalized voltage stress of the switch \( S_1 \) is shown to be 4.8 at \( M_g \) of 2 and \( I_g \) of 0.7. Hence, the peak switch voltage can be calculated as \( V_{S1} = M_{DM} \times V = 4.8 \times 147 \text{ V} = 706 \text{ V} \) over the output load range. From Fig. 3(c), the peak value of normalized current stress of the switch \( S_1 \) is shown to be 5.2 at \( M_g \) of 2 and \( I_g \) of 1.36. Hence, the peak switch current can be calculated as \( I_{S1} = \frac{J_{S1}}{V/R_n} = 5.2 \times 147 / 9.8 = 78 \text{ A} \) over the output load range.

From Fig. 3(b), the peak value of normalized voltage stress of the output diode \( D_4 \) is shown to be 4.2 at \( M_g \) of 2 and \( I_g \) of 0.4. Hence, the peak output diode voltage can be calculated as \( V_{DM} = M_{DM} \times V = 4.2 \times 147 = 617 \text{ V} \) over the output load range. The current stress of the output diode is equal to the output current.

B. Details of the component design

**Semiconductors**

The peak blocking voltage of the switch is approximately 670V as shown in Table 1. The peak current which this switch must conduct coincides with the peak tank inductor current plus output load current, or approximately 78 A at the maximum load. Two IGBTs (HGTG 34N100E2) were used in parallel for this prototype. A single IGBT with a higher current could be used here. These IGBTs do not contain anti-parallel diodes, which are not necessary for this rectifier. The input bridge diodes must block the same peak voltage as the IGBT, and must conduct the peak switch current. Six input bridge rectifier diodes (RURG 50100) were used in this prototype. The output diodes must block the same peak voltage as the output side resonant tank capacitor voltage, or approximately 560 V, and must conduct the output load current, or approximately 40 A. One output diode (RURG 50100) was used in this prototype.

**Tank Capacitors**

Twenty-seven silver mica capacitors (DPPM10S1K), of value 10 nF and 0.87 A rms current rating, were utilized in
parallel for the input side tank capacitors. Hence, total rms current carrying capacity is $27 \times 0.87$ A and the peak blocking voltage is 1000V. Eighteen capacitors (DPPM10S1K), of value 10 nF, were utilized in parallel for the output side tank capacitors. Hence, total rms current carrying capacity is $18 \times 0.87$ A and the peak blocking voltage is 1000 V.

**Magnetic Devices**

There are five magnetic devices in the power stage of the experimental circuit. The input filter inductance is 0.5 mH for each phase. This value was chosen to obtain a full-load line current THD of approximately 5%. THD is inversely proportional to the values of these inductors. The air gap length consists of 3 mm in the inner leg and 3 mm in the outside legs of an EE 75/68/19 ferrite core. Solid wire was used for these input filters which have following specifications:

(a) Core dimensions: magnetic cross-section area = 3.23 cm$^2$, magnetic path length = 18 cm, core volume = 58.1 cm$^3$.
(b) Wire: number of turns = 85, mean length per turn = 14 cm, wire size = AWG #11, resistivity = 0.04137 m$\Omega$cm.

The resonant tank inductance is 17 $\mu$H. The air gap length consists of 3 mm in the inner leg and 3 mm in the outside legs of an ETD 54-3F3 ferrite core. To reduce the proximity effect of the winding, the flat copper foil winding is used for the resonant tank inductor which has following specifications:

(a) Core dimensions: magnetic cross-section area = 2.54 cm$^2$, magnetic path length = 14.4 cm, core volume = 36.58 cm$^3$.
(b) Wire: number of turns = 13, mean length per turn = 7.1 cm, flat copper foil cross sectional area = 36 mm (width) $\times$ 0.5 mm (thickness) = 18 mm$^2$.

The output filter inductance is 2 mH. The maximum current is the maximum output load current, or approximately 40 A. For this experiment, an existing iron-laminated commercial product (2 mH, 100 A) was utilized as an output filter inductor. This device is much larger than necessary in both inductance and current rating, but was used because it was readily available.

**IV. Experimental Results**

The single-switch 3φ multi-resonant ZCS HPF buck-type rectifier as shown in Fig. 4 was built. The dc output voltage $V$ is 147 V with an rms ac input voltage of 240 V (L-L, rms). The maximum output power 6 kW is obtained at the switching frequency 89.3 kHz with switch conduction time 6.5 $\mu$sec, 50% output power 3 kW is obtained at a switching frequency of 68 kHz with switch conduction time 6.5 $\mu$sec, and 10% output power 600W is obtained at the switching frequency 19.2 kHz with switch conduction time 6.5 $\mu$sec. The input filter inductors $L_a$, $L_b$, and $L_c$ are 0.5 mH each and the output filter inductor is 2 mH. The input side resonant tank capacitors $C_{11}$-$C_{13}$ are connected in a Y configuration with 270 nF each. The value of the output side resonant tank capacitor $C_4$ is chosen to be equal to $C_3 = 2/3 \times C_2$ or 180 nF. This choice leads to a good compromise between low transistor voltage stress and low input current harmonics. The resonant tank inductor $L_r$ is 17 $\mu$H. Hence, the resonant frequency $f_0$ is 91 kHz and characteristic impedance $R_0$ is 9.72 $\Omega$. The load resistance $R_L = 3.6 \Omega$ is connected for the maximum load, $R_L = 7.2 \Omega$ is connected for the 50% load, and $R_L = 36 \Omega$ is connected for the 10% load.

Figures 5-7 shows the measured waveforms of the input line current $i_a$ with its ac phase voltage $V_{ac}$ together with the spectral analysis of the measured input current at three different operating points. Figures 8-10 show the voltage waveforms of the three input side resonant tank capacitors $C_{11}$-$C_{13}$ at three different operating points. The resonant voltage wave shapes of $V_{C11}$-$V_{C13}$ are clearly divided by three different periods. During the first period, the voltages of three resonant capacitors are increasing linearly with slope proportional to the input currents. During the second period, the resonant capacitors are ringing together with the resonant tank inductor $L_r$, until capacitor voltages reach zero voltage. Finally, $V_{C11}$-$V_{C13}$ remains at zero for the third period. Hence, the input current waveform becomes proportional to the input voltage waveform. Figure 11 shows the current and blocking voltage waveforms of the switch. Figure 12 shows the voltage waveform of the output侧 of the rectifier and the current waveform of the switch. The high frequency ringing of the switch blocking voltage waveform $V_{S1}$ shown in Fig. 11 is caused by the resonant tank inductor and the internal capacitance of the input bridge diodes. However, the energy losses caused by this ringing is negligible.

Table 1 shows the measured stresses of the switch and the output diode at three different load conditions. Table 3 shows the measured rms harmonic currents of the line input current. A spectrum analyzer was used to measure the magnitudes of the harmonics which are contained in the input line current. The total harmonic distortion of the line current waveform is calculated numerically based on this measurement. The percentage of the total harmonic distortion was calculated for the first ten significant harmonics ($2^k \sim 11^k$). The measured rms harmonic currents of the line input current are compared with the harmonic limits of the IEEE - 519 and IEC - 555 regulations. The results show that these measured harmonic values are quite acceptable for most applications, and could be further reduced if desired by choosing larger input filter inductances.

Finally, Table 2 shows the measured efficiency of the rectifier at various operating points. The losses of the control circuit are not included. It has the best efficiency 94.05 % at the maximum load. Experimental results show the feasibility of the wide load range control with low stresses and high efficiency.
Fig. 5. Measured waveforms and spectral analysis of the input line current $i_a$ with its ac phase voltage $V_{an}$ for the experimental rectifier circuit at maximum output power 6 kW (vertical scale: 50 V/div, 10 A/div and horizontal scale: 2 msec/div), (vertical scale: 10 dB/div and horizontal scale: 60 Hz/div). The fundamental component of the input current $I_{1max}$ is 14.9 A.

Fig. 6. Measured waveforms and spectral analysis of the input line current $i_a$ with its ac phase voltage $V_{an}$ for the experimental rectifier circuit at 50% output power 3 kW (vertical scale: 50 V/div, 5 A/div and horizontal scale: 2 msec/div), (vertical scale: 10 dB/div and horizontal scale: 60 Hz/div). The fundamental component of the input current $I_{1max}$ is 7.66 A.

Fig. 7. Measured waveforms and spectral analysis of the input line current $i_a$ with its ac phase voltage $V_{an}$ for the experimental rectifier circuit at 10% output power 600 W (vertical scale: 50 V/div, 1 A/div and horizontal scale: 2 msec/div), (vertical scale: 10 dB/div and horizontal scale: 60 Hz/div). The fundamental component of the input current $I_{1max}$ is 1.54 A.
Table 1. Measured stresses of the switch and the output diode at the maximum, 50%, and 10% load

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<td>670</td>
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<th>Output power [kW]</th>
<th>Peak diode voltage [V]</th>
<th>Peak input voltage [V]</th>
<th>Peak diode current [A]</th>
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<td>340</td>
<td>41</td>
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<td>340</td>
<td>20.5</td>
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<td>0.6</td>
<td>560</td>
<td>340</td>
<td>4.1</td>
<td>4.1</td>
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Table 2. Measured efficiency of the experimental rectifier at the maximum, 50%, and 10% load

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<td>239.6</td>
<td>15.63</td>
<td>6486.4</td>
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<td>6100.5</td>
<td>385.9</td>
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<td>7.66</td>
<td>3169.6</td>
<td>144.95</td>
<td>20.35</td>
<td>2949.7</td>
<td>219.9</td>
<td>93.06</td>
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<td>240.9</td>
<td>1.52</td>
<td>634.2</td>
<td>144.85</td>
<td>3.94</td>
<td>570.7</td>
<td>63.5</td>
<td>89.99</td>
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Table 3. Measured current harmonics at several load conditions (The fundamental component of the input current I_{rms}: 14.9 A at maximum load, 7.66 A at 50% load, and 1.54 A at 10% load)

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<tr>
<th>Harmonic number</th>
<th>Maximum load 6 kW, rms current /percent</th>
<th>50% load 3 kW, rms current /percent</th>
<th>10% load 600W, rms current /percent</th>
<th>IEC 555 limits 380V to 415V</th>
<th>IEEE 519 limits (Ishort circuit/Iload)&lt;20</th>
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<tr>
<td>3</td>
<td>0.09A/0.6%</td>
<td>0.08A/1.04%</td>
<td>26mA/1.67%</td>
<td>2.3A</td>
<td>4%</td>
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<tr>
<td>5</td>
<td>0.62A/4.1%</td>
<td>0.24A/3.13%</td>
<td>9mA/0.58%</td>
<td>1.14A</td>
<td>4%</td>
</tr>
<tr>
<td>7</td>
<td>0.4A/2.6%</td>
<td>0.05A/0.65%</td>
<td>12mA/0.78%</td>
<td>0.77A</td>
<td>4%</td>
</tr>
<tr>
<td>9</td>
<td>0.03A/0.21%</td>
<td>0.01A/0.13%</td>
<td>0.7mA/0.05%</td>
<td>0.4A</td>
<td>4%</td>
</tr>
<tr>
<td>11</td>
<td>0.08A/0.54%</td>
<td>0.02A/0.26%</td>
<td>9mA/0.58%</td>
<td>0.33A</td>
<td>4%</td>
</tr>
<tr>
<td>2</td>
<td>0.04A/0.27%</td>
<td>0.02A/0.26%</td>
<td>2mA/0.13%</td>
<td>1.08A</td>
<td>1%</td>
</tr>
<tr>
<td>4</td>
<td>0.05A/0.34%</td>
<td>0.02A/0.26%</td>
<td>3.5mA/0.23%</td>
<td>0.43A</td>
<td>1%</td>
</tr>
<tr>
<td>6</td>
<td>0.02A/0.14%</td>
<td>0.003A/0.04%</td>
<td>0.5mA/0.03%</td>
<td>0.3A</td>
<td>1%</td>
</tr>
<tr>
<td>8</td>
<td>0.01A/0.07%</td>
<td>0.005A/0.07%</td>
<td>0.5mA/0.03%</td>
<td>0.23A</td>
<td>1%</td>
</tr>
<tr>
<td>10</td>
<td>0.02A/0.14%</td>
<td>0.005A/0.07%</td>
<td>0.5mA/0.03%</td>
<td>0.18A</td>
<td>1%</td>
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</table>

| THD             | 5.0%                                    | 3.4%                               | 2.0%                               | 5%                          |

Fig. 8. Measured voltage waveforms $V_{C1}$-$V_{C2}$ of the input side resonant tank capacitors at maximum output power 6 kW (vertical scale: 100 V/div and horizontal scale: 5 μsec/div).

Fig. 9. Measured voltage waveforms $V_{C1}$-$V_{C3}$ of the input side resonant tank capacitors at 50% output power 3 kW (vertical scale: 100 V/div and horizontal scale: 5 μsec/div).
V. Conclusion

In this paper, the design and breadboard implementation of a single-switch three-phase high power factor multi-resonant rectifier delivering an 147 V (DC) at 6 kW from a 3φ 240 V (L-L, rms) AC input has been described. Experimental results demonstrate total harmonic distortion of less than 5% at the full output power, less than 3.5% at 50% output power, and less than 2% at the 10% output power, in an open loop rectifier. The rectifier efficiency is about 94% at full load. The measured rms harmonic currents of the line input current are compared with the harmonic limits of the IEEE - 519 and IEC - 555 regulations. The results show that these measured harmonic values are quite acceptable for most applications, and could be further reduced if desired by choosing larger input filter inductances.

References


