Unity Power Factor Isolated Three-Phase Rectifier With Two Single-Phase Buck Rectifiers Based on the Scott Transformer

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Abstract—This paper proposes an isolated three-phase rectifier power-factor correction using two single-phase buck rectifiers in continuous conduction mode. The use of the Scott transformer renders a simple and robust rectifier to operate with unity power factor. With only two active switches, the rectifier is able to generate symmetrical currents in the line and a regulated voltage output without any necessary synchronous switches. The proposed control technique with sinusoidal pulse width modulation utilizes a feedforward of the output inductor current and only one voltage control regulates the output. Complete simulation results under closed-loop operation are given and a 12-kW prototype has been implemented in the laboratory, which demonstrated to operate successfully with excellent performance, and thus can feasibly be implemented in higher power applications.

Index Terms—AC–DC converters, buck rectifier, power supplies, power-factor correction (PFC) converters, sinusoidal pulse width modulated (SPWM), three-phase rectifier.

I. INTRODUCTION

THREE-PHASE switch-mode power supplies employing a diode-rectifier-type utility interface are widely used in telecommunications, data processing, and other industrial systems. Those converters connected to the mains have the potential of injecting current harmonics that may cause voltage distortion. These harmonics can be significantly reduced if the input power factor is corrected by shaping the input current in each of the three phases so that it is sinusoidal and in phase with the phase voltage. Due to this fact, switch-mode rectifiers for power-factor correction (PFC) have gained considerable attention. Further advantages for the use of PFC rectifiers are their adaptability to different line voltages and the fact that they preregulate the dc output voltage, which may be supplying a dc–dc converter.

In many cases, bidirectional rectifier topologies are not necessary and unidirectional topologies offer some advantages, including a decrease in the number of power switches, natural protection for dc bus short circuit, and less processing of energy for active switches [1]–[4]. Furthermore, in addition to unity power factor, safety and robustness are also important for medium- and high-power applications; therefore, low-frequency isolation is used. Moreover, isolated rectifiers have been widely employed in the electrochemical and petrochemical industries, and subway applications [5]–[7].

Many studies employ a three-phase rectifier with single-phase PFC modules [8], [9]. In [8], a three-phase switch-mode rectifier employing three single-phase boost PFC circuits with direct output coupling is presented. Basically, this topology uses three power switches although it has a high component count and is not isolated. In [9], a three-phase PFC scheme is proposed using two single-phase PFC modules. The two-phase system is produced by means of a 0.14-pu-rated autotransformer connected to the three-phase input. However, this topology is also not isolated. When a regulated output voltage is not required, a number of methods have been proposed to lower the harmonics generated by diode rectifier-type utility interfaces [10]–[16]. One approach is to use a conventional 12-pulse converter that requires two six-pulse converters connected through isolation transformers.

The first three-phase boost rectifier based on the Scott transformer was proposed in [17] and its practical aspects were analyzed in [18]. Another boost rectifier with different output connections is proposed and studied in [5], [19]–[21]. In principle, the Scott transformer provides galvanic isolation and sine and cosine secondary voltage waveforms for the high-power factor rectifiers, resulting in a perfectly regulated dc output voltage. In [5], a unity power factor three-phase boost rectifier with a split dc bus based on the Scott transformer was proposed (see Fig. 1). This rectifier has a split dc bus and the voltages across the switches are \( V_s/2 \). The control method employed to manage the currents of the two boost inductors, \( L_T \) and \( L_M \), is an instantaneous average current control. Each rectifier presents an independent current loop with an individual reference current, generating sinusoidal secondary currents in phase with their respective secondary voltages.

In this paper, an isolated three-phase buck rectifier based on the Scott transformer is proposed, substantiated by a detailed discussion involving theoretical considerations, and finally a prototype is designed to prove the proposed performance. The proposed topology is depicted in Fig. 2. This application uses two single-phase buck rectifiers in continuous conduction mode with output connected in parallel. Furthermore, this topology offers some advantages over previous studies involving buck rectifier, such as a regulated output voltage and only one \( LC \) output filter, absence of inrush current, and protection against short circuit.

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When a low-frequency isolation is required, traditional three-phase rectifiers can be used by placing in the input, a three-phase transformer. However, this option does not benefit from the uncoupling of the secondary phases, requiring complex control algorithms and mathematical models [1], [22], [23]. Moreover, to obtain sinusoidal input currents in continuous conduction mode usually requires using three or more active switches. The proposed rectifier takes advantage of the uncoupling of the secondary phases and uses a simple control with only a single current sensor combined with well-known techniques, which are applied in single-phase rectifiers. It also uses the reduction phase provided by Scott connection and obtains sinusoidal input currents with only two switches. Thus, the proposed scheme offers a simple control strategy, flexibility using single-phase modules, simpler design, competitive efficiency, and only one inductor and two active devices.

II. SINGLE-PHASE BUCK RECTIFIER

The basic circuit of a single-phase buck rectifier combines a diode rectifier with a step-down chopper with input and output filters. In the discontinuous conduction mode, the input current harmonic distortion depends on the ratio between the output voltage average value and the input voltage peak value, which is a downside. Another disadvantage of the discontinuous conduction mode is that the peak and rms currents are very high, leading to high conduction losses in the switches [24]–[27]. Alternatively, in a continuous conduction mode, with a low-frequency output inductor designed in such a way that it behaves as a constant current source, the problem stated earlier no longer exists [24]. Albeit, as a drawback, this case requires much larger inductance than that of discontinuous conduction mode, and larger inductance increases physical size and weight of the inductor.

The single-phase buck preregulator with feedforward of the output inductor current [24] is shown in Fig. 3. This technique proposes to eliminate the distortion of the input current even when the output inductor current presents a large ripple. In this control strategy, the output voltage sample is compared to a reference voltage and the resulting error is injected in an appropriate voltage controller. The output of the controlled voltage is multiplied by a sample of rectified input voltage and divided by a sample of the current in the output inductor. Finally, this resulting signal is compared with the saw-tooth signal thus generating the drive signal to the switch.

III. SCOTT CONNECTION TRANSFORMERS

The Scott connection is one alternative to convert the three-phase to two-phase transformation that uses two single-phase transformers. The connection is represented in Fig. 4, with two single-phase transformers, $T_M$ and $T_T$. The primary windings are fed by two different voltages, $v_{AO}(t)$ and $v_{CB}(t)$, that are
generated from a symmetrical three-phase system \( v_A(t), v_B(t), \) and \( v_C(t) \). The voltages \( v_A(t) \) and \( v_B(t) \) represent a two-phase voltage system on the secondary winding, with a phase angle of 90° between them. The phasor diagram is represented in Fig. 5, where \( A, B, \) and \( C \) correspond to the three terminals of a three-phase system; \( N \) represents the neutral point; and \( v_A(t) \) and \( v_B(t) \) represent the secondary voltages.

Each secondary winding is simply a single-phase winding, and the voltage across it and the current in it do not differ from what would be expected in an ordinary single-phase transformer. On the other hand, in the case of the three-phase side, it is interesting to consider the actual voltages and currents, which are as follows:

\[
|V_{\alpha 0}| = \frac{\sqrt{3}}{2} |V_{CB}| \quad (1) \\
|I_{\alpha 0}| = |I_{CB}|. \quad (2)
\]

By multiplying the voltage across each transformer by its current, the equivalent size of each transformer is obtained. The group output should be multiplied by 0.577 in the case of the main transformer and 0.5 for the teaser transformer. Therefore, in a Scott-connected group, the two-phase windings are equivalent to the windings of two ordinary single-phase of the same output, although on the three-phase side, the winding of the main transformer is increased by 15.5% above what would be required in a single-phase transformer of the same output. Assuming that the primary and secondary windings of an ordinary single-phase transformer each occupy the same space, then, in a Scott-connected group, a transformer is necessary with 7.75% greater capacity in the main transformer than a single-phase transformer.

**IV. Steady-State Analysis**

In the theoretical study involving the unity power factor isolated three-phase rectifier, only the secondary circuitry was considered. Hence, the secondary windings of the Scott transformer are considered to be ideal ac power sources. Moreover, the full-bridge diode rectifiers were substituted by power sources that represent the rectified secondary voltages \( v'_A(t) \) and \( v'_B(t) \). The topology in Fig. 2 can be reduced to the circuit given in Fig. 6.

The secondary voltages of the Scott transformer are sine and cosine waveforms [5]. Therefore, the rectified voltages at the inputs of the buck converters are

\[
v'_A(t) = V_p \cdot |\sin(\omega \cdot t)| \quad (3) \\
v'_B(t) = V_p \cdot |\cos(\omega \cdot t)|. \quad (4)
\]

The purpose of using a buck PFC is to correct the power factor of the structure by forcing the input current to follow the shape of the rectified secondary voltage. For that, instantaneous average duty cycles of the switches are

\[
d_{\alpha}(t) = K_v \cdot |\sin(\omega \cdot t)| \quad (5) \\
d_{\beta}(t) = K_v \cdot |\cos(\omega \cdot t)| \quad (6)
\]

where \( K_v \) is the modulation index.

The buck diode voltages are, therefore, given by multiplying input voltages rectifiers by average duty cycles of the switches

\[
v_{D\alpha}(t) = V_p \cdot K_v \sin(\omega \cdot t)^2 \quad (7) \\
v_{D\beta}(t) = V_p \cdot K_v \cos(\omega \cdot t)^2. \quad (8)
\]

The equivalent circuit in Fig. 6 can be reduced to the circuit in Fig. 7, whereas the inductor voltage is shown in

\[
v_{L_\alpha}(t) = v_{D\alpha}(t) + v_{D\beta}(t) - v_o(t). \quad (9)
\]

Substituting (7) and (8) into (9), we obtain

\[
V_{L_\alpha}(t) = V_p \cdot K_v - v_o(t). \quad (10)
\]

The inductor voltage has no dc component and considering average voltage yields

\[
v_o(t) = V_o = V_p \cdot K_v. \quad (11)
\]

The high-frequency components of voltage were neglected by considering only the instantaneous average values of the buck diode voltages. Even so, ideally, the high-frequency components...
of the voltage would stay on the output filter, leaving the dc com-
ponent free to stay on the load, resulting in a constant voltage
output. This indicates that the inductor current feedforward is not
necessary to obtain a unity power factor, considering a resistive
load and symmetrical network.

The complete schematic diagram with respective waveforms
is depicted in Fig. 8. In this representation, the carriers are 180°
phase shifted from each other.

A. Input LC Filter

The natural leakage inductance of the low-frequency trans-
former usually is very low, but this inductance is significant
at high-frequency filters. Taking advantage of that, the high-
frequency input filter uses the leakage inductance of the sec-
ondary winding. Insofar, the input filter is accomplished by
adding the capacitor $C_f$.

B. Output Inductor Current Ripple

The rectifier’s operation is possible with the same carriers or
individual carriers with phase shifted from each other. However,
the synchronism of the carriers affects the design of the output
filter. A difference phase in 180° offers better results for the
output inductor current ripple.

For comparison, in Fig. 9, the voltage inductor with 180°
phase shifted apart (a) and same phase carriers (b) is presented
with respective inductor current ripple shown in Fig. 10(a)
and (b). Note that the maximum current ripple occurs with
the same carrier in the rectifiers modules. In addition, the
switch frequency $\omega_s$ is 20 times larger than the network
frequency $\omega$.

Clearly, in the first case (a), the voltage frequency is higher
than that in the second case (b), which, naturally, allows a lower
inductor current ripple. Furthermore, the maximum inductor
voltage is obtained in the second case due to the additive input
voltages.

In the presented rectifier, with phase-shifted carrier, the in-
ductor current ripple will be maximum in 0.5 ratio cycle and
on peak network waveform, as in dc buck converters. In this
case, the modulation index is 0.5. Applying (12), results evi-
dence maximum ripple inductor current with carriers that are
180° phase shifted from each other

$$\Delta I_{\text{max}} = \frac{V_p}{4 \cdot L_o \cdot f_s}. \quad (12)$$

On the other hand, with the same phase carriers, the maximum inductor current ripple occurred on a different network sine waveform point, when modulation index is about 0.7. In this case, the maximum inductor current ripple is determined by

$$\Delta I_{\text{max}} = \sqrt{2} \cdot \frac{V_p}{4 \cdot L_o \cdot f_s}. \quad (13)$$

V. CONTROL STRATEGY

Fig. 11 shows the control block for the complete system, where $K_v$ is the waveform input gain, $A$ is a voltage error output, $B$ is a shape waveform to current reference, $C$ is a sample of average input voltage, and $D$ is a shape of inductor current ripple. This technique is similar to that in a single-phase buck preregulator with feedforward of the output inductor current [24].

The output voltage is measured and compared to reference voltage in an appropriate voltage controller. In each buck module, the output of the voltage controlled $A$ is multiplied by a shape waveform reference $B$ and divided by both the shape inductor current ripple $D$ and the rms value of the input voltage squared $C^2$. The resulting signal is compared with the sawtooth signal or triangle signal, generating the drive signal for the switches $S_α$ and $S_β$. Finally, each buck preregulator module can carry the same amount of power simply by sharing the same voltage error amplifier output.

VI. SIMULATION RESULTS

Simulation results prove the effectiveness of the proposed three-phase rectifier. In order to analyze the operation of the proposed rectifier, a digital simulation was performed and then compared with experimental results. The proposed control strategy shown in Fig. 11 was implemented, and used for simulation analysis. Table I shows the system specifications.

The simulation study seeks to verify the inductor current ripple first with 180° phase shifted between both carriers and later with same phase carriers. The waveforms inductor currents are shown in Fig. 12, for phase-shifted carriers, and Fig. 13, for the same carriers. The maximum ripple current is about 2-A peak-to-peak in the first case, and 3-A peak-to-peak in the second case. These results are different when compared to Fig. 10, because the modulation indexes and switch frequencies are different. In this case, the modulation index is about 0.75 and is 0.5 in the previous case (see Fig. 10).

Figs. 14 and 15 show the simulation of secondary voltages and current waveforms where low-distortion current waveforms can be observed, resulting in a total harmonic distortion (THD) near to 2%, for nominal output power. There is a phase
shift between voltage and current waveforms due to the input filter.

In Fig. 16, the output inductor current and the input currents in the secondary winging are shown. Note that the secondary currents \( i_\alpha(t) \) and \( i_\beta(t) \) of the buck modules which are 90° phase shifted from each other have equal amplitudes. Further, both currents do not present distortion at zero crossing, which is a characteristic of single-phase boost PFC converters. The results for the line currents can be seen in Fig. 17, where the THD of line currents was about 2%.

### VII. EXPERIMENTAL RESULTS

After meticulous simulation study and analysis, a 12-kW three-phase buck isolated rectifier prototype was implemented

<table>
<thead>
<tr>
<th>Circuit element</th>
<th>Nominal Value</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_F )</td>
<td>( n_F=11:14 )</td>
<td>laminated iron-core transformer</td>
</tr>
<tr>
<td>( T_M )</td>
<td>( n_M=19:19:42 )</td>
<td>laminated iron-core transformer</td>
</tr>
<tr>
<td>Input bridge</td>
<td>40 A / 800 V</td>
<td>SKKD 40F08 (Semikron)</td>
</tr>
<tr>
<td>rectifier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L_L )</td>
<td>3.5 mH</td>
<td>laminated iron-core inductor</td>
</tr>
<tr>
<td>( S_A ) and ( D_A )</td>
<td>75 A / 1200 V</td>
<td>SKM 100 GAR 123D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Semikron)</td>
</tr>
<tr>
<td>( S_B ) and ( D_B )</td>
<td>75 A / 1200 V</td>
<td>SKM 100 GAR 123D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Semikron)</td>
</tr>
<tr>
<td>( C_r )</td>
<td>4 x 1500 ( \mu )F / 450 V</td>
<td>B43456A5158M000 (Epcos)</td>
</tr>
<tr>
<td>( C_{B1}, C_{B2} )</td>
<td>8 x 10 ( \mu )F</td>
<td>B32676G4106K (Epcos)</td>
</tr>
</tbody>
</table>
and evaluated in laboratory, in order to validate the proposed structure. The experimental setup was built using analog circuitry with an integrate circuit UC3854B (Unitrode) [28] and 4-QuadrantMultipler/Divider AD734 A (analog devices) [29].

The design specifications of the prototype are presented in Table I, and Table II shows the dc mains component value. Fig. 18 shows the power circuit implemented. Fig. 19 presents a photograph of the Scott transformer and in Fig. 20 the rectifier prototype is shown.

Figs. 21 and 22 show the experimental results of the 12-kW prototype. The THDs of the secondary voltages were 2.2% and 2.3%. The THDs of the secondary currents were 3.8% and 4.5%. The currents are nearly sinusoidal in shape, thus providing conditions to obtain a low THD value as expected. The power factors were 0.996 and 0.992.

Fig. 23 shows input the currents $i_{\alpha}(t)$ and $i_{\beta}(t)$ of the buck PFCs and output inductor current $i_L(t)$, where $i_{\alpha}(t)$ and $i_{\beta}(t)$ are 90° phase shifted from each other and with equal amplitudes. This result confirms that the output powers of the two buck modules are equal.

The experimental lines’ input currents are shown in Fig. 24, whereas the total harmonic distortions of the line currents for full load operation are $\text{THD}_A = 3.8\%$, $\text{THD}_B = 4.1\%$, and $\text{THD}_C = 3.7\%$. The magnitude and shape waveforms are quite different from each other because the input voltages are not symmetrical and have harmonics distortions. Each buck module can carry the same amount of power; therefore, if there are different input voltages there will be different input currents.
Fig. 22. Current $i_β(t)$ and voltage $v_β(t)$ (10 A/division, 200 V/division, and 5 ms/division).

Fig. 23. Secondary currents $i_α(t)$, $i_β(t)$, and inductor current $i_L(t)$ (10 A/division and 4 ms/division).

Fig. 24. Line currents $i_A(t)$, $i_B(t)$, and $i_C(t)$ (20 A/division and 5 ms/division).

Fig. 25. Converter efficiency.

Fig. 25 shows the tested efficiency of the three-phase rectifier with transformer losses. The efficiency data were measured for an output power range of 25–95% at 12 kW. A peak efficiency of 95.10% was obtained at 11.5 kW, which proves the validity and good performance of the proposed topology.

VIII. CONCLUSION

This paper introduces a novel unity power factor isolated three-phase rectifier based on the Scott transformer and single-phase buck rectifier in continuous conduction mode. A thorough analysis is presented, corroborated by simulation studies and the successful design of a system composed of two single-phase buck rectifiers connected to a Scott transformer. This topology has only two switches where each buck module is rated for half of the output power. The resulting input line currents are nearly sinusoidal in shape with low harmonic distortion and unity power factor.

The proposed control strategy, which employs a feedforward of the output inductor current, allows using high inductor current ripple without distortion input current. Moreover, a small inductor can also be used, which reduces significantly size, weight, and cost of the buck rectifier. A second feedforward input voltage is proposed to distribute the total power between them when the input voltage is unbalanced. And finally, a common voltage control loop for both buck PFCs is employed to regulate the output voltage.

A 12-kW laboratory prototype was successfully implemented. The experimental results demonstrate the efficient performance of the proposed system, where the power factor depends on the relation between the output voltage average value and the input voltage peak value. The low-pass LC input filters were obtained with leakage inductances from the Scott transformer and it is not necessary to add inductors, only capacitors. Moreover, the output filters are a simple LC filter for high-frequency components.

The use of the Scott transformer provided low-frequency isolation, which is desirable in some applications due to the robustness and safety it provides. In these cases, this rectifier is certainly a promising option since it presents unity power factor by using only two active switches and it uses a simple well-known control strategy. Therefore, this proposed structure is recommended for high-power installations.

REFERENCES


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