Reduced Redundant Power Processing ($R^2P^2$) PFC Voltage Regulators: Circuit Synthesis and Control

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Abstract --- High input power factor is becoming a mandatory requirement, in addition to tight output regulation, of dc power supplies that derive power directly from the ac mains. In principle, the power factor correction (PFC) and output regulation functions are separately achieved by two power stages. This paper addresses the amalgamation of the two power stages to form a PFC voltage regulator. The focus is the non-cascading structure that allows a higher overall efficiency to be achieved. Unlike the conventional cascade configuration, the circuits discussed in this paper allow part of the input power to be processed by only one stage, thereby reduce the amount of power redundantly processed by the two constituent power stages. This paper describes in particular a systematic synthesis method and some important issues related to the control of such converter circuits.

I. INTRODUCTION

High input power factor and low input-current harmonics are becoming mandatory design criteria for switching power supplies, in addition to a tight output voltage regulation. Recently, there have been numerous attempts in combining a so-called power-factor-correction (PFC) switching stage with a conventional dc/dc converter to form a high-power-factor voltage regulator which converts power from the ac mains to a resistive load [1]-[8]. Of much research interest is, moreover, the amalgamation of two stages to form the required PFC voltage regulator. The conventional approach is to cascade the two stages [2]-[4], which allows simple circuit and control design, but is less efficient due to redundant processing of power. In this paper we present a systematic procedure for generating converter circuits that provide PFC and voltage regulation, with less redundant processing of power. The essential feature of these circuits is the non-cascading structure that allows part of the input power to be processed by only one converter stage. We will discuss the synthesis procedure and some important control issues.

II. REVIEW OF BASIC CONFIGURATIONS

The basic requirement of the afore-described combined system, to which we simply refer as PFC regulator, is the presence of an energy storage element which buffers the difference between the instantaneous input power and the output power. We can therefore regard the general configuration of a voltage regulator with PFC capability as a three-port network terminating in an input voltage, a low-frequency storage element and an output load. In Tse-Chow [5, 6], sixteen basic configurations of PFC regulators have been derived, each of which is composed of two basic switching converters. One of these is the conventional cascade configuration in which a PFC stage is cascading with a dc/dc converter stage [2]-[4]. The other fifteen have non-cascading structures which, in theory, have a higher efficiency compared to the cascade configuration. The improved efficiency can be attributed to the reduced redundant power processing ($R^2P^2$) feature of the non-cascading structures [5, 6]. However, not all fifteen configurations can be readily implemented in practical forms. Upon close inspection of these configurations, we can easily conclude that four out of the fifteen permit simple interconnections and transformer isolation. Figure 1 shows the power flow representations of these four configurations, as originally published in Tse-Chow [5, 6]. In the next section we will present a systematic procedure for synthesizing PFC regulator circuits that arise from these four basic configurations.

III. SYNTHESIS OF $R^2P^2$ PFC REGULATOR TOPOLOGIES

We begin with the four simplest power flow representations shown in Fig. 1. Since the input and load are voltage terminated, the use of voltage converters and capacitive storage becomes a convenient choice. The basic voltage converters are shown in Fig. 2. In general, an $R^2P^2$ circuit can be realized by two voltage converters connecting the input, storage and load ports. The crucial question is how to connect the ports with two converters, such that the power flow configuration concerned can be realized.

A. Transformation of Power Flow Graphs into Equivalent Circuits

In transforming the power flow representations of Fig. 1 into equivalent circuits, the following basic connection rules should be observed:

1. Since the ports are voltage terminated, connection of any two ports simultaneously to a converter should be realized by a series circuit connection.
2. Connection of a port with the inputs (or outputs) of two converters should be realized by a parallel circuit connection.

Based on these rules and Fig. 1, we can develop equivalent circuit representations for the four basic configurations of $R^2P^2$ PFC regulators, as shown in Fig. 3.

B. Placement of Constituent Basic Converters

The next logical step in the synthesis process is to place converters appropriately in the rectangular boxes of Fig. 3, paying attention to the polarity markings of the input and output terminals of the converters. In general, referring to Fig. 2, power flows through a converter from terminals $X^+$ to $Y^+$. Thus, in order to ensure power flows in the appropriate directions, we place converters in the circuits of Fig. 3 in such a way that terminals $X^+$ to $X^-$ and $Y^+$ to $Y^-$ of the basic converters of Fig. 2 match those in the $R^2P^2$ PFC regulator circuits. However, the choice of basic converters to be placed in the $R^2P^2$ PFC regulator circuits is not arbitrary, as will be discussed in the next subsection.

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C. Constraints on the Choice of Basic Converters

We now consider using non-isolated basic converters for realizing converters 1 and 2, and examine the constraints in the choice of converters. We first observe that all non-isolated converters have a direct short-circuit path between input and output terminals, during the entire or part of a switching period.

- For the non-isolated buck and boost converters, regardless of how the switch, diode and inductor are re-arranged, there is a short-circuit path either between $X^+$ and $Y^+$, or between $X^-$ and $Y^-$. 
- For the non-isolated buck-boost converter, regardless of how the switch, diode and inductor are re-arranged, there is a short-circuit path either between $X^+$ and $Y^-$, or between $X^-$ and $Y^+$.

Clearly, in choosing a non-isolated basic converter for placement in an $R^2P^2$ circuit, care should be taken to ensure that the short-circuit paths imposed by the basic converters do not affect the intended connections. The allowable short-circuit paths can be readily found by inspection of the $R^2P^2$ circuits of Fig. 3.

1. For configuration A, short-circuit paths are allowed between
   (a) $X^+$ and $Y^+$ of converter 1; and
   (b) any $X$ and $Y$ terminal of converter 2.

2. For configuration B, short-circuit paths are allowed between
   (a) $X^-$ and $Y^-$ of converter 1; and
   (b) $X^+$ and $Y^+$ of converter 2.

3. For configuration B, short-circuit paths are also allowed between
   (a) $X^+$ and $Y^-$ of converter 1; and
   (b) $X^+$ and $Y^+$ of converter 2.

4. For configuration C, short-circuit paths are allowed between
   (a) $X^-$ and $Y^+$ of converter 1; and
   (b) $X^-$ and $Y^-$ of converter 2.

5. For configuration C, short-circuit paths are also allowed between
   (a) $X^+$ of converter 2.

6. For configuration D, short-circuit paths are allowed between
   (a) $X^-$ and $Y^+$ of converter 1; and
   (b) any $X$ and $Y$ terminal of converter 2.

From the above observations and the earlier observations regarding the presence of short-circuit paths in the basic non-isolated converters, we can deduce the type of basic non-isolated converters that can be used for converters 1 and 2 in a non-isolated $R^2P^2$ PFC regulator. The main results are stated as follows and summarized in Table 1, along with some previously reported circuits.

A. For configuration A, converter 1 can only be a buck-boost converter, and converter 2 can be any converter.

B. For configuration B, two cases are possible. If converter 1 is a buck or a boost converter, converter 2 can only be a buck-boost converter. If converter 1 is a buck-boost converter, converter 2 can be a buck or a boost converter.

C. For configuration C, two cases are possible. If converter 1 is a buck-boost converter, converter 2 can only be a buck or a boost converter. If converter 1 is a buck or a boost converter, converter 2 can only be a buck-boost converter.

D. For configuration D, converter 1 can only be a buck-boost converter, and converter 2 can be any converter.
Fig. 3: Equivalent circuits of the simplest reduced redundant power processing ($R^2P^2$) configurations. Rectangular blocks denote converters.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Conv. 1</th>
<th>Conv. 2</th>
<th>Reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>buck-boost</td>
<td>buck-boost</td>
<td>Zhoa</td>
</tr>
<tr>
<td>A</td>
<td>buck-boost</td>
<td>buck-boost</td>
<td>Chow et al. [10]</td>
</tr>
<tr>
<td>A</td>
<td>buck-boost</td>
<td>boost</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>buck</td>
<td>boost</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>buck-boost</td>
<td>boost</td>
<td></td>
</tr>
<tr>
<td>C</td>
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<td>buck</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>boost</td>
<td>boost</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>buck-boost</td>
<td>buck-boost</td>
<td>Garcia et al. [7]</td>
</tr>
<tr>
<td>D</td>
<td>boost</td>
<td>boost</td>
<td>SEPIC</td>
</tr>
<tr>
<td>D</td>
<td>boost</td>
<td>boost</td>
<td>BIFRED [1]</td>
</tr>
</tbody>
</table>

Table 1: Constraints on the choice of converters for non-isolated $R^2P^2$ PFC regulator topologies

D. Requirement for Isolation Between Input and Load

The requirement of isolation between the input and load necessitates the use of transformer-isolated converters for either or both constituent converters. The simplest implementation for configurations A and D is to have only converter 2 isolated, and in any such implementation, converter 1 must be a buck-boost converter while converter 2 can be any isolated converter. Of course, if converter 1 is also isolated (though not necessary), any combination of converter types is possible.

Moreover, configurations B and C would require transformer isolation for both converters 1 and 2, and hence can employ any combination of basic isolated converters.

IV. Circuit Synthesis Examples

In this section we will apply the afore-described synthesis procedure to construct practical $R^2P^2$ PFC voltage regulators.

Example 1: Realization of Configuration A — As mentioned before, the simplest way to provide isolation between the input and the load for configuration A is to use an isolated converter for converter 2. Note that converter 1 need not be isolated. Thus, we can employ any isolated converter for converter 2, but necessarily use a buck-boost converter for converter 1 (to avoid having to use an isolated converter for converter 1). Let us choose a buck converter for converter 2. Placing the two converters appropriately in the equivalent circuit of configuration A shown in Fig. 3, we obtain the circuit shown in Fig. 4 (a). The transformer isolated version is shown in Fig. 4 (b).

Example 2: Realization of Configuration B — We consider configuration B. Suppose we employ a buck-boost and a buck converter for converters 1 and 2 respectively. Similar to Example 1, we obtain an $R^2P^2$ PFC regulator, as shown in Fig. 5. Note that both isolation is required of both converters 1 and 2 in order to provide isolation for the $R^2P^2$ PFC regulator.

Example 3: Realization of Configuration C — Consider configuration C. Suppose we employ a buck-boost and a buck converter for converters 1 and 2 respectively. Likewise, we obtain a new PFC regulator, as shown in Fig. 6.

Example 4: Realization of Configuration D — Like configuration A, isolation can be achieved for configuration D by employing an isolated converter for converter 2, and there is no need for converter 1 to be isolated. Thus, we can employ any isolated converter for converter 2, but necessarily use a buck-boost converter for converter 1 (to avoid having to use an isolated converter for converter 1). Fig. 7 shows a possible $R^2P^2$ PFC regulator circuit arising from configuration D. This circuit has been tested experimentally by Garcia [7].
Fig. 4: (a) A possible implementation for configuration A using a buck-boost and a buck converter for converters 1 and 2; (b) isolated version using a buck-boost and a transformer-isolated forward converter for converters 1 and 2. Core reset arrangement omitted for brevity.

V. Basic Control Requirements

A. Fundamental Control Theorem

The basic requirement of the control of a PFC regulator is to regulate the power flow among the input, load and storage ports. To order to take full control of the amount of power being injected to and released from the storage, that being injected to the load, and that being taken from the input, the two constituent converters should be controlled separately. The following theorem is valid for all $R^2P^2$ as well as conventional cascade PFC regulators.

Theorem: For any PFC regulator consisting of two simple converters, it is not possible to achieve perfect unity power factor and output regulation simultaneously under the control of only one control parameter.

Proof: We will prove this theorem by contradiction. First we assume that unity p.f. and output regulation are achieved with only one control parameter, $\xi(t)$, controlling both converters. It is worth noting that we are considering power flows at twice the mains frequency. Suppose the power processed by converter 1 and converter 2 are $F_1(\xi(t))$ and $F_2(\xi(t))$, respectively. Thus, we hope to find $\xi(t)$ such that PFC and output regulation are satisfied simultaneously. We will exemplify the proof with configuration A. Assuming that the converters are lossless and referring to Fig. 1, the PFC requirement dictates that, for all $t$,

$$F_1(\xi(t)) = 2P_o \sin^2 2\pi f_m t - P_o \Rightarrow \quad F_1 = F_1^{-1}(2P_o \sin^2 2\pi f_m t - P_o) \tag{1}$$

where $P_o$ is the output power. However, output regulation requires that, for all $t$,

$$F_2(\xi(t)) = P_o \Rightarrow \quad \xi(t) = F_2^{-1}(P_o) \tag{2}$$

which contradicts (1). Likewise, for all other configurations, we will arrive at obvious contradiction if we begin with the assumption of using only one parameter for control. Thus, in general we are not able to maintain PFC and output regulation using only one control parameter, q.e.d.

B. Control Solutions

It should be apparent that if two separate control parameters are allowed, then the control problem can be solved. (A straightforward proof can be constructed based on the above theorem.) Two forms of the solution can be logically deduced:

1. The power flow functions $F_1$ and $F_2$ are controlled separately by $\xi_1(t)$ and $\xi_2(t)$, where $\xi_1(t) \neq \xi_2(t)$.

2. One of the power flow functions is controlled by two control parameters $\xi(t)$ and $\psi(t)$, while the other one is controlled by either $\xi(t)$ or $\psi(t)$.

As we will see later, the above first solution covers the conventional design of cascading a PFC pre-regulator and a dc/dc converter, which are under separate control. The second solution, moreover, covers the single-stage design utilizing both duty cycle modulation and frequency modulation for achieving almost perfect PFC and fast regulation [8].

C. Practical Applications and Choice of Operating Modes

The usual parameters available for control are the duty cycle $d$ and the switching frequency $f_s$. For converters operating in discontinuous mode, both $d$ and $f_s$ are available control parameters. However, for converters operating in continuous mode, only $d$ is available since such converters are immune to variation of switching frequency. For brevity we write the power flow function for a continuous-mode
Fig. 6: (a) A possible implementation for configuration C using a buck-boost and a buck converter for converters 1 and 2; (b) isolated version using a flyback and a forward converter for converters 1 and 2. Core reset arrangement omitted for brevity.

(CM) converter as \( F_{CM}(d(t)) \) and that of a discontinuous-mode (DM) converter as \( F_{DM}(d(t), f_s(t)) \).

As studied in Section V, we generally need two separate control loops for controlling two parameters. Moreover, operating modes of the converters will affect the complexity of the control problem. It is not difficult to see the following results which are straightforward extensions of the above discussion.

**Operating Regime 1:** When both converters are in CM operation, the use of two separate duty cycle signals for the two converters is mandatory. The power flow functions are

\[
P_1 = F_{CM1}(d_1(t))
\]

\[
P_2 = F_{CM2}(d_2(t))
\]

(3) (4)

where \( P_1 \) and \( P_2 \) denote the power flows through the two converters, \( F_{CM1}(\cdot) \) and \( F_{CM2}(\cdot) \) are the respective power flow functions, and \( d_1(t) \) and \( d_2(t) \) are the duty cycle signals controlling separately the two converters.

**Operating Regime 2:** When one converter is in CM operation and the other in DM operation, we may employ any combination of two control parameters chosen from two available duty cycles and a switching frequency, i.e.,

\[
P_1 = F_{CM1}(d_1(t), f_s(t))
\]

\[
P_2 = F_{DM2}(d_2(t), f_s(t))
\]

(5) (6)

**Operating Regime 3:** When both converters are in DM operation, we may employ any combination of two control parameters chosen from two available duty cycles and two available switching frequencies, i.e.,

\[
P_1 = F_{DM1}(d_1(t), f_s(t))
\]

\[
P_2 = F_{DM2}(d_2(t), f_s(t))
\]

(7) (8)

It is worth noting that the above control cases are applicable to all \( R^2P^2 \) configurations as well as conventional cascade configurations.

**VI. EXPERIMENTAL TESTS AND COMPARISONS**

Because of the ease of isolation, configurations A and D represent practical design choice. We have constructed prototype circuits corresponding to Figs. 4 and 7. In each experimental circuit, the two constituent converters are controlled separately, one with a TL494 for output regulation and the other with a UC3854 for PFC. All circuits are designed and tested for a power range from 20W to 100W. In brief, we obtain power factor up to 0.997 for each prototype. Moreover, since our purpose is to reduce redundant power processing, we specifically measure the efficiency of each constituent converters and compare their product with the measured overall efficiency, under the same voltage stress for each power level. For example, Fig. 8 compares the efficiencies for \( V_C \) at 160V and 230V for the circuit of Fig. 4. Similar tests were performed for other values of \( V_C \). Fig. 9 shows a plot of efficiency versus \( V_C \) at 100W output power. From Fig. 8, we see that the efficiency of the \( R^2P^2 \) converter is generally improved over that of a cascade structure consisting of the same two constituent converters. Also, for a lower value of \( V_C \), the overall gain in the efficiency is higher, as shown in Fig. 9. This agrees with the efficiency formula given in Tae-Chow [6]:

\[
\eta_{-11A} = \eta_1 \eta_2 + k \eta_1 (1 - \frac{\eta_1}{\eta_2})
\]

(9)

where \( \eta_1 \) and \( \eta_2 \) are the efficiency of the buck-boost stage and of the forward stage, respectively, and \( k \) is the ratio at which power is split at the input. For the circuit of Fig. 4, \( k \) is

\[
k = \frac{V_0}{V_C + V_0}
\]

(10)

Finally the total harmonic distortion is measured for different \( V_C \) and output power levels, as shown in Fig. 10.
Fig. 8: Efficiency comparison of configuration-A circuit (fig. 4(b)), showing improved overall efficiency over a cascade structure for (a) \( V_C = 160V \); and (b) \( V_C = 230V \).

Fig. 9: Efficiency versus \( V_C \) at 100W for configuration-A circuit (fig. 4(b)), confirming the efficiency formula (9); calculated curve is based on (9) and measured values of \( \eta_1 \) and \( \eta_2 \); experimental curve is from direct measurement of the overall efficiency.

Fig. 10: Measured total harmonic distortion versus output power.

VII. CONCLUSION

In this paper a synthesis procedure is derived to generate non-cascading PFC regulator circuits which shows reduction in the amount of power redundantly processed by the two constituent power stages. Also discussed are some issues related to the choice of control parameters and operating modes. Experimental measurements confirm the improved efficiency.

REFERENCES


