Manufacturing and Cost Analysis of Power-Factor-Correction Circuits

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Abstract – **This paper presents a comparative manufacturing (quality, performance, and reliability) and cost analysis of three different power-factor-correction approaches which are commonly used in the power-supply industry. The three approaches evaluated in the paper are passive, active two-stage, and active single-stage power-factor-correction approaches. The analysis is aimed at exposing the manufacturing and cost advantages and disadvantages of each circuitry at different output power levels.**

I. INTRODUCTION

The expected imposition of the line-current harmonic regulations for power supplies intended for the European market, defined in the EN61000-3-2 document, and in the corresponding Japanese voluntary specifications has prompted many power supply manufacturers to intensify their efforts towards finding cost-effective solutions to comply with these requirements. Generally, in low-power, cost-sensitive applications, the passive power-factor-correction (PFC) approach has been adopted by the majority of the power-supply manufacturers [1], [2]. However, at higher power levels and/or in applications where low total harmonic distortion (THD) and high power factor (PF) need to be achieved, active PFC approaches are the only practical choice.

The most commonly used active approach that meets high power-quality requirement is the two-stage approach [3]. In this approach, a non-isolated boost converter, which is controlled in such a manner that the rectified line current follows the rectified line voltage, is used as the input stage that creates an intermediate dc bus with a relatively large second-harmonic ripple. This front-end PFC stage is than followed by a dc/dc converter which provides isolation and high-bandwidth output-voltage regulation. For higher power levels, the front-end boost PFC stage is operated in the continuous-conduction mode (CCM), whereas the discontinuous-conduction mode (DCM) operation is commonly used at lower power levels due to a simpler control. Although relatively simple, mature, and viable in a wide range of power, the two-stage approach suffers from the increased circuit complexity which translates to an increased cost.

In an effort to reduce the component count and cost, a number of active single-stage PFC techniques has been introduced lately [4]-[7]. Generally, in a single-stage approach, PFC, isolation, and high-bandwidth control are performed in one step.

As one of the world's largest power supply manufacturers, Delta Electronics Inc. has been manufacturing power supplies with PFC feature for a long time. Generally, in low-end power supplies the PFC function is implemented by a simple, passive, line-frequency LC filter, whereas at higher power levels the two-stage approach with average-current control for the input stage is Delta's standard approach. Recently, Delta has introduced the first products which use an active single-stage approach.

In this paper, Delta's experience related to the manufacturing and cost issues of the power supplies with PFC function is summarized. Specifically, merits and limitations of different PFC approaches with respect to the output power level are discussed.

II. REVIEW OF PFC APPROACHES

A. Passive Approach

In this approach, a full-bridge rectifier with an LC filter is used to meet the line-current harmonic-limit specifications. Generally, choke L of the low-frequency filter can be placed either on the dc or ac side of the rectifier. The passive PFC technique is most suitable for applications with a narrow line-voltage range, e.g., European or Japanese power lines. However, it can be also employed in power supplies operating in the universal line-voltage range (90 - 265 Vac) to simultaneously meet the European and Japanese harmonic-limit specifications. Nevertheless, in the universal-line-range applications, front ends with a voltage-doubler rectifier (with manual or electronic switch) require much smaller and lighter inductors compared to those required for wide-range front ends. Fig. 1 shows the dc-side implementation of the passive PFC in a front end with voltage-doubler rectifier [2].

The major advantages of the passive PFC technique compared to the active PFC techniques are higher efficiency, superior reliability, and lower cost. However, the major drawback of the passive, LC-filter PFC is a relatively large weight of the choke. In fact, the weight of the choke usually requires careful mechanical considerations in order to meet shock and vibration specifications. Additional drawback of

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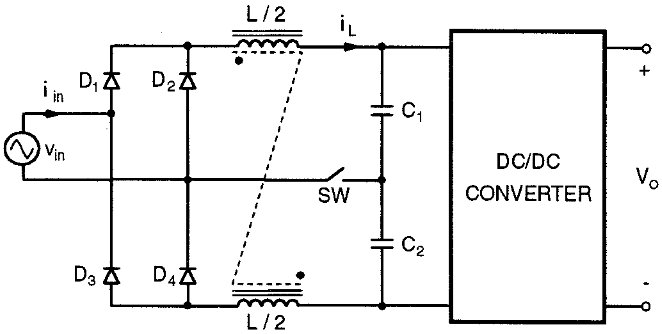

Fig. 1 Passive PFC with range-select switch

the passive PFC approach is that the filter-capacitor (bulk-capacitor) voltage, which is the input to the dc/dc-converter output stage, varies with the line voltage. This varying input voltage has a detrimental effect on the efficiency of the dc/dc converter. In addition, in applications where the power supply is required to provide a hold-up time, the capacitance of the bulk capacitor has to be increased due to the varying bulk-capacitor voltage compared to the capacitance which would be required if the bulk-capacitor voltage were constant.

As a result, the passive PFC approach seems attractive for power levels below 300 W, especially for applications with a voltage-doubler rectifier. In fact, in these applications Delta uses a split PFC choke on the dc side along with the standard range-select switch (110 V / 220 V). It should be noted that the relative performance evaluation and cost analysis of the other approaches is performed with respect to this passive approach.

B. Active Two-Stage Approach

The block diagram of the active two-stage approach is shown in Fig. 2. In this approach, two independent converters are used to achieve line-current shaping and wide-bandwidth regulation of the output voltage. The front-end converter, which is usually implemented using the boost topology, performs input-current shaping (ICS) by employing a low-bandwidth control which can be implemented by a number of dedicated PFC controllers. In universal-line range applications, the output voltage of the front end, which contains a strong second harmonic because of the low-bandwidth control, is regulated at 380 - 400 Vdc. This intermediate bus voltage is further processed by a step-down, dc/dc-converter output stage which provides safety isolation as well as the high-bandwidth regulation of the output voltage. Due to a virtually constant bus voltage, V_B, the efficiency of the dc/dc-converter output stage can be optimized. In addition, because of a relative high bus voltage, the capacitance of the bulk capacitor can be minimized for a given hold-up time requirement. However, the two-stage approach suffers from an increased circuit complexity since it requires two switches and two controllers with associated circuitry.

The performance and cost of a two-stage approach are very dependent on the choice of the control ICs, boost rectifiers, and power transistors. Generally, at Delta, the performance optimization is usually considered if there is a reasonable cost justification.

C. Active Single-Stage Approach

Today, there are many active single-stage PFC approaches available in the power-supply industry. Generally, the major advantage of the active single-stage approach compared to the active two-stage approach is that the single-stage approach requires only one controller as shown in the block diagram of the single-stage approach in Fig. 3. At lower power levels (< 200 W), the approaches which can be implemented with a single switch are extremely attractive because they seem to present an additional opportunity to reduce the cost of the PFC function. Generally, the active single-stage approach offers the performance (THD and PF) which is better than the corresponding performance of the passive, but not as good as that of the active two-stage approach. However, the active single-stage approach has a big advantage over the passive approach because its light weight and smaller size. The major deficiency of any single-stage circuit is that the voltage of the internal energy-storage (bulk) capacitor varies with the line voltage and load current. Due to these dependencies, in some single-stage circuits, the peak energy-capacitor voltage is well above 450 V, which makes these circuit impractical because of high cost of a high-voltage storage capacitors. In the

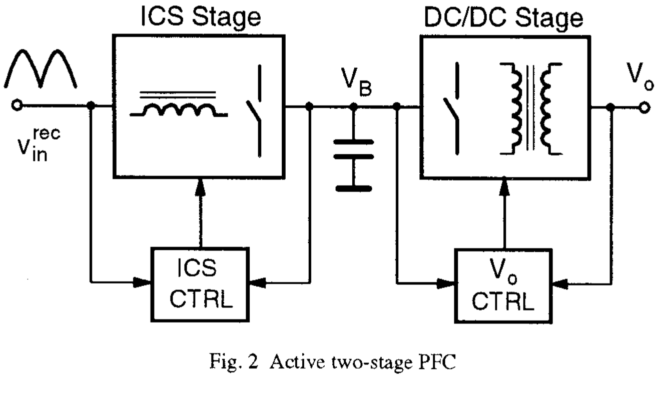

Fig. 2 Active two-stage PFC

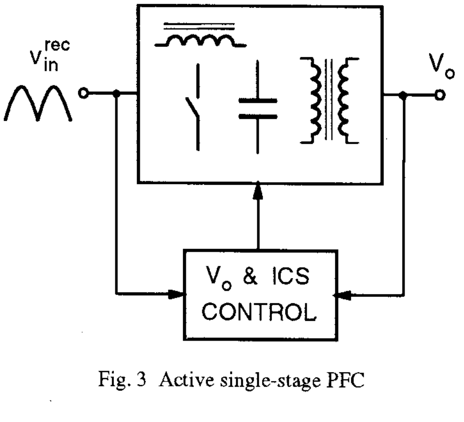

Fig. 3 Active single-stage PFC

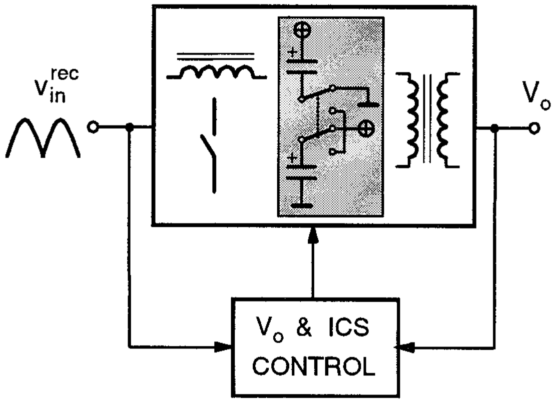

Fig. 4 Single-stage PFC with range-select switch

proprietary single-stage techniques used by Delta, the bulk capacitor voltage is kept well below 450 V. However, even in these circuits, their performance and cost-effectiveness are penalized because of the varying internal storage capacitor voltage, especially in applications requiring a hold-up time such as computer power supplies. The need for high-voltage (450-V), high capacitance energy-storage capacitors, can be eliminated by employing a Delta proprietary approach which uses a range-select switch (110 V / 220 V) to configure 250-V capacitors in series for 220-V operation or in parallel for 110-V operation.

In this paper, the approaches with both wide-range and range-select switch (110 V / 220 V) options are considered. These designs are optimized based on the component and manufacturing costs of the extra components (e.g., boost inductor, diode, etc.) and also different type of components to meet the requirements (e.g., different power MOSFETs for the main switch, 450-V capacitor for wide-range and 250-V capacitors for the range-select switch version).

TABLE I
RELATIVE COMPARISONS OF KEY PERFORMANCE FACTORS OF THREE PFC APPROACHES

	PASSIVE	ACTIVE TWO-STAGE	ACTIVE SINGLE-STAGE
THD	High	Low	Medium
Power Factor	Low	High	Medium
Efficiency	High	Medium	Low
Size (Volume)	Medium	Large	Small
Weight	Very High	Low	Low
Bulk Cap Voltage	Varies	Constant	Varies
Control	Simple	Complex	Simple
Component Count	Very Low	High	Medium
Power Range	≤ 200 - 300 W	Any	≤ 200-300 W
Design Difficulty	Low	Medium	High

The major characteristics of the three PFC approaches discussed in this paper are summarized in Table I.

III. EVALUATION OF PFC APPROACHES

To simplify the analysis and comparison of the different PFC approaches, the following assumptions are used:

- Output power levels of 100 W, 145 W, 200 W, and 300 W are considered.
- All power supplies have the same five output voltages (+5V, +3.3V, +12V, -12V, and -5V), plus a +5V standby voltage. The output currents are proportional to the output power levels. For example, the maximum current of the +5V output is 12 A for the 100-W power supply, while it is 17.4 A for the 145-W power supply.
- All power supplies have the same power density (W/in^3).
- All power supplies have the same annual production volume and are built at the same factory.
- Only the cost of the PFC circuit is analyzed and the rest of the power supply is assumed to be properly adjusted.
- All the evaluations are based on Delta's circuits and their component costs.
- The components and manufacturing costs are being considered to be of the highest priority.
- Only the main output power circuit is considered and other options (e.g. sleep mode) are not considered in the cost analysis.

For comparison of the different PFC approaches, four major categories are used: cost, efficiency, component count, and manufacturing complexity. Cost is defined as total cost of ownership, which includes components cost, manufacturing cost, and design cost. It also reflects the cost of meeting Delta's quality requirements (e.g., derating component guidelines, warranty cost, etc.). Efficiency is the total efficiency of the power supply at maximum load. Delta uses the efficiency numbers in cost evaluation of its products. However, these numbers do not reflect Delta's design capabilities at higher efficiency levels. The third category is the total component count, which includes the electrical and key mechanical parts. The manufacturing complexity is used to describe the level of difficulty in producing different PFC circuits. For example, a larger passive PFC choke results in added design complexity and manufacturing process to assure that the power supply meets all the mechanical requirements. Also, an extra daughter card which holds the extra components will result in an extra operation in manufacturing; taller components such as bulk capacitors result in extra mounting operation in the production line, etc.

In this paper, cost, component-count, and manufacturing-complexity evaluations of the different PFC approaches are performed with respect to the passive approach.

A. Evaluation of PFC approaches at 100 W

The 100-W PFC cost, efficiency, component-count, and manufacturing-complexity comparisons are presented in Table II. It can be concluded that although the passive solution has the lowest total cost, the single-stage PFC with range-select switch is close enough to be a very good alternative solution. The cost impact can be easily justified by size reduction of the PFC choke and the easy of manufacturing of this part. This benefit can be used in smaller packages (e.g., Net PCs) in the future. The wide-range single-stage PFC has a lower component count than the single-stage PFC with range-select switch, but it requires 450-V bulk capacitors, whereas the range-select switch approach uses 250-V capacitors.

TABLE II
EVALUATION OF PFC APPROACHES AT 100 W

	Passive	Single-Stage	Single-Stage w/ Sw	Two-Stage
Cost [%]	100	113	110	117
Efficiency [%]	75	72	72	65
Component Count [%]	100	110	112	130
Manufacturing Complexity [%]	100	120	115	140

B. Evaluation of PFC approaches at 145 W

The 145-W PFC cost, efficiency, component-count, and manufacturing-complexity comparisons are presented in Table III. Again, the passive option seems to be the best solution, however, the size of the PFC choke is now larger, which results in increased manufacturing complexity. Therefore, in some applications, (e.g., low-profile packages), the single-switch PFC with range-select switch will be the preferred solution.

TABLE III
EVALUATION OF PFC APPROACHES AT 145 W

	Passive	Single-Stage	Single-Stage w/ Sw	Two-Stage
Cost [%]	100	110	106	115
Efficiency [%]	75	72	72	65
Component Count [%]	100	110	112	126
Manufacturing Complexity [%]	100	120	110	130

C. Evaluation of PFC approaches at 200 W

The 200-W PFC cost, efficiency, component-count, and manufacturing-complexity comparisons are presented in Table IV. As the output power increases, it is more difficult to meet shock and vibration requirements with the passive solution. Therefore, the manufacturing complexity of the passive PFC increases towards the single-stage PFCs.

TABLE IV
EVALUATION OF PFC APPROACHES AT 200 W

	Passive	Single-Stage	Single-Stage w/ Sw	Two-Stage
Cost [%]	100	103	101	105
Efficiency [%]	75	72	72	65
Component Count [%]	100	110	110	116
Manufacturing Complexity [%]	100	115	110	120

D. Evaluation of PFC approaches at 300 W

The 300-W PFC cost, efficiency, component-count, and manufacturing-complexity comparisons are presented in Table V. It can be concluded that at this output power level, the two-stage PFC is the most attractive and less complex solution from the manufacturing point of view.

TABLE V
EVALUATION OF PFC APPROACHES AT 300 W

	Passive	Single-Stage	Single-Stage w/ Sw	Two-Stage
Cost [%]	100	105	104	103
Efficiency [%]	75	72	72	65
Component Count [%]	100	110	108	114
Manufacturing Complexity [%]	110	130	120	100

According to the above evaluation, the followings could be concluded:

- If the output power is less than 100 W, the wide-range single-stage PFC and the passive PFC are valid options.
- If the output power is between 100 W and 145 W, the passive PFC and the single-stage PFC with range-select switch are good solutions.

- If the output power is between 145 W and 200 W, the single-stage PFC with range-select switch is more suitable than the passive approach due to the size of the PFC choke.
- Above 200 W, the conventional two-stage PFC seems to be the best choice.
- Passive PFC and single-stage PFC with range-select switch can be designed to be an add-on option to minimize the added cost. This feature gives the customer the opportunity to design the power supply with PFC option and defer its implementation until standard requirements such as IEC61000-3-2 become mandatory.

IV. SUMMARY

In this paper, three different power-factor-correction approaches which are commonly used in the power-supply industry are reviewed, analyzed, and evaluated: passive PFC, active two-stage PFC, and active single-stage PFC with and without range-select switch. The PFC approaches are evaluated at four different output power levels. For comparison of the PFC approaches four major categories are used: cost, efficiency, component count, and manufacturing complexity. At output power levels below 100 W the wide-range single-stage PFC and the passive PFC are the preferred options, while at output power levels between 100 W and 145 W the passive PFC and the single-stage PFC with range-select switch seem to be the best solutions. Further, at output power levels between 145 W and 200 W, the single-stage PFC with range-select switch is more suitable than the passive approach due to the size of the PFC choke. Finally, at output power levels above 200 W, the two-stage PFC presents the best choice.

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