CHAPTER 4

COMPARISON BETWEEN CCM TWO-STAGE AND SINGLE-STAGE POWER FACTOR CORRECTION CONVERTERS

4.1 Introduction

As discussed in Chapter 1, normally the active PFC converters can be divided into two categories: the two-stage approach and the single-stage approach. The two-stage approach is the most commonly used approach [A6, A7]. In this approach, an active power factor correction stage is adopted as the front-end to force the line current tracking the line voltage. A DC/DC output stage provides the isolation and the tightly regulated output voltage to meet the load requirement. However, this approach suffers from some drawbacks in low-power cost-effective applications because it requires additional PC components and complicate PFC control circuit. Thus it has high cost and large size.

A low cost alternative solution to this problem is to integrate the active PFC stage with the isolated high quality output DC/DC stage into one stage. It is the single-stage PFC approach. In this approach, the PFC switch and its controller are saved while the converter still have fair input current and isolated high quality output. For the single-stage PFC converter, the CCM S^2-PFC converters are more attractive than DCM S^2-PFC converter. The CS S^2-PFC converter as presented in the previous chapter can be an example of the CCM S^2-PFC converter.

Normally, it is expected that the S^2-PFC converter will have lower cost than the two-stage PFC converters. However, it depends on the different applications. In [C2], a general comparative manufacturing and cost analysis of the different PFC approaches is presented. In this chapter, a detailed comparison study between the CCM S^2-PFC converter and the two-stage converter is given for universal line application with the hold-up time requirement. First, the topology and control approaches are compared and then a group of data and curves about the component ratings are given for different output power levels. The merits and limitations of these two approaches are also discussed.

4.2 Comparison between CCM two-stage and single-stage PFC converters

4.2.1. Differences of two active PFC approaches and example circuits

4.2.1.1 Active two-stage PFC approach

The general structure of a two-stage PFC converter is shown in Fig. 4.1. There are two independent power stages. The first PFC stage is normally a boost or buck/boost (or flyback) converter. It has a PFC inductor and a PFC switch. The PFC controller senses the input voltage/current waveforms and forces the input current to trace the input voltage. Therefore, the unit input power factor is achieved. There is an energy storage bulk capacitor C_B on the output side of the front-end stage to provide a roughly regulated DC bus voltage with small second order harmonic. The bus voltage V_B is roughly regulated around 380-400 Vdc while the line input voltage changes from 90 Vac to 265 Vac. The high intermediate bus voltage V_B can minimize the bulk capacitor value while the hold-up time is concerned. Also, the narrow range dc input makes it easy to optimize the DC/DC output stage. The second stage is the isolated output stage. This stage has at least one PWM switch to tightly regulate the output voltage. There is an independent PWM controller, which provides an almost constant duty-cycle to the DC/DC stage switch to regulate the output voltage.

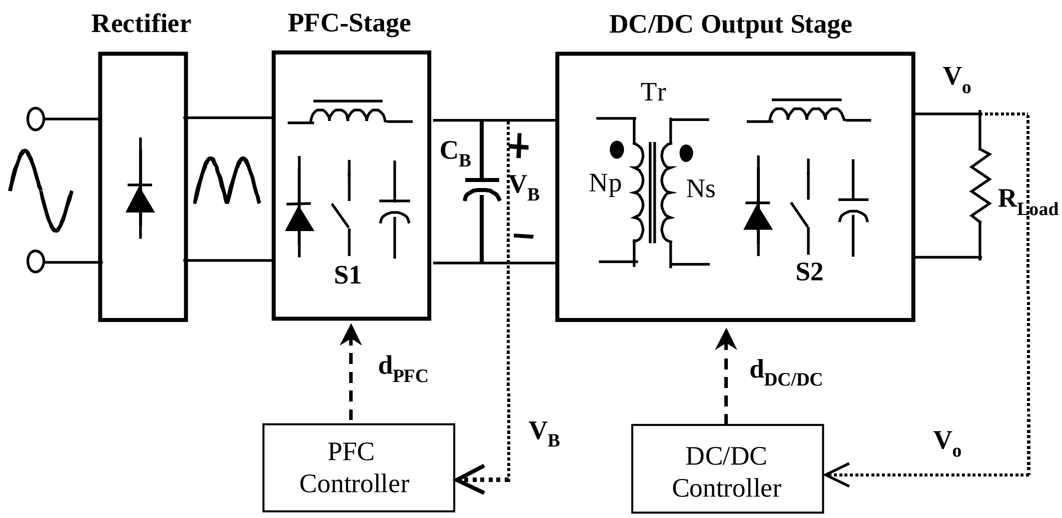


Figure 4.1 Active Two-Stage PFC Converter

Figure 4.2(a) shows the input current and voltage waveforms of the two-stage PFC converter and Fig. 4.2(b) shows the value of duty-cycle waveforms of the PFC and DC/DC stages. The PFC front-end stage and DC/DC output stage has different independent control signals. The PFC duty cycle changes while the instantaneous line voltage changes, but the DC/DC duty cycle keeps a constant value during a line cycle.

Figure 4.3 shows the example circuit of the two-stage PFC converter in this analysis. It has a CCM boost PFC converter as front-end stage and a forward converter as the DC/DC output stage. S1 is the PFC switch and S2 is the forward switch. C_B is the bulk energy storage capacitor, which provides a roughly regulated dc voltage for the forward stage and stores energy for sufficient hold-up time. The RCD reset circuit is chosen for the forward converter to have the best cost-performance for low power application. The input voltage range is from 90 Vac to 265 Vac and the output voltage is 5 V regulated dc voltage.

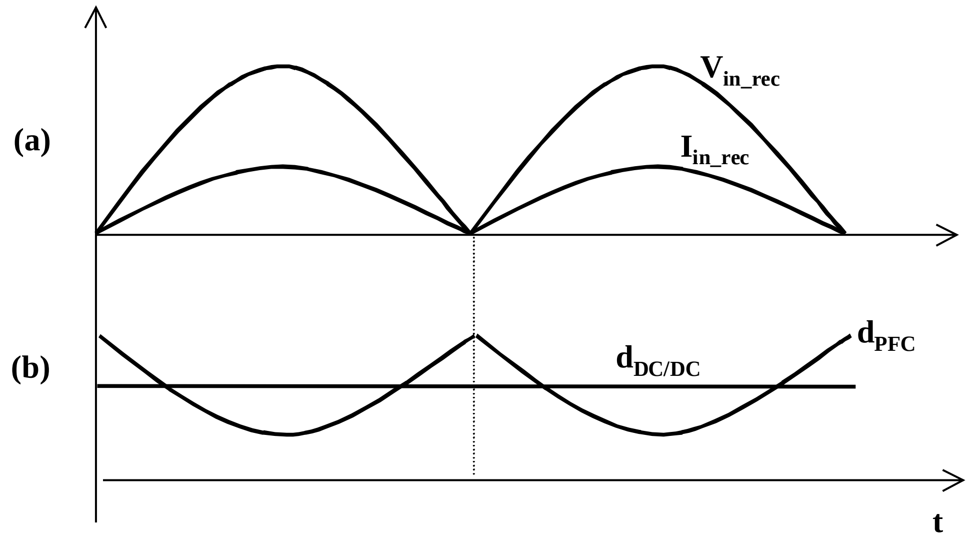


Fig 4.2 Waveforms of Two-Stage PFC Converter

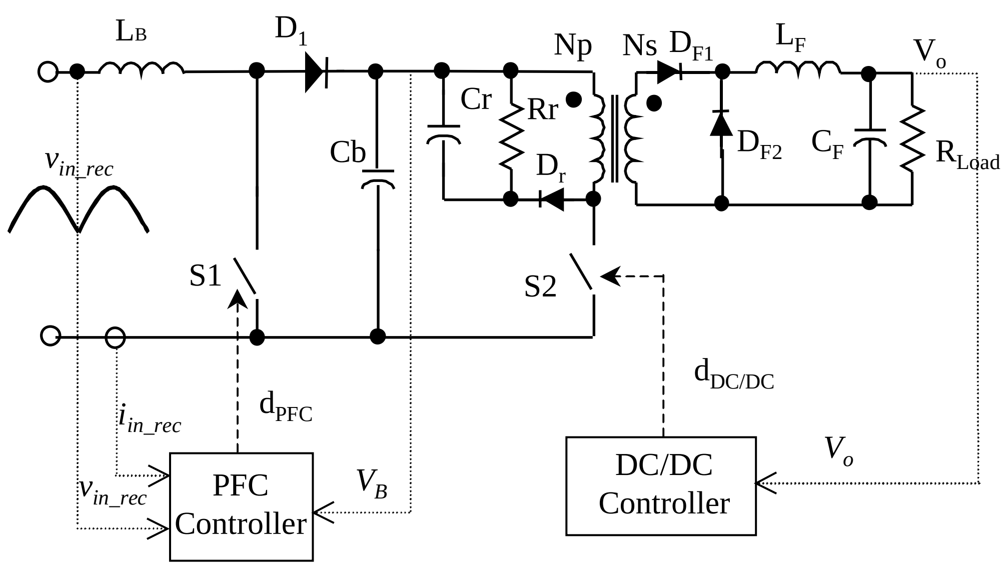


Figure 4.3 CCM Boost PFC Front-End and RCD Clamped Forward Output Stage

4.2.1.2 Active single-stage PFC converter

The general structure of single-stage PFC converter is shown in Fig. 4.4. Compared to the two-stage approach, the single-stage approach uses just one switch to shape the input current and regulate the output voltage at the same time. The output voltage feedback controller is the only controller here. It has a high bandwidth so the output voltage is tightly regulated. While this converter is working on steady state, the control duty-cycle is an almost constant value during the line cycle. The PFC function is automatically achieved based on the principle of the circuit operation instead of on the additional PFC duty-cycle controller. Normally, the input power factor is not perfect but is already good enough to meet the IEC PFC requirement.

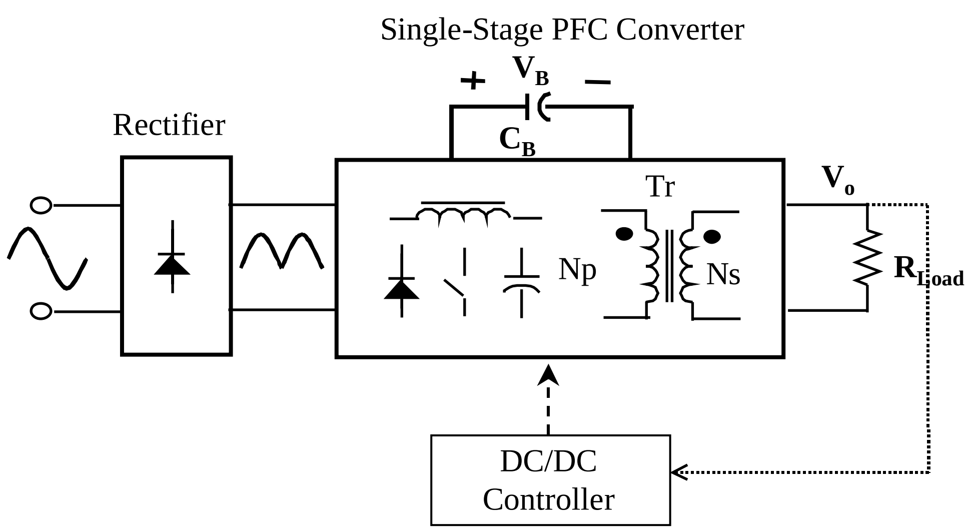


Figure 4.4 Active Single-Stage PFC Converter

For any PFC converter, the instant input power is pulsating but the output power is a constant dc value during the line cycle. Thus there must be an energy storage capacitor C_B to store the unbalanced energy so that the output is free of line ripple. However, unlike the two-stage PFC converter, the bus voltage V_B here is no longer a roughly regulated constant value because the only controller here is focusing on the regulation of output voltage. It results in a very wide voltage range of V_B for universal line input. Normally, it is close to 130 V at low line and is higher than 400 V at high line for today's single-stage PFC converters. That is very undesirable. The wide voltage range makes it very hard to optimize the DC/DC stage and at the same time requires a huge high voltage bulk capacitor to meet the hold-up time requirement. The single-stage PFC converter saves the PFC controller and PFC switch, so it may have a lower cost compared to the two-stage approach. However, later calculations show the component ratings may be higher than in the two-stage PFC.

Figure 4.5 shows one example circuit for the analysis of the single-stage PFC converters, which is the CCM CS S^2-PFC converter. It uses an additional inductor L_1 to achieve the CCM single-stage PFC function. An active clamped (ACL) reset circuit is necessary on the forward output converter to make maximum duty cycle as high as possible, therefore overcoming the disadvantage of low bus voltage at low line.

From the complexity of power stage and control circuit viewpoint, it is clear that the single-stage PFC is simpler than the two-stage PFC converter. However, further calculations need to be done to carefully compare the component ratings, size and cost of these two approaches for different output power levels. In this chapter, the major component ratings of these two approaches are compared.

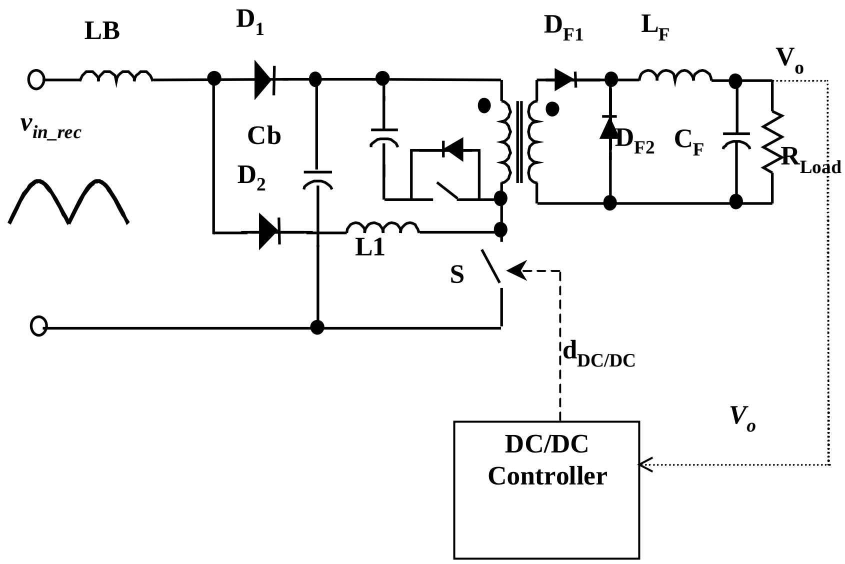


Fig. 4.5 CCM Single-Stage PFC Converter with ACL Forward Output Stage

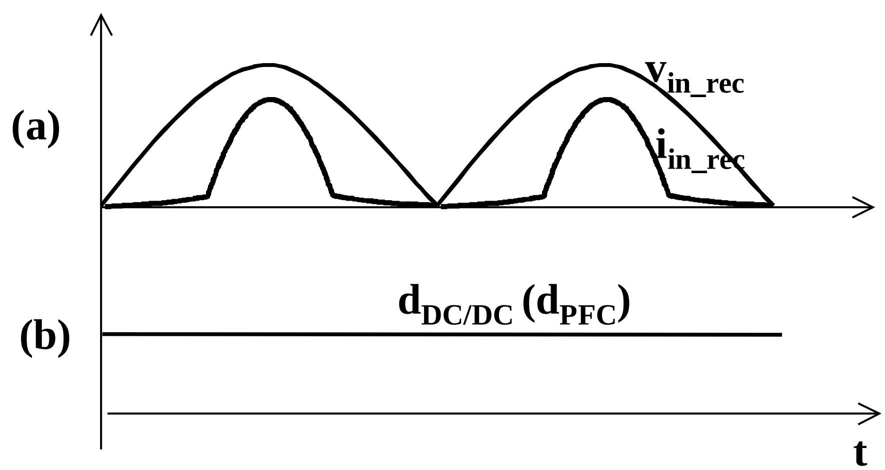


Fig. 4.6 Waveforms of the Single-Stage PFC Converter

4.2.2 Comparison of the component ratings of two active PFC approaches

There are some assumptions made to simplify the calculation and comparison:

- Input voltage is universal line voltage, from 90 V ac to 265 V ac.
- Output voltage is 5 Vdc and output power levels are 50 W, 100 W, 200 W, 300 W and 400 W respectively.
- Hold-up time is required for all the calculations.
- The switching frequency is assumed to be 100 kHz for both the PFC switch and the DC/DC switch. Also, it is assumed high frequency MOSFET devices are used for all the switches.
- For the two-stage PFC converter, the PFC stage efficiency η_{PFC} is assumed to be about 0.9 and the DC/DC stage efficiency η_{DC} is about 0.9. So the overall efficiency η is about 0.8. For the single-stage PFC converter, it is assumed that the overall efficiency η is about 0.7.
- It is assumed that in the two-stage PFC converter the bus voltage is regulated at 400 Vdc. At the same time, the bus voltage of the single-stage PFC converter is estimated to be 130 - 400 Vdc while the line voltage varies from 90 Vac to 265 Vac.

The major component ratings are calculated, including the input inductance and current rating, the PFC and Forward DC/DC switch rating, the PFC bus diode current rating, the bulk capacitor rating and the output inductance and current rating. All of these together will determine the overall cost, size and efficiency.

4.2.2.1. Comparison of the Hold-Up Bulk Capacitors.

Many applications require the hold-up time of the power supply. This means that when the input line fails, the converter can still provide the maximum output power for a required time interval, i.e., the hold-up time. For the PFC converter, the high voltage bulk capacitor is also used to provide sufficient hold-up time as a big energy storage component. The rating of the hold-up capacitor can impact the total size and cost significantly. The capacitance C_B is determined by the difference between the low line (90 Vac) heavy load capacitor voltage V_{B_90} and the designer-defined minimum capacitor voltage V_{B_min} , the hold-up time t_{hold} , the maximum output power P_{o_max} and the forward stage efficiency η_{dc}. This can be obtained from Eq. (4.1).

$$C_B = \frac{2 \cdot \dfrac{P_{o\_\max}}{\eta_{dc}} \cdot t_{hold}}{V_{B\_90}^2 - V_{B\_\min}^2} \qquad (4.1)$$

For a two-stage PFC converter, the bus voltage V_{B_90} is regulated around 400 V and the minimum voltage V_{B_min} can be designed at 300 V as an example. It is still a relatively high voltage. Because the energy stored on the capacitor is directly proportional to the square of the capacitor voltage, the hold-up capacitance here can be a small value. For example, while t_{hold}=10 ms, P_{o_max}=100 W, C_B is just 37.8 μF. However, for the CS single-stage PFC converter, the low line bus voltage is not regulated and will be as low as 130 V while the input voltage reaches its minimum value. So the energy stored on the capacitor will be much less than on the high line. Therefore, if the V_{B_min} is selected as 90 V for example, C_B must be at least as high as 284 μF to maintain the same hold-up time. The capacitor is seven times larger than the two-stage PFC capacitor. Figure 4.7 shows the relationship between the C_B and hold-up time t_{hold} while the output power is 100 W. It shows that the single-stage PFC converter requires a much larger hold-up capacitance than the two-stage PFC converter. In both cases, the capacitor voltage rating is 450 Vdc. Figures 4.8(a) and (b) show the curves of bus capacitance V_B versus output power P_{omax} for the two-stage PFC and single-stage PFC respectively. They also show that the CS single-stage PFC always requires higher hold-up capacitance than two-stage PFC converter for all power levels. Also, for a particular converter, the capacitance increases while the hold-up time increases.

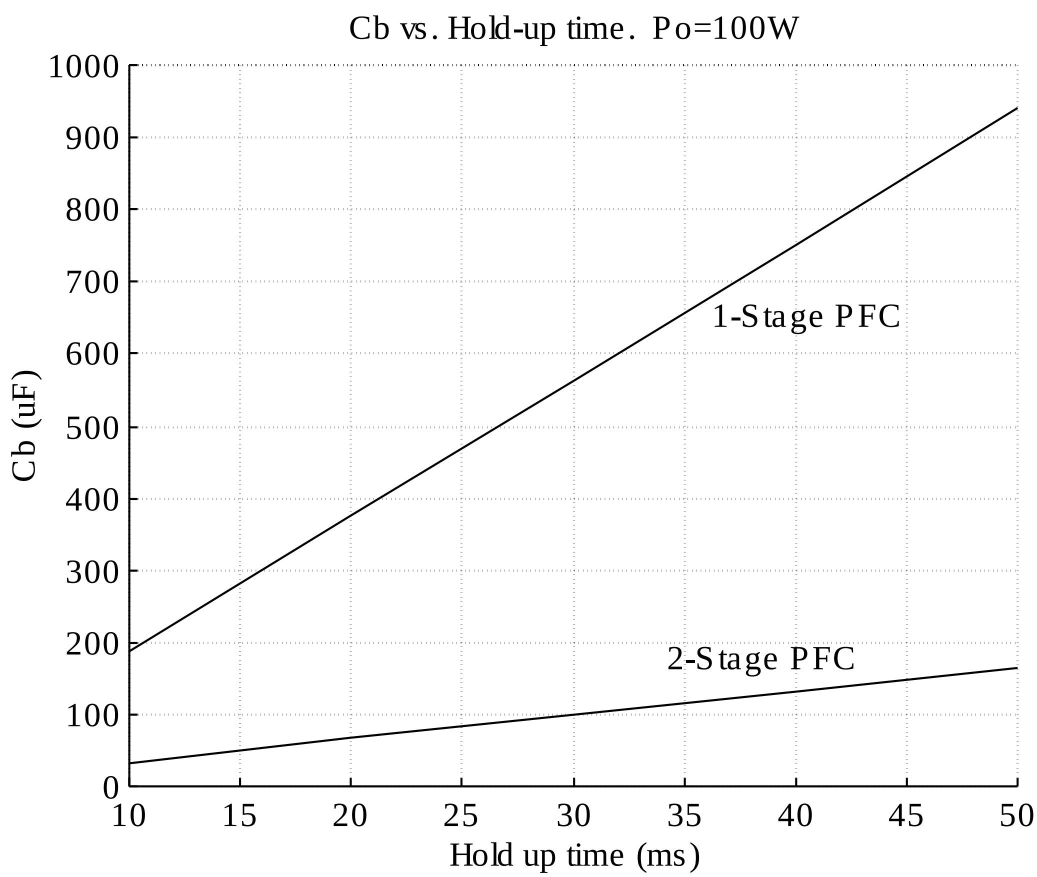
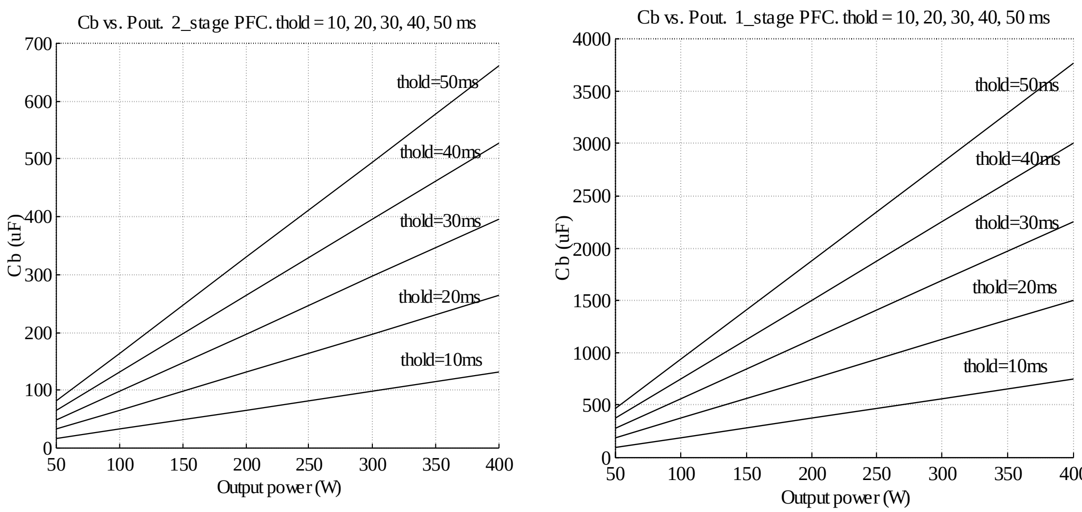


Figure 4.7 C_B vs. Hold-up time @ Po=100 W



(a) (b)

Fig. 4.8 (a) 2-stage FPC, C_B vs. Output power Po
(b) 1-stage PFC, C_B vs. Output power Po

4.2.2.2 Comparison of the power switches and diodes.

In the two-stage PFC converter, there is a PFC switch and a DC/DC switch to handle the PFC current and the DC/DC output current, respectively. The single-stage PFC converter combines these two switches into one to save one switch. However, now the combined switch need handles both the PFC current and the forward current so that it has a higher current rating. The current through the switch will determine the size of the switch and the loss on the switch. Because MOSFET is used as the power switch, the rms switch current is concerned in our comparison.

$$I_{in\_pk} = \sqrt{2} \cdot \frac{P_{o\max} / \eta}{V_{in\_\min}} \tag{4.2}$$

$$I_{S1} = \sqrt{\int_0^{\pi} (1 - \frac{\sqrt{2} \cdot V_{in\_min}}{V_B} \cdot \sin(x)) \cdot I_{in\_pk}^2 \cdot \sin(x)^2 dx} \quad (4.3)$$

For a two-stage PFC converter, the PFC switch rms current I_{S1} can be calculated from Eq. (4.3). Where the minimum input line voltage V_{in_min}=90 Vac, bus voltage V_B=400 V, the peak input current I_{in_pk} can be calculated from Eq. (4.2). Also, the forward switch current I_{S2} can be calculated from Eq. (4.4).

$$I_{s2} = \frac{P_{o\max}/V_o}{N} \cdot \sqrt{D_{FWD}} \quad (4.4)$$

N is the forward transformer turns ratio and D_{FWD} is the forward duty-cycle. N and D_{FWD} can be determined by the given circuit specifications.

For a single-stage PFC converter, the input current cannot be calculated mathematically from a closed form equation because the input current is not a good sinusoidal waveform. Therefore, a numerical program is used to calculate the input current waveform and then the rms current I_s is also obtained numerically.

Figure 4.9 shows the comparison of the current ratings between the two-stage PFC converter and single-stage PFC converter. It shows the rms switch current in the single-stage PFC is even higher than the sum of both switch currents in the two-stage PFC converter. This means that the single-stage PFC switch is larger and also has a higher loss than any switch in the two-stage PFC converter.

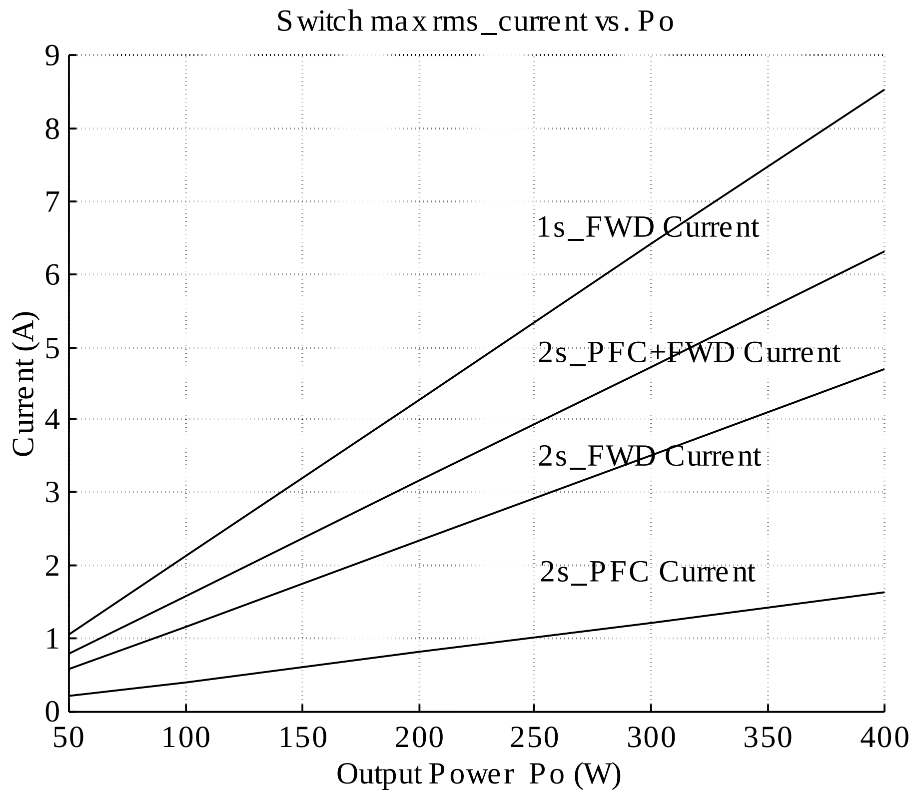


Figure 4.9 Switch rms current vs. output power

Where the PFC diode rating is concerned, the average diode current is calculated. For a two-stage PFC converter, the diode current can be calculated from mathematical equations while in the single-stage PFC converter, the average diode current can only be calculated numerically. Figure 4.10 shows the comparison of PFC diode current ratings. The single-stage PFC converter has a higher diode current than two-stage PFC converter for all the power levels. The diode voltage ratings in both cases are about 400 Vdc.

Also, Fig. 4.11 shows the average current rating of the forward output diodes versus the output power. It is clear that the single-stage PFC converter also has a higher current through the output rectifier diodes. At the same time, the voltage ratings of the output diode are different. It is 12 V in two-stage PFC and 35 V in the single-stage PFC in our calculations.

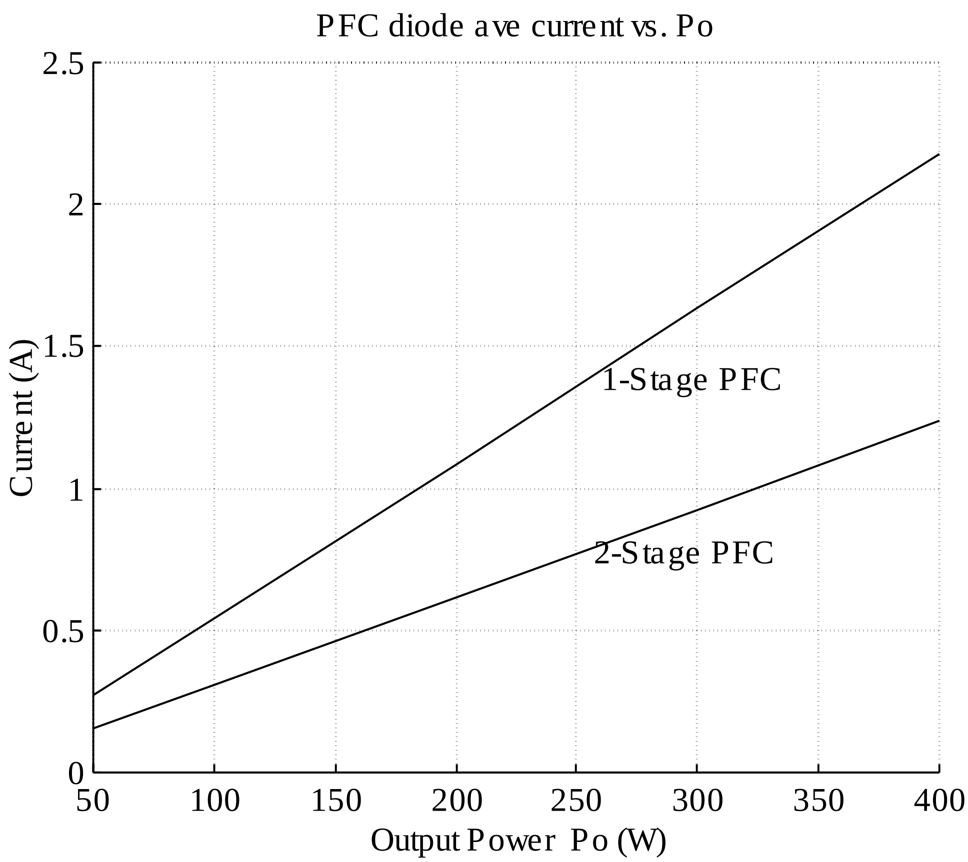


Figure 4.10 PFC diode average current vs. output power

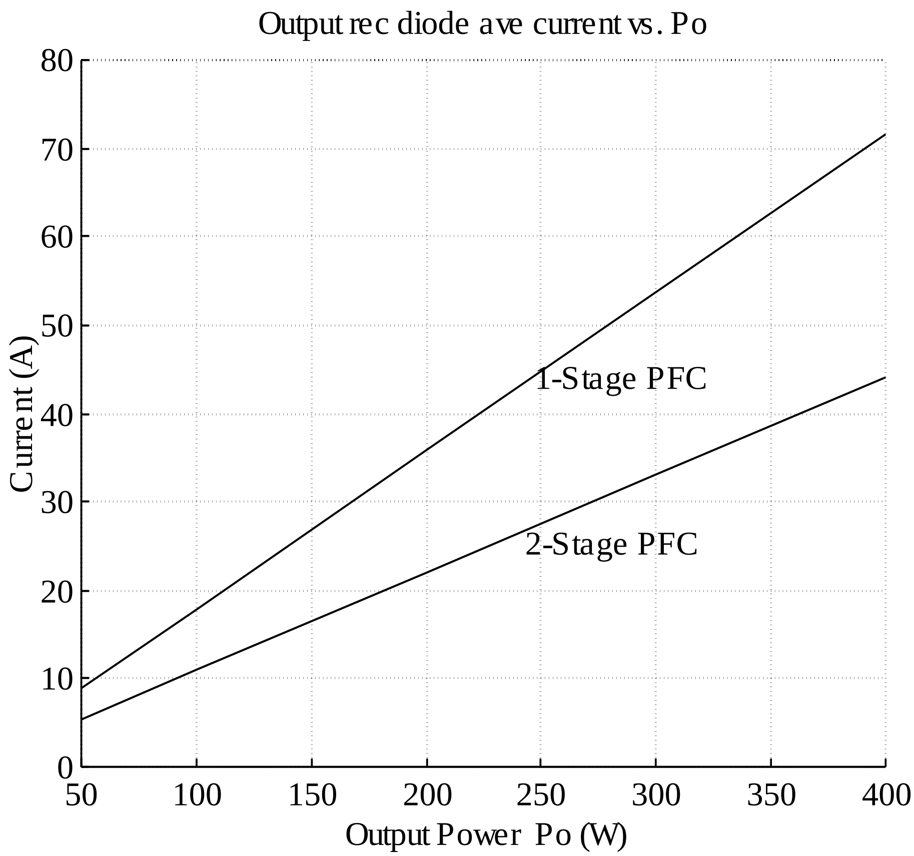


Figure 4.11 Output rectifier diode current vs. Po

4.2.2.3 Comparison of inductors.

a) *Input PFC Inductor.*

The input inductance in the two-stage PFC converter is determined by the maximum ripple and PFC duty cycle [A7]. However, in the design of a single-stage PFC converter, the inductor current ripple is not the most important issue [C1]. In fact, the bus voltage stress, the DCM/CCM operating modes and the input current power factor are more critical concerns than the current ripple. So it does not make too much sense to compare the inductance of these two design cases. However, we can assume that they have similar inductance in both cases and then compare the input inductor peak current.

Figure 4.12 shows the comparison of the peak input inductor current. In the two-stage PFC, the current value can be calculated while in the single-stage PFC converter the current value is obtained from the numerical solution. The figure shows the single-stage PFC converter has a higher inductor current than the two-stage PFC converter.

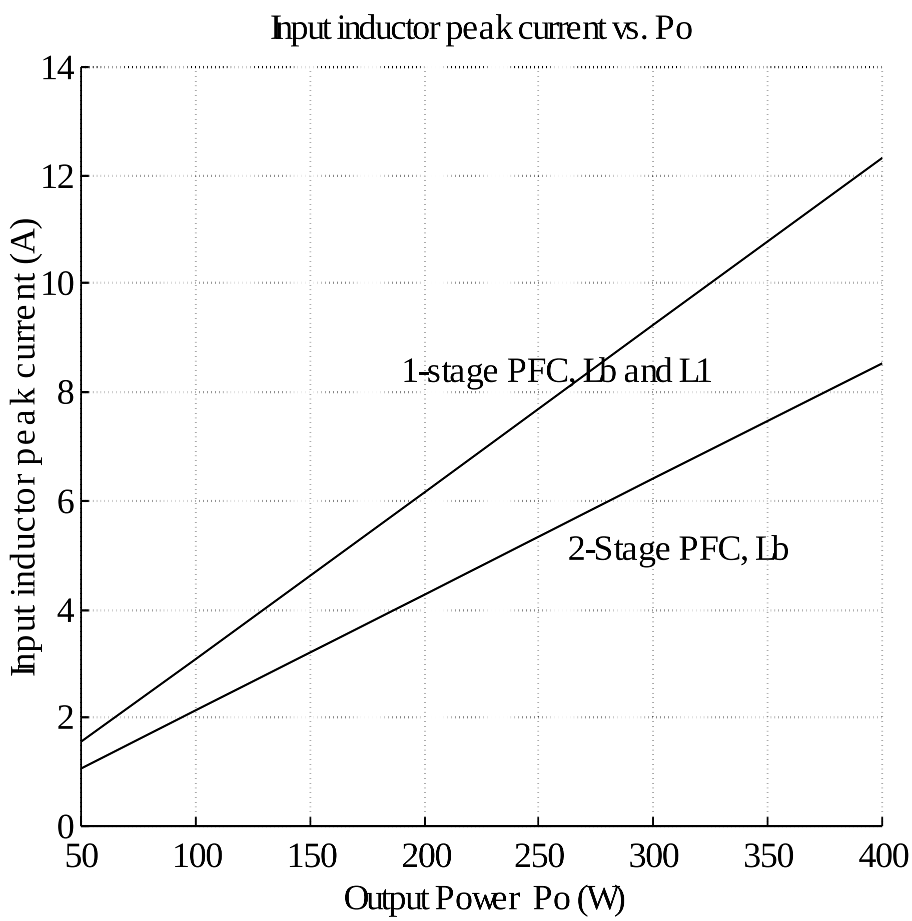


Figure 4.12 Input inductor peak current vs. Po

b). Output inductor rating.

To compare the output inductors, we assume that the output current has the same amount of ripple. This means the peak currents through the output filter inductors in both cases are the same. However, because the single-stage PFC converter has a very wide bus voltage range, the forward duty-cycle also changes a lot while the line changes. This requires a larger output inductance.

Figure 4.13 shows the difference of the output inductance between the two-stage PFC converter and the single-stage PFC converter.

As a conclusion, Table 1 gives a total comparison between two converters for a particular case. The output power is 100 W and the hold-up time is 10 ms. This table shows that the single-stage PFC converter needs higher rating components in comparison with the two stage PFC converters. This is true at all power levels.

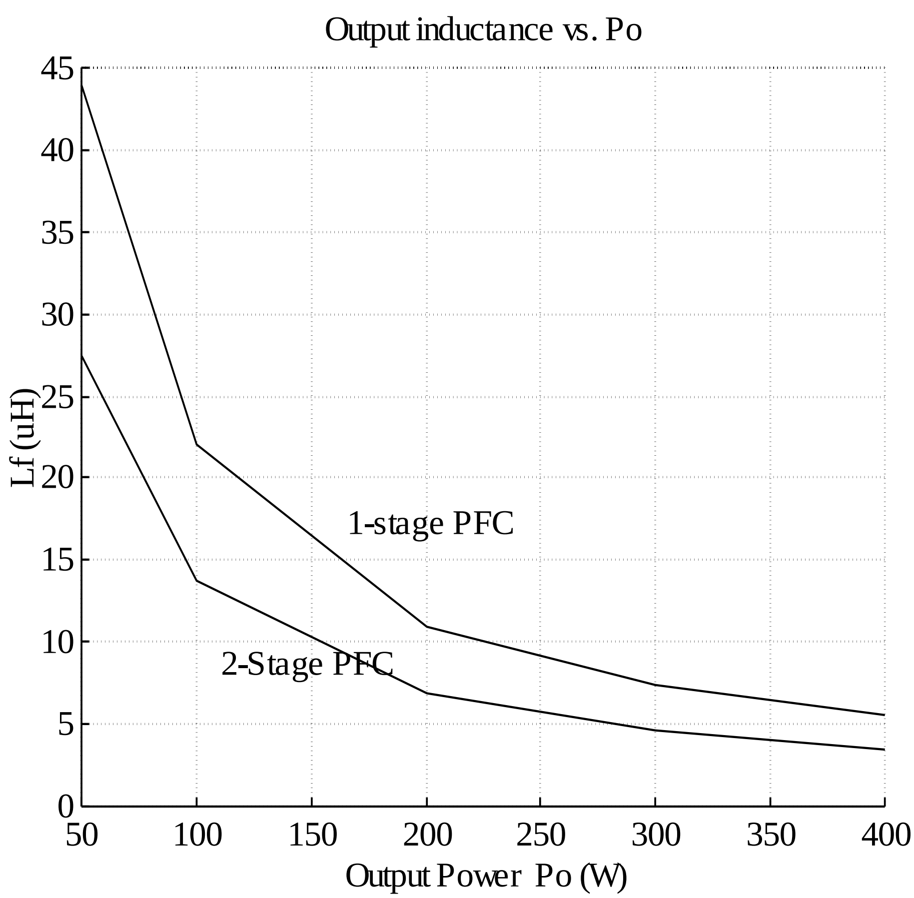


Figure 4.13 Output filter inductance vs. Po

According to the above comparison figures, the following is concluded:

- For universal line application, because the CS single stage PFC converter has a very wide bus voltage range, it requires higher rating components compared to the two-stage PFC converter. Actually, all the present single-stage PFC converters have a similar wide bus voltage range problem.
- The total loss in the CS single-stage PFC converter may be higher than in the two-stage PFC converter due to the high current and voltage stress. It results in lower efficiency in the single-stage PFC converter.
- The CS single-stage PFC converter saves the PFC switch and control circuit so the total cost is reduced even if it may have higher rating components than a two-stage PFC converter. It may be attractive for lower power applications while the component rating difference is not so significant. However, for higher power level application, the two-stage PFC converter will be more attractive.

It needs to be pointed out that the major reason for most of the disadvantages of the CS single-stage PFC converter is its wide bus voltage range for universal line operation. The wide bus voltage range makes most of the major components in the CS single-stage PFC converter have a higher rating than the two-stage PFC converter. Because all the present integrated single-stage PFC converter have the same wide bus voltage range problem, it is possible for all of them have larger rating components than a two stage PFC converter. Although in this comparison the CS single-stage PFC converter is chosen as the example circuit, the results can be also applied to other similar single-stage PFC converters. Also, the comparison shows that if the bus voltage range of single-stage PFC converter can be reduced, the overall cost and performance of it can be improved significantly. This can be the direction of very interesting future work.

Table 1. Comparison between Two-stage PFC Converter and CS Single-stage PFC converter.

(Output: 5V / 100W, Hold-up time: 10 ms)

	Two-Stage PFC	CS 1-Stage PFC
Reset Circuit	RCD Clamp Reset	Active Clamp Reset
Duty Cycle	D_{oper} = 0.45 D_{max} =0.60	D_{90V} = 0.49 D_{265V} = 0.16 D_{max} = 0.7
Input inductor peak current	2.13 A	3.08 A
Bus voltage	Vmin = 300 V Voper = 400 V	Vmin = 90 V Voper = 130-400 V
Forward Trans. Turns Ratio	33	11.5
PFC Switch Rating	1.172 A / 400 V	NA
PFC Diode Rating	0.309 A / 400 V	0.544 A/ 400 V
Forward Switch Rating	0.407 A/ 727 V	2.152 A/ 574 V
Output diode rating	11.0 A / 12 V	16.8 A/ 34.9 V
Bus Capacitor	37.8 uF / 450 V	284 uF / 450 V
Output Inductor	13.7 uH / 22 A	21.0 uH / 22 A

4.3 Summary

In this chapter, the two-stage PFC converter and CS single-stage PFC converter are reviewed, analyzed and compared. The comparison is done for different output power levels, from 50 W to 400 W. The component value, voltage and current rating are given in those curves to show the differences of these two PFC approaches. The CS single-stage PFC converter has a simpler power stage and control circuits. However, it has higher components rating and lower efficiency compared to the two-stage PFC converter because of its very wide bus capacitor voltage range. The final choice between these two circuits will be determined by the trade-off between the additional PFC component cost in the two-stage approach and the increased cost due to high component ratings in the single-stage approach. Generally speaking, for low-power cost-sensitive applications, the single-stage PFC approach is more attractive. For the higher power applications, the two-stage PFC approach will be much better. Also, this study shows that the universal-line narrow bus-voltage range single-stage PFC techniques will be a very interesting research topic.