CHAPTER 1

INTRODUCTION

1.1 Background

Conventionally, most of the power conversion equipment employs diode rectifiers or thyristor rectifiers to convert AC voltage to DC voltage before processing it. Such rectifiers produce very poor power factor with a large displacement factor and strong harmonic currents because these power converters absorb energy from the AC line only when the line voltage is higher than the DC bus voltage. Usually, the input power factor of these kinds of converters is as low as 0.65 [A1, A2]. More stringent international requirements to limit the line input current harmonics, such as IEC 1000, have been proposed and will be enforced to limit the harmonic currents drawn by the off-line equipment. As a result, power factor correction (PFC) has become one of the most popular topics in power electronics research. The major objective of this research is to achieve good input power factor with high efficiency, small size and low cost.

The power factor is defined as the ratio of the average power to the apparent power at an AC terminal [A3]. Assuming an ideal sinusoidal input voltage source, the power factor can be expressed as the product of two factors, the distortion factor and the displacement factor, as given in Eq. (1.1). The distortion factor Kd is the ratio of the fundamental root-mean-square (RMS) current to the total RMS current. The displacement factor K_θ is the cosine of the displacement angle between the fundamental input current and the input voltage.

$$PF = K_d \cdot K_\theta \tag{1.1}$$

$$K_d = \frac{I_{rms(1)}}{I_{rms}}$$

$$K_\theta = \cos\theta$$

If a converter has a power factor less than one, the converter will absorb higher apparent power than the real power it consumes. The implication is that the AC power line needs to be rated with a higher VA rating than the power consumption of the power converter that supplies it. Furthermore, the harmonic currents produced by the power converter will pollute the power line and affect other users. The conventional diode-rectifiers always produce large amount of harmonic current. One simple solution is to add a bulk inductor in front of the dc bus bulk capacitor as a passive filter to improve the input power factor. However, the passive filter components are very bulky and not very effective under wide load variations. Another solution is the active approach. A high frequency switch mode power factor correction converter is used to replace the conventional diode rectifier as the PFC stage. It forces the input line current to trace the input line voltage to achieve good input power factor. So off-line power equipment usually have two stages, a PFC front-end stage and a load regulator output stage. However, the additional PFC stage will increase the cost and reduce the efficiency of the overall system. This kind of disadvantage is very undesirable for low-power supplies such as consumer electronic products. In order to reduce the component counts and also to improve the overall performance, a number of single-stage PFC (S^2-PFC) techniques have been introduced recently.

This thesis will focus on the study and improvement of the single-stage PFC techniques. In the next section, the current power factor correction techniques will be reviewed.

1.2 Review of active power factor correction techniques

1.2.1 Two-Stage PFC Approach

The active power factor correction converters for low power application usually 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. In this approach, an active power factor correction stage is adopted as the front-end to force the line current tracking the line voltage and therefore achieve the unit input power factor. The PFC front-end stage converts the AC input voltage into a DC voltage on a bulk bus capacitor. Then a conventional DC/DC converter is used as the second output stage to provide isolation and regulated output voltage.

Figure 1.1 shows the general structure of the two-stage PFC converter. There are two independent power stages. The first PFC stage is normally a boost, buck/boost or flyback converter, which has a high frequency input PFC inductor in series with the input line. Also, a PFC switch and PFC diode is necessary. There is an independent PFC controller, which senses the input voltage and current, then controls the PFC switch to achieve good input current waveform. The controller is often achieved by current mode PFC control chip such as the UC3854. The PFC front-end stage also provides a roughly regulated high DC bus voltage V_B with small second order harmonic ripples on the bulk bus capacitor C_B. V_B is normally regulated around 380-400 Vdc while the line input voltage can change from 90 Vac to 265 Vac for the universal-line applications. V_B can also be regarded as the input voltage of the second isolated DC/DC output converter. The output converter can be any DC/DC converter with a tightly regulated output voltage $V_{o.}$ Here, V_o is regulated by the high bandwidth DC/DC PWM controller.

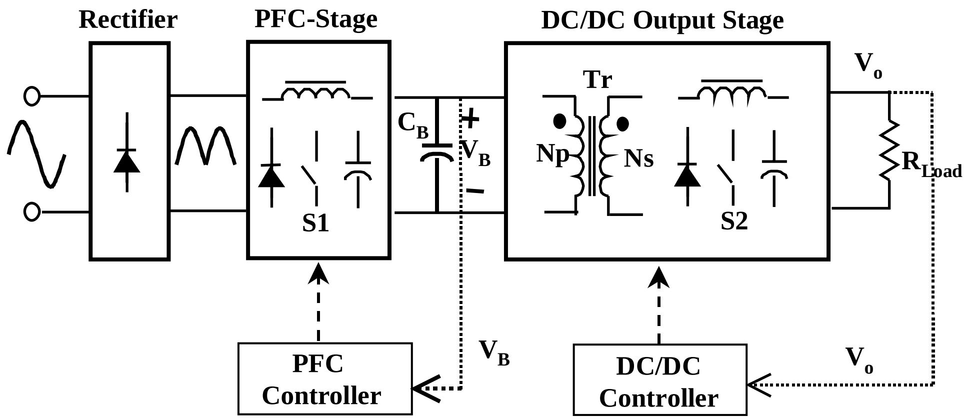

Figure 1.1. General structure of active two-stage PFC converter

Figure 1.2 shows an example of a two-stage PFC converter. It is a boost PFC converter followed by a forward DC/DC converter. The input inductor of the PFC converter works in both discontinuous and continuous current modes.

The active two-stage PFC converter has good input power factor and can be used with low and high power applications. This technique is quite mature and has good performance. However, it requires an additional PFC power stage and PFC controller, so the component count and total cost is increased. It is very undesirable for low power level supplies used in consumer electronic products such as a computer power supply. Besides, because an additional power converter is in series with the main power flow, the total efficiency is also decreased.

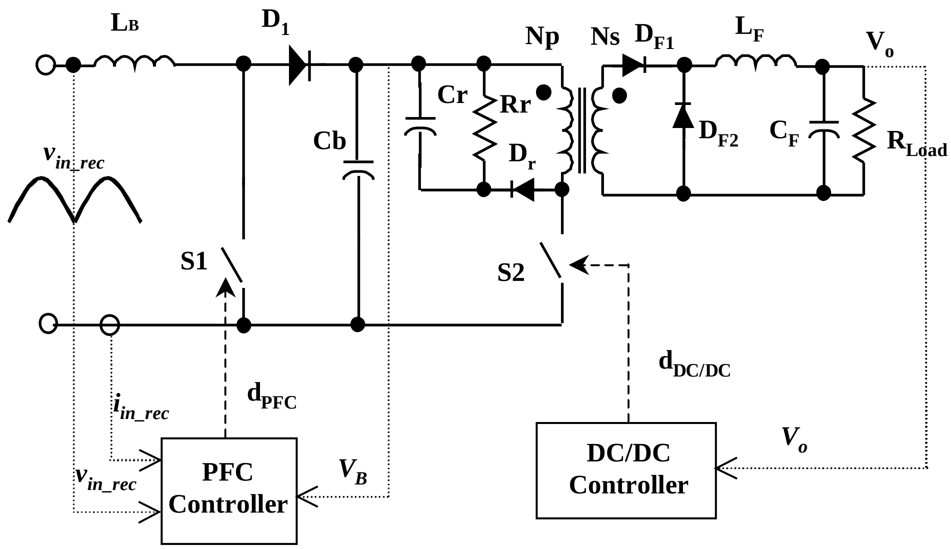

Figure 1.2. CCM Boost PFC Front-End and RCD Clamped Forward Output Stage

1.2.2 Single-stage PFC approach

In order to reduce the additional component count and cost introduced by the PFC stage in the two-stage PFC converter, a number of single-stage (S^2-PFC) techniques have been presented in recent years. [B1 – B19]. In the S^2-PFC converter, input current shaping, isolation and tightly regulated output are achieved in one step with only one switch through one power stage. Figure 1.3 shows the general structure of the S^2-PFC converter. A PFC inductor is still necessary but the PFC switch and PFC controller are saved. The only controller here is the high bandwidth DC/DC controller which focus on the tight regulation of the output voltage. The switch duty-cycle is almost constant during one line cycle on steady state. It means the input power factor correction function is automatically achieved based on the principle of circuit operation instead of the PFC control. Still, an internal bulk capacitor C_B is needed to handle the different power between the input pulsating power and constant output power, so that the output voltage can be tightly regulated. Normally, the input power factor is not unity but the input harmonic current is small enough to meet the IEC regulation.

Figure 1.4 shows the example circuit of S^2-PFC converter, which integrates the PFC stage with the DC/DC output stage by a single switch. The basic idea is that for a PWM DC/DC converter, the voltage controller provides constant switching duty-cycle during one line

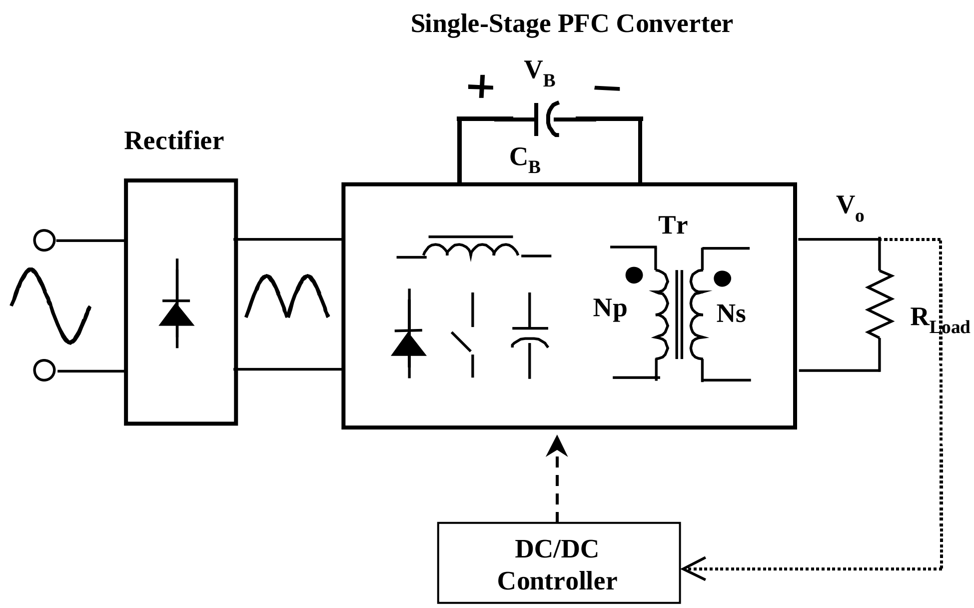

Figure 1.3. General Structure of Active Single-Stage PFC Converter

cycle. At the same time, for a discontinuous current mode (DCM) boost converter, the input current waveform is close to the sinusoidal waveform if the switching duty-cycle is also constant. It means the PFC function can be achieved without PFC controller. So, the DCM boost converter and PWM DC/DC converter can share one switch with the same constant duty-cycle to achieve two functions: input current shaping and output voltage regulation. The circuit in Fig. 1.4 is just an example of the integrated DCM S^2-PFC converters. It is necessary to point out that this circuit has a big disadvantage that it has very high bus capacitor voltage stress at high line, light load because of the unbalanced power between the input power and the output power [B3, B15]. A high voltage stress means high component rating, high cost and low efficiency.

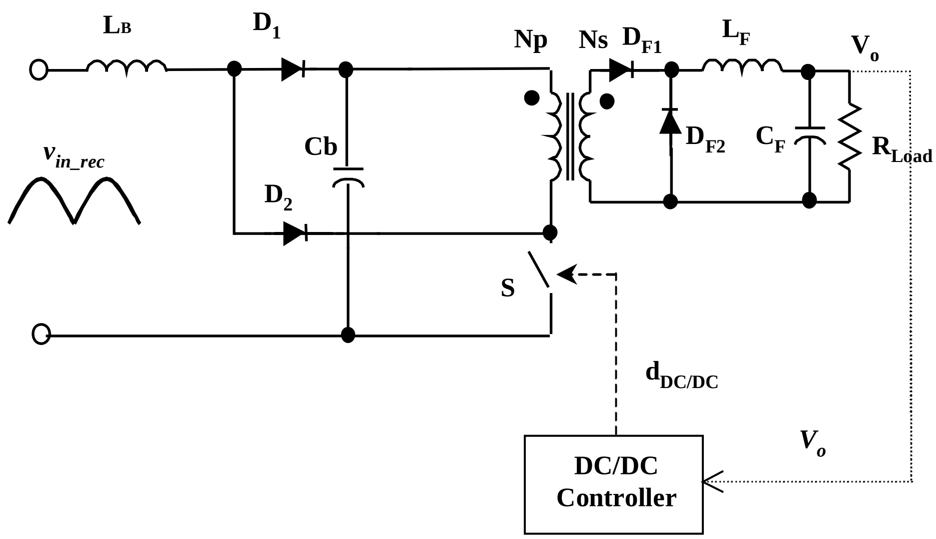

Figure 1.4. Integrated DCM Single-Stage PFC Converter with Forward Output Stage

To overcome this problem, several techniques have been proposed in recent years. One is the variable switching frequency scheme [B16]. It reduces the voltage stress but the efficiency is still lower than the two-stage approach. In addition, it is difficult to optimally design inductive components, such as inductors and transformers, for wide range switching frequency operation.

A better way to reduce the bulk capacitor voltage stress and improve the efficiency is the bus-voltage-feedback scheme [B10, B15]. Figure 1.5 shows the example circuit with this concept. The additional transformer winding N_1 can feedback the bus capacitor voltage V_B during the charging mode of the PFC inductor. Therefore, when the converter works in light load, the input power is automatically reduced and the input power and output power can be easily balanced. As a result, the bus capacitor voltage stress is limited close to 400 Vdc at high line light load with a careful design. Furthermore, the feedback winding can also provide a direct-energy-transfer path from the input to the dc output. So the overall component rating is reduced and efficiency is improved. This makes the single-stage PFC technique practical and attractive.

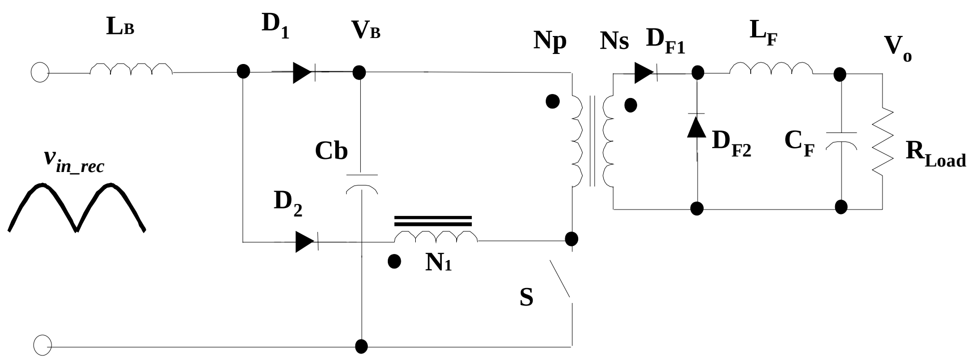

Figure 1.5. DCM Single-Stage PFC Converter with bus capacitor voltage V_B feedback

However, the efficiency of DCM S^2-PFC converter is still not high enough because of the DCM operation. The current stress on the switch is high so that the switching loss and conduction loss is also quite high. Besides, the DCM input current requires a large EMI filter to get rid of the high frequency switching noise generated by the converter. As a conclusion, the DCM S^2-PFC is only attractive for low power applications such as computer and networking power supplies.

Several continuous current mode (CCM) S^2-PFC converters have been presented recently to achieve better efficiency, smaller EMI filter and lower cost [B6, B7, B13]. Figure 1.6 shows two interesting circuits of CCM input current S^2-PFC converter. They still look like a boost converter combined with the PWM DC/DC converter with constant duty-cycle control. However, because the input inductor is in CCM mode, the PFC principle is not as straightforward as in the DCM S^2-PFC converters. The optimal design is more difficult to achieve than the DCM S^2-PFC circuit. Normally, the input current of CCM S^2-PFC has higher distortion than in the DCM converter. However, it is good enough to meet the IEC PFC regulation. Generally, the CCM S^2-PFC converters are more attractive than DCM S^2-PFC converters, especially in higher power level application such as computer power supplies.

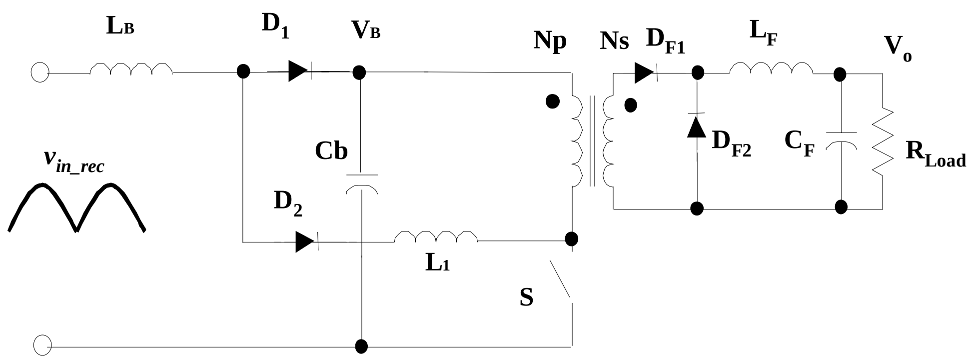

Figure 1.6. (a) CCM Single-Stage PFC Converter with additional inductor

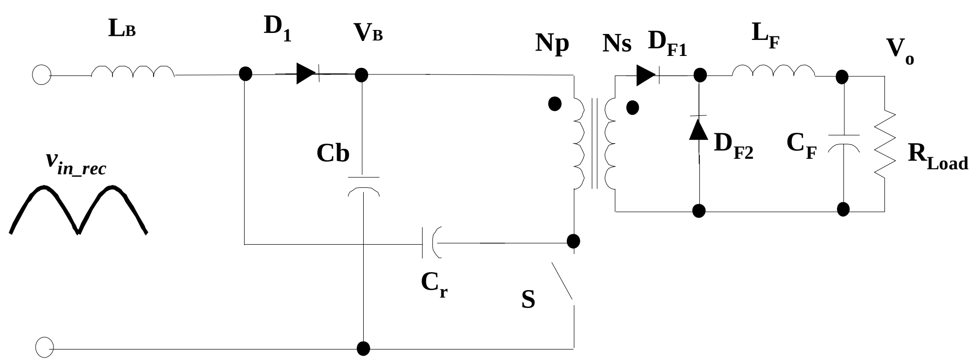

Figure 1.6. (b) CCM Single-Stage PFC Converter with high frequency capacitor

How to understand, analyze, optimize and improve these single-stage converters become a very interesting topic in recent power electronics research.

1.3 Motivation and Objectives

The preceding discussion of the current status of power factor conversion techniques demonstrates the need for the further research in this area. Specifically, three areas need to be addressed:

1. So far, there are several interesting integrated single-stage PFC techniques. It is very necessary to synthesize the generalized structure of the integrated single-stage PFC converters. After that, based on the generalized structure, it is important to derive the general power-factor-correction condition of the single-stage PFC converters. Also, the generalized structure will be helpful to derive several new topologies in the integrated single-stage PFC families. Therefore, the major objectives of this thesis research are to generalize and understand the present single-stage PFC techniques.

2. As an example of CCM S^2-PFC converter, the circuit in Fig. 1.6(a) has smaller EMI filter and higher efficiency than DCM S^2-PFC converters. It is necessary to further understand this circuit and find out the design consideration. Besides, this technique has its own problems and limitations. Further improvements need to be developed to make the CCM S^2-PFC technique more practical and attractive.

3. One major reason that the single-stage PFC techniques are interesting is because single-stage PFC converters save one PFC switch and controller. Generally speaking, for low power application, it has lower cost. However, this conclusion is not always true. For universal line applications, a detailed study is necessary to compare these two approaches to find the merits and limitations of different techniques.

1.3 Thesis Outline

Chapter 1 briefly reviews the present PFC techniques. Also, it lists the research objectives and provides the research outline.

Chapter 2 gives a general study of the integrated single-stage PFC technique. First, the generalized structures of integrated single-stage PFC converters are synthesized. Based on the generalized structures, the general necessary PFC condition of single-stage PFC converters are derived and verified. Also, several new integrated single-stage PFC topologies are derived.

Chapter 3 focuses on the study and improvement of the current-source CCM S^2-PFC converter. The operating mode is analyzed first. Then the circuit intuitions and design optimizations are presented. Also, focusing on the limitation of this converter, an improved CCM S^2-PFC converter with a low-frequency auxiliary switch is developed and experimental verified.

Chapter 4 compares a two-stage PFC to a single-stage PFC converter. It shows the single-stage PFC converter has its limitations for universal line applications with hold-up time requirement. It points out that the future research is necessary to overcome the disadvantage of the present universal-line S^2-PFC converters.

Conclusions are given in Chapter 5.