Average current mode control employs a control circuit that regulates the average current (input or output) based on a control signal $I_{cp}$. For a PFC controller, $I_{cp}$ is generated by the low frequency dc loop error amplifier (and it is simply the current equivalent of the signal $V_i$ as depicted in Figure 1-17. The current amplifier is both an integrator of the current signal and an error amplifier. It controls the wave shape regulation, while the $I_{cp}$ signal controls the dc output voltage. The current $I_{cp}$ develops a voltage across $R_{cp}$. For the current amplifier to remain in its linear state, its inputs must be equal. Therefore, the voltage dropped across $R_{shunt}$ must equal the voltage across $R_{cp}$, since there can be no dc current in the input resistor to the non-inverting input of the current amplifier. The output of the current amplifier is a “low frequency” error signal based on the average current in the shunt, and the $I_{cp}$ signal.

This signal is compared to a sawtooth waveform from an oscillator, as is the case with a voltage mode control circuit. The PWM comparator generates a duty cycle based on these two input signals.

**ON Semiconductor NCP1650 Family**

ON Semiconductor offers a line of highly integrated PFC controllers, with a novel control scheme [6]. This chip’s control circuit uses elements from the critical conduction mode units, as well as an averaging circuit not used before in a power factor correction chip. The basic regulator circuit includes a variable ac reference, low frequency voltage regulation error amplifier and current shaping network.

This chip incorporates solutions to several problems that are associated with PFC controllers, including transient response, and multiplier accuracy. It also includes other features that reduce total parts count for the power converter [7]. The simplified block diagram of this approach is shown in Figure 1–19. More details of this approach can be found in the references provided at the end of this chapter.
In addition to the NCP1650, which works in a traditional boost PFC topology, the NCP165x family also consists of NCP1651 and NCP1652. The NCP1651 and NCP1652 allow a single-stage, isolated step-down power conversion with PFC for many low-mid power applications where the output voltage is not very low and can handle some ripple. As shown in Figure 1–20, the NCP1651 based flyback converter provides a uniquely simple alternative to two-stage approaches commonly used. The NCP1651 includes all the relevant significant feature improvements of the NCP1650 and also includes a high-voltage start-up circuitry.
Predictive Control of CCM PFC

The preceding section outlined some of the inherent complexities of CCM PFC control and how NCP1650 helps overcome some of those complexities. In recent years, a newer control technique has been introduced which greatly simplifies the control algorithm of the CCM PFC controllers. As incorporated in the NCP1653 and NCP1654 from ON semiconductor, this technique is known as predictive control since it uses the sensed current to determine (predict) the required duty cycle instead of generating the reference signal based on input voltage sensing.

The average inductor current in a system with good PF must be proportional to the input voltage:

\[ I_{\text{coil}}(t) = I_{\text{in}}(t) \times \frac{V_{\text{in}}}{V_{\text{out}}} \]

for CCM operation, where \( d_{\text{off}} \) is the duty cycle of power switch off time.

Hence \( d_{\text{off}} \propto \frac{V_{\text{sum}}}{V_{\text{ref}}} \)

The way the predictive CCM PFC controller works is to control the power switch on time by summing a ramp signal with a signal proportional to the coil current. As a result, the higher the sensed coil current, lower the on time and higher the off time, satisfying the relationship above. Figure 1–21 shows the current shaping scheme. Some ramp is summed with a signal proportional to the coil current.

\[ V_{\text{sum}} = V_{\text{sense}} + \frac{I_{\text{ref}} \cdot \text{ton}}{C_{\text{ramp}}} \]

The power switch stops conducting when \( V_{\text{sum}} \) exceeds the current reference. Hence, one can deduct \( \text{ton} \) and consequently \( d_{\text{off}} \).

\[ d_{\text{off}} = 1 - \frac{\text{ton}}{T_{\text{SW}}} \]

\[ d_{\text{off}} = 1 - \left( \frac{I_{\text{ref}} \cdot T_{\text{SW}}}{L_{\text{ref}} \cdot T_{\text{SW}}} - \left( C_{\text{ramp}} \cdot V_{\text{ref}} \right) + \frac{C_{\text{ramp}} \cdot V_{\text{sense}}}{I_{\text{ref}} \cdot T_{\text{SW}}} \right) \]

If \( I_{\text{ref}} \cdot T_{\text{SW}} = C_{\text{ramp}} \cdot V_{\text{ref}}, \) i.e. \( I_{\text{ref}}, C_{\text{ramp}}, \) and \( V_{\text{ref}} \) also act as the oscillator to control the operating frequency, one can obtain

\[ d_{\text{off}} = \frac{V_{\text{sense}}}{V_{\text{ref}}} = k \cdot I_{\text{coil}}(t) \]

which leads to near-unity power factor. More details on this approach are provided in a later chapter.

Advanced Approaches for PFC

The major control algorithms (CrM, CCM and DCM) and their combinations allow many options for the designers. In addition to these, the search for higher efficiency and modularity has lead to advanced architectures being utilized for the leading edge applications. These approaches are getting into the mainstream applications only now. However, given their
highly advanced nature, the designer has to be careful about staying clear of any intellectual property (IP) implications when considering these approaches. In this handbook, two such advanced approaches are presented in later chapters.

The bridgeless PFC solutions arose from the recognition that the diode bridge at the front-end of any PFC typically contributes 2% power losses at full load. If the bridge can either be eliminated or combined with other functions, these losses can be averted. With this in mind, many topologies have been presented in the industry publications and also have been used in some of the higher end applications (UPS being one of them) in the past few years. The bridgeless solutions involve distinctly more complex control and also require acute awareness of the grounding loops when implementing them. Most known implementations involve moving the boost inductor to the ac side of the bridge and replacing the lower diodes of the rectifier bridge with switches in order to replicate boost converters for each leg.

Another recent trend is to apply the interleaving concept to the PFC circuits. In interleaving operation, a single converter is replaced by 2 or more paralleled converters each operating out of phase so that the ripple current when summed at the output or input has a cancelling effect and results in lower filtering requirements. Other benefits of interleaving are modularization, heat dispersion and ability to optimize cost/performance of a smaller module which is much easier due to component availability. Against this, there are potential negatives such as higher component count and a more complex control function.

**Component Selection for PFC Circuits**

The basic PFC boost converter is one of the simplest converter types (along with buck and buck-boost converters) around. Consequently, the number of components required for power stage is minimal – one inductor, one power switch, one diode and one output capacitor. So, when adding an active PFC circuit to an existing power converter, the component requirements are not very complex. Additional components such as the input bridge and EMI filter are already existent in all ac connected power converters.

While the power stage is simple, the component selection is by no means trivial and there are many critical choices to be made while optimizing the design for required performance. Given the recent trend for higher efficiency, the component selection plays an even more significant role and it has been shown that a proper component selection alone can boost the PFC efficiency by 2-3% for a given topology.

**PFC Inductor**

The PFC inductor (also referred to as boost inductor or coil or PFC choke), is very important to the operation of the PFC circuit. It must be designed to prevent saturation and consistently provide good power factor. The value of inductance is selected based on commonly available equations. For CCM, the value of inductor tends to be higher than the value for the DCM or CrM operation. However, that does not mean that the size of the inductor is always higher for the CCM operation. The size depends on the inductance value and the rms current through the inductor. The key consideration is in selecting the right core material and winding size for a given inductor. The higher peak-peak current ripple means that the core losses are higher for the CrM operation. It is often more difficult to use a cheap powder iron core for the CrM operation and achieve the required efficiency. The other key consideration is the type of core. Toroids are the most popular because they offer low cost, but if the number of winding turns is high, a bobbin based winding may facilitate easier winding. Some advanced designs use this approach with Ferrite cores to get better flux control.

**PFC Diode**

The choice of PFC diode plays a crucial role in the efficiency and EMI performance of a CCM boost converter. At the instance of the boost switch turn-on, the diode is carrying significant current in the CCM operation. Since this diode is a high voltage diode, it typically suffers from reverse recovery phenomenon (forced by slower recombination of minority carriers) which adds to the losses and ringing. It is important to use ultrafast diodes (preferably with soft recovery characteristics) to mitigate this problem. In recent years, alternative rectifier solutions based on more advanced materials have been proposed, but cost constraints limit their applicability in mainstream applications. For the CrM or FCCrM operations, the requirement is different since the diode always turns off at zero current and hence there are no reverse recovery issues to be faced. In these applications, the important criterion is to optimize the forward drop of the diode to improve efficiency. ON Semiconductor has recently introduced PFC diodes (MUR550 series) for these applications.

**PFC Switch**

The choice of PFC switch is based on the cost vs. performance trade-off. The recent advances in MOSFET technology has helped in moving this trade-off more quickly in the direction of higher performance. With a 500 V or 600 V FET, the important issue is to select the FET with right level of $R_{ds(on)}$ to get low conduction losses without increasing switching losses.
significantly. Blindly selecting the lowest available \( R_{\text{ds(on)}} \) FET will not yield the highest efficiency and will actually increase the cost of implementation. Of equal importance is effective MOSFET drain capacitance. This capacitance must be charged and discharged every switching cycle. Choosing a MOSFET with low capacitance will reduce switching losses and increase efficiency.

**Current Sense Resistor**

The current sense resistor is another important contributor to conduction losses and it is important to minimize the voltage drop across it at full load. In higher end designs, this is achieved by employing current sense transformers. However, in more typical designs, the choice of current sense resistor is dictated by the requirements of the PFC controllers. Many controllers require a fixed 1 V signal and that leads to contribution of about 1% losses. In many of ON Semiconductor’s PFC controllers, through negative sensing scheme, the current sense signal is user programmable and hence can be optimized further.

**Conclusion**

The number of choices available to the PFC designer has grown significantly over the past few years. This is due to the increased interest in complying with IEC61000-3-2 and its derivatives, coupled with an enthusiastic spirit of competition among the semiconductor suppliers. The end users reap increasing benefits as PFC becomes better and more cost effective. Power Supply designers benefit from the increasing capability of these IC controllers, with more options available to execute the designs.

On the other hand, the designer’s job has become more complicated as a result of the plethora of design approaches at his fingertips. Just surveying them is difficult enough, but understanding each of them well enough to make an informed, cost-effective choice is a big challenge. It has been an objective of this chapter to increase the designer’s awareness of this trend and to provide some insight into the details. In the remaining chapters of this handbook, we expand on the individual approaches and attempt to provide benchmarking that will make this selection easier.
References

The following references were chosen for their relevance to the material in this paper, and are but a small sample of the vast library available to the interested reader.