**New methods for digitally controlled bridgeless PFC converters**

Highly efficient power supply units for consumer electronics

In order to attain sustainable energy economics, topics like energy generation and transmission should be discussed in connection with the influences of energy consumption. With regard to the future energy system the topic ‘renewable and novel energy generation’ is only one part which should be focused. Furthermore, novel technologies for power consumption also play a major role. Especially the efficiency of consumer electronic devices, with focus on their power supply units, provides a high potential for energy saving, because of the high amount of used units. This article outlines novel control methods to realize modern and highly efficient power supplies. The primary goal is to achieve an operation efficiency better than 96% specifically for bridgeless boost power factor correction (PFC) converters. This will be possible due to new digital control methods combined with the suitable circuit topology. As this report explains, a basic bridgeless boost PFC stage could operate with a digital control at which the feedback values are only based on a voltage measurement across the PFC choke and a DC-link voltage measurement. Thereby higher cost efficiency, higher power density and higher operation efficiency can be reached in comparison to conventional solutions.

**Technical background**

For power supply units with an input current less than 16 A per phase, the standard IEC 61000-3-2 defines guidelines and limits for harmonic current emissions and the EMC behavior, by which the power factor is affected. To implement that benchmark a multiplicity of technical options are thinkable. Figure 1 shows a conventional solution which is still often used today. This conventional boost PFC rectifier consists of a standard full bridge rectifier with a downstream DC/DC-boost converter. This topology is used for simple converters without limits for the construction size. The further descriptions in this article are based on the basic bridgeless boost PFC topology which is represented in Figure 2. This topology is applicable for the continuous conduction mode (CCM), as well as the discontinuous conduction mode (DCM). Furthermore, both transistors can be driven by the same PWM signal whereby the drive circuit can be implemented in a simple way. The EMC behavior of that bridgeless power stage requires an additional input filter. Solutions for this are given by complex but known EMC filter systems.
Novel digital control strategies

Control basis

The basis for the novel digital control methods for the bridgeless boost PFC rectifier (Figure 2) is given by the known simple control loop in Figure 3 which is also used for the conventional boost PFC rectifiers. The reference for the voltage control loop is given by $V_{ref}$. The parameters $k_i$ and $k_v$ are conversion factors. The mathematical basis for the digital control is defined by the standard boost-converter behavior. The result of the combination of those basic equations shows the Duty Cycle $D_{on}$ which represents the ON time of the transistors (Equation (1)).

$$D_{on}(t) = \left(1 - \frac{i_L(t)}{v_{out}(t)R_{in}}\right)$$  \hspace{1cm} (1)

Fig. 3. Control loop for standard PFC rectifiers.

Thereby the circuit should represent an ohmic input resistance ($R_{in}$) behavior. The inductor current ($i_L(t)$) and the output voltage ($v_{out}(t)$) are measured feedback values of the control loop. To realize this digitally, a micro-processor is necessary. Properties like the analog to digital conversion, sample rate, internal clock rate or the PWM resolution have to be observed.

Solution #1: ‘current-mode control method’

For that control method a measurement of the input current is necessary. The current measurement can be implemented in different ways, for example with commercial current transformers, LEM-transducers or with a sense resistance circuit. The simplest solution is given by the sense resistor in combination with a differential amplifier circuit. The control basis, which is described in Equation (1), represents the framework for that method. The challenge hereby is the precision of the current measurement. The current through the inductor ($i_L$) typically shows a triangular ripple for CCM mode which is represented in Figure 4. Based on this the assumed ideal current through the sense resistor ($i_{sense}$) manifests the specific behavior. Referring to this, it is essential to set the sample points ($t_{sample}$) for the current measurement exactly to half of the current fall time to get the correct average value ($i_{sense,avg}$) with regard to the switching period. Another drawback of the current measurement is given by the conduction losses, especially in this case for the sense resistor. Based on the circuit specification and the sense resistor value ($R_{sense}$) of 100 mOhm, only the conduction losses of the sense resistor reaches a theoretical maximum of approximately 200 mW.

Fig. 4. Current forms for CCM mode operation.

Solution #2: ‘voltage-mode control method’

To realize higher operation efficiency it is essential to eliminate the losses of the current sense resistance measurement. This can be achieved by obtaining feedback values via simple voltage measurements. The information about the inductor current could be reconstructed via the voltage drop ($v_L(t)$) across the PFC-choke as shown in Equation (2) and (3). In correlation to that, the standard behavior of that PFC inductor on CCM mode is pictured in Figure 5 for one switching period ($T_{sw}$). Thereby the current value of $\Delta i_{L,n}$ is equal to the changing of the inductor current for one switching period, at which the index $n$ of $\Delta i_{L,n}$ is used as a counter. The addition of each current changings represents the actual inductor current value $i_{L,n}$ including the DC offset (Equation (4)). For the technical implemen-
ntation of this control method two different possibilities are described in the following sections 3.3.1 and 3.3.2.

\[
\delta i_{L,n} = \Delta i_{L,\text{on}} + \Delta i_{L,\text{off}}
\]

\[
\delta i_{L,n} = \frac{1}{i_{\text{PPC}}} \cdot \left[ \int_{0}^{T_{\text{on}}} v_{L}(t) \cdot dt + \int_{0}^{T_{\text{off}}} v_{L}(t) \cdot dt \right]
\]

\[
i_{L,n} = \sum_{n=0}^{x} \delta i_{L,n}
\]

**Op-amp integrating amplifier**

Another method to capture the PFC-choke voltage \(v_{L}(t)\) uses a conventional integrating amplifier circuit. Thereby the mathematical background from the Equations (2), (3) and (4) are not implemented into the digital source code of the micro-processor. Hence, this solution results correct measurements also for the DCM mode. The real hardware setup of the integrating op-amp typically produces a drift of the output signal. But therefore several solutions are known. In comparison to the ‘current-mode control’ this solution brings lower conduction losses and an additional reduction of fitted components like op-amps, resistors and capacitors. The output signal of the integrating amplifier is stressed by a ripple, whereby the output voltage is sampled exactly from half of the ON or OFF time to get the correct average value of \(i_{L,n}\) regarding the active time slot. Generally this method needs a lower performance for the micro-processor as the ‘voltage-mode control method’ with its two sample points on each switching period.

**Conclusion**

Both presented control solutions were analyzed by means of several simulations models. Based on that, both are theoretically applicable and results in an acceptable input behavior. For the basic bridgeless boost PFC converter in combination with a ‘current-mode control method’ an acceptable input behavior could be achieved in comparison to conventional PFC circuits. Regarding the internal circuit losses the ‘voltage-control method’ brings best operation efficiency in a simple way. The digital control is not simple but a commercial midrange micro-processor can be used for it. The analysis of the hardware implementation has to be finished before a detailed statement referring to the practicable application of both solutions can be made. With these novel control methods the construction costs are reducible. Furthermore an increasing operation efficiency and power density of the power stage could be achieved.