UNITY POWER FACTOR CORRECTION FOR ELECTROMAGNETIC VIBRATION HARVESTERS

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Abstract: In this paper the performance of vibration energy harvesters coupled to unity power factor power conditioning circuits is considered. The potential benefits of the more advanced unity power factor converter topologies over standard diode rectifiers, especially where voltage conversion and/or regulation is required, are described. Issues of stability and maximum power operation are considered for switching converters. Two particular PFC (power factor correction) topologies are discussed along with their application to electromagnetic vibration energy harvesters. Practical low power unity power factor converter circuits, built from discrete devices, are presented along with experimental and simulation results. Finally the practical issues of digital implementation of ultra low-power unity power factor converters are discussed along with potential to exploit the advanced power conditioning topologies for frequency tuning.

Keywords: Power harvesting, power factor correction, electromagnetic vibration harvesters

INTRODUCTION

Vibration energy harvesting devices produce an AC output which is not useful for most electrical systems and thus power conditioning to produce regulated DC must be considered an essential element of any harvesting system. To provide a smoothed DC output from an electromagnetic generator a rectification stage is required between the source and the load. The simplest solution is to use a peak rectifier, containing a full-bridge rectifier and smoothing capacitor. Where regulation is required either a series-pass or shunt regulator is added on the DC side. Though often the simplest solution, the most basic of these schemes are inefficient over variable operating conditions (e.g. input vibration amplitude or load power), and can incur significant losses. The load impedance presented to the harvester by the peak rectifier appears real (i.e. dissipative) at the fundamental frequency only, but the current drawn from the harvester contains harmonics which contribute to losses. Where the regulator is linear, maximum power can only occur at one particular operating condition and with characteristic reduced efficiency. Where switch mode regulators are employed, stability issues can prevent peak power operation [1]. The adoption of a unity power factor architecture, where the load presented to the harvester by the power conditioning circuit appears resistive, not only reduces harmonics drawn by the harvester but may also reduce the complexity: A large smoothing capacitor is not required on the input of the converter and the unity power factor converter can also be configured to provide both level shifting, regulation and/or control the operating point of the harvester.

PFC TOPOLOGIES

Unity power factor converters or power factor correction converters synthesise a real input impedance hence power is drawn from the source with unity power factor. A unity power factor converter can be made using any of the common switching topologies, but due to their simplicity the three basic arrangements: buck, boost and fly-back are more commonly used. However, when low input current distortions are required more complex topologies, such as SEPIC and Ćuk are used [2].

Operating a switching converter in discontinuous current mode (DCM) causes the average input current to inherently follow the line voltage, thus appearing resistive to the harvester. It can be shown that with fixed frequency operation the input resistance is dependent on duty cycle, D, by:

$$R_{in} = 2Lf/D^2 \qquad (1)$$

Where L is the value of the inductor, f is the switching frequency.

Switching converters operating in continuous current mode (CCM) use instead a negative feedback control techniques to force the input current to follow the line voltage in order to present a resistive load to the harvester.

STABILITY

Once unity power factor correction has been achieved with either of the schemes mentioned above, it is natural design step to apply output voltage regulation with an outer voltage loop. However as shown in [1] if the harvester's source impedance is greater than a ¼ of the load impedance the Middlebrook's stability criterion is violated. The constant input power nature of a voltage regulated switching converter makes operation near the peak power point unstable. Under closed-loop voltage control the generator can suffer from an inability to start-up, unless soft-started, as well as stalling under power demands at or above the peak power point of the generator. Both these conditions are unrecoverable unless the excitation level is increased, or if the converter is restarted under lower power demands.

The solution to the unstable behaviour caused by the switching converter proposed by [1] is to remove the voltage loop and replace it by a shunt regulator. With this strategy when the demanded power increases above the peak power point, voltage regulation is simply lost instead if stalling the harvester. This strategy also solves start-up issues along with other key advantages. Power consumption of the control circuits is reduced and by removing the analogue multiplier, an element of the voltage loop that is not normally micro-power is eliminated.

UNITY PFC

In this section two unity power factor converters designed for electromagnetic transduction energy harvesters with power outputs between 3-100mW are presented. If the power overhead of any power conditioning system applied to an energy harvester must be at no more than 10% of the maximum output power of the harvester, in this case it should be no more than 300µW or 10mW.

Discontinuous current mode

A unity power factor corrector based upon the discontinuous mode flyback converter for a vibration based electromagnetic energy harvester is shown in (Fig. 1) The simple topology lends itself well to low power applications through its inherently resistive input characteristic at fixed duty cycle operation and simple power conditioning drive electronics. Further the DC link voltage of the fly-back topology can be greater than or less than the input voltage whilst still maintaining regulation and advantage over boost converter topologies.

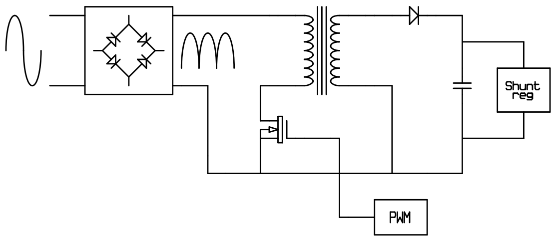

Fig 1: Open loop DCM flyback converter.

The control electronics has been built using micro-power off-the-shelf discrete components, and consumes only 180µW of quiescent power. Input current and voltage waveforms for the connection between an energy harvester and the open loop DCM fly-back PFC are shown in (Fig. 2). Peak amplitudes of voltage and current are approximately 3.5V and 10mA respectively, giving a power of 17.5mW. It is seen that the shape of the current waveform conforms to that of the voltage waveform, indicating that the input resistance is linear with applied voltage.

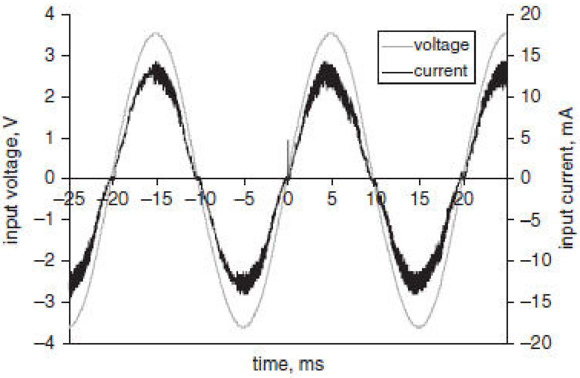

Fig 2: Input waveforms from open loop DCM fly-back converter showing unity power factor [1].

Continuous current mode

Amongst the large number of current control techniques average current mode control proves to be the most popular due to its low distortion input current waveforms and noise immunity over peak current control for example [3]. For this reason a unity power factor corrector based upon a boost converter operating in CCM shown in (Fig. 3) was built. Another advantage of the boost converter in CCM is that since the inductor conducts for entire switching period the input current waveforms are improved further.

Since average current mode control requires an extra compensated current sense error amplifier a higher quiescent power consumption of 200µW is incurred, this is only slightly higher than for the DCM converter.

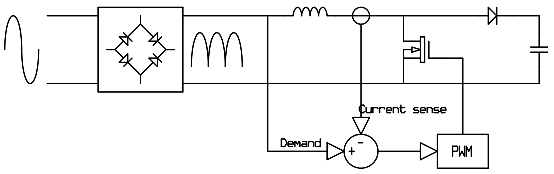

Fig 3: Closed loop CCM boost converter.

Simulations of input current and voltage waveforms of the close loop CCM boost PFC are shown in (Fig. 4). It is seen that the shape of the current waveform conforms to that of the voltage waveform, indicating that the input resistance is linear with applied voltage.

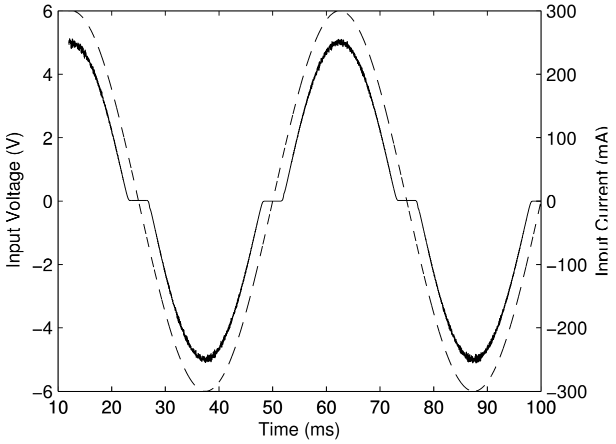

Fig 4: Input waveforms from closed loop CCM boost converter showing unity power factor. Current (-), Voltage (--).

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DIGITAL IMPLEMENTATION

The operating point for peak power for a linear harvester is largely static and independent of the input level of vibration. However for a non-linear harvester this is not true. Since Newton-Raphson and gradient decent type algorithms are easy to implement digitally, a digital implementation of a PFC could provide maximum power point tacking capability for a non-linear harvester.

Commercial digital controller IC's such as UCD3020 feature configurable topologies, DPWM (Digital Pulse Width Modulation) generation, loop compensation, A/D converters for current sensing as well as many other advance features for implementing PFC. However with power consumption in excess of 165mW, they are intended for high power applications. Reported research efforts on complete microcontroller solutions for digital PFC aim at reducing costs over their analogue counterparts [4],[5] or improving the voltage response and line current distortion [6]. However, little attention has been given to a digital PFC for energy harvesting generators, possibly due to the power constraints of such a system.

A key component of a fixed frequency switching converter is the pulse width modulator. Microcontrollers are easily able to generate high resolution PWM with counter-based techniques. However, as shown in (Fig. 5), even with an ultra low power MSP430 microcontroller, power consumption for modest switching frequencies can exceed 1mW. The high power consumption is due to the fact that the required counter clock frequency is 2^N times the switching frequency. For example an 8-bit PWM with a switching frequency of 40kHz requires a clock frequency of over 10MHz. Therefore the digital solutions by [4],[5] and [6] are not suitable for the power levels reported here.

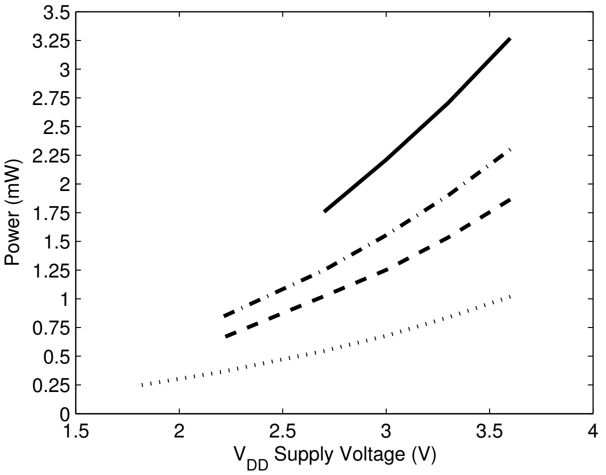

Fig 5: Power consumption MSP430f2013 generating 8-bit PWM at 75% duty cycle in low power mode 0 (CPU off) PWM frequency 55kHz (-), 39kHz(--), 31kHz(...), 16kHz(-.-).

Power consumption of the microcontroller can be reduced by removing PWM synthesis overheads away from the microcontroller. Since analogue techniques such as those reported in [1] provide PWM at micro-power levels a hybrid analogue-digital approach to DPWM was investigated. The basic structure of the hybrid DPWM (Fig. 6) consists of a micro-power comparator where the inverting input is connected to an analogue sawtooth oscillator and the non-inverting input to an N bit digital to analogue converter, DAC.

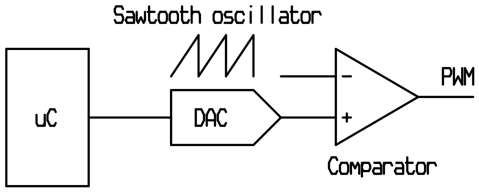

Fig 6: Hybrid analogue/digital DPWM

Microcontrollers with on board DACs such as the MSP430f2616 can actively consume around 150µW [7]. Despite low power external devices rated with quiescent current in the tens of micro-amps peak currents reach many magnitudes above this. A simple 8-bit R-2R scheme was built using 0.1% precision 375kΩ resistors. Power consumption was computed from equations presented in [8] and is dependent on the digital value of DAC as shown in (Fig. 7). The average power consumption was found to be as low as 18µW.

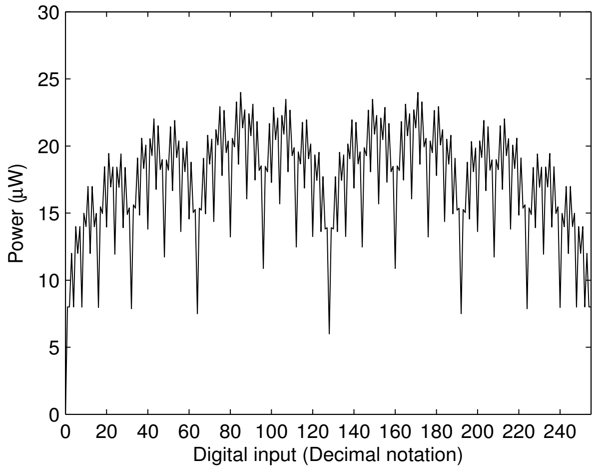

Fig 7: Power consumption of an 8-bit R-2R DAC with R=375k Vref=3V.

An 8-bit hybrid analogue-digital DPWM controller based on the R-2R DAC and an MSP430 microcontroller was built. Quiescent power consumption was measured at 60µW, when operating at 32kHz.

Future Applications

With a digital PFC peak power point tracking algorithms can be developed for non-linear harvesters provided the control electronics can be implemented at microwatt level. It has also been demonstrated by [9] that the reactive component of an electric load presented to an energy harvester can be used to tune the harvester system to significantly increase the output power away from the resonant peak of the device. Further if a variable power factor achieved through a digital implementation of a PFC coupled with a bidirectional switching converter, opens the possibly for electrical tuning of the generator allowing it to match the input frequency of vibrations.

CONCLUSION

Two micro-power unity power factor topologies with application to electromagnetic energy harvesters have been presented. The discontinuous mode fly-back converter provides the simplest low power solution since operating in DCM intrinsically causes it to appear as a unity power factor load. Slightly higher power consumption of the control electronics required for average current mode control of the CCM boost converter was incurred; however, micro-power consumption was still achieved.

The peak power tracking advantages of digital PFC have been highlighted as well as discussion on the difficulties associated with implementing digital control for unity power factor correction, however low power solutions to DPWM have been found.

Finally the boost converter PFC topology may have some limited use with electromagnetic harvesters since to maintain regulation the output voltage must be higher that the peak input voltage, though average current mode control has been achieved at micro-power levels, which must be accomplished in order to provide variable power factor for advanced power conditioning topologies for frequency tuning.

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