MICROWATT MAXIMUM POWER TRANSFER TRACKING DIGITAL CONTROL CIRCUIT FOR A FULL-WAVE BOOST RECTIFIER FOR EFFICIENT POWER EXTRACTION

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Abstract: A complete power conditioning system, based on a non-synchronous boost rectifier topology, is presented in this work. The low-power, self-starting system rectifies and boosts the energy harvester's output voltage, whilst actively maximising the power transferred to the energy storage element. The low quiescent power overhead of 44 µW, and an effective maximum power transfer tracking control makes up to 69% of the maximum extractable power available for the load electronics.

Keywords: energy harvesting, maximum power transfer, rectifiers, low-power electronics

INTRODUCTION

Rectification and voltage boosting are essential in electromagnetic energy harvesting systems. In addition to these, maximising the power available to the load is of increasing importance with the trend of miniaturisation of the mechanical structure.

Maximum power transfer tracking (MPTT), unlike maximum power point control [1][2], considers not only the current operating point of the energy harvesters, but also the losses incurred during the power conversion, and the quiescent power overheads. Current research trends aim to improve overall system effectiveness by designing control strategies with low power overhead penalties [3] [4].

In this work, a complete, fully-autonomous power conditioning system with MPTT control is implemented for a low-power electromagnetic energy harvester. Efficient power extraction is demonstrated under dynamic output conditions at sub-milliwatt power levels.

POWER CONDITIONING SYSTEM

Overview

The power conditioning system, shown in Fig. 1, is adapted from the low-power system presented in [5] by the addition of the measurement and control circuitry.

In resonance, the electromagnetic energy harvester generates up to 870 µW, 0.7 V_{rms} output, at 43.6 Hz, 4 $m{\cdot}s^{-2}$ excitation, at its peak power point. Passive voltage quadrupler circuit based start-up circuitry, disabled during normal converter operation, ensures self-start capabilities under zero stored energy conditions. The ancillary circuits, that provide polarity detection and high-frequency, variable duty ratio gate drive signals, draw a total quiescent current of 19 µA at 2 V_{DC} output including gate charge losses. Voltage regulation is achieved using low-power linear regulators with fixed 1.5V and 1.8V outputs. Finally, a 68 mF supercapacitor acts as the main energy storage element.

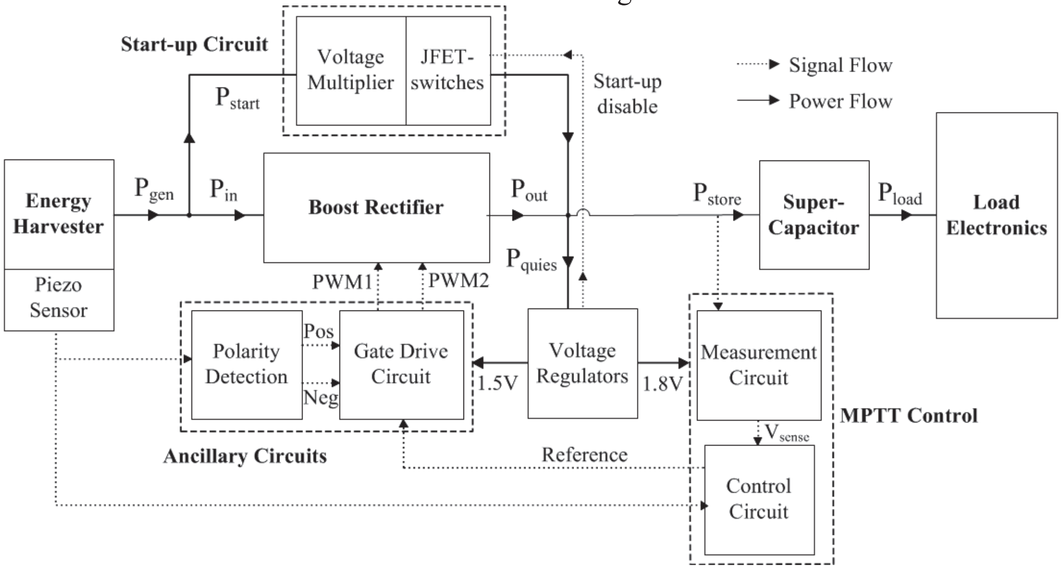

Fig. 1: System diagram of the power conditioning system.

Power Converter

The full-wave, non-synchronous rectifier, Fig. 2, comprises of two n-type MOSFETs (PMF-280UN), and two Schottky diodes (1PS79SB30). The harvester coil inductance is used as the boost inductor of the step-up topology. The output capacitance *C1* of the converter is a 30 µF ceramic capacitor that provides a low impedance path for the switching-frequency current.

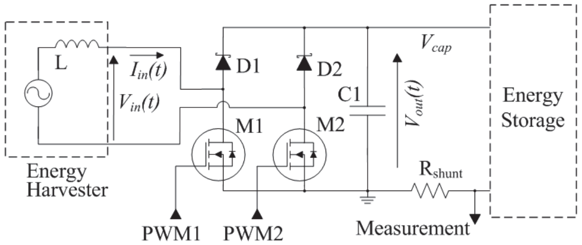

Fig. 2: Non-synchronous boost rectifier circuit.

The converter is operated analogously to a typical switched-inductor boost converter with M1 – D1, and M2 – D2 active during the positive, and the negative generated voltage half-cycles, respectively. The primary switching transistor is commutated at a fixed switching frequency of 32.768 kHz with variable duty ratio, whilst the secondary transistor is kept on for the half-cycle period. Conversion efficiency in excess of 80%, including quiescent losses, is demonstrated at sub-milliwatt power levels with this topology in [5].

MPTT Control Circuit

The combination of low output power, and large capacity energy storage results in relatively slow charge-up times. Consequently, the output voltage of the power converter can be assumed near constant during the period whilst the control algorithm converges to a solution. This enables monitoring of the transferred power based on the short-term average output current, measured using a 150 Ω precision shunt resistor in the return path as shown in Fig. 2.

The microcontroller based circuit implementation is shown in Fig. 3. A low-power current amplifier (MCP-6031), based on an active low-pass filter Sallen-Key architecture [6], conditions the current measurement, with a gain of 30 V/V. The active low-pass filter is designed to implement a 2nd order Butterworth filter with a cut-off frequency of 21.5 Hz, in order to provide a slow-varying average output current measurement. The output of the current-sense amplifier V_{sense} is sampled by the microcontroller's on-board ADC at a 10-bit resolution, that translates to approximately 400 nA / LSB.

A non-maskable interrupt is generated by the threshold-crossing detector circuit (MAX-9119) that monitors the output signal of the thin-film piezo sensor bonded to the electromagnetic energy harvester's cantilever. This circuit is similar to the polarity detection circuitry used in [5].

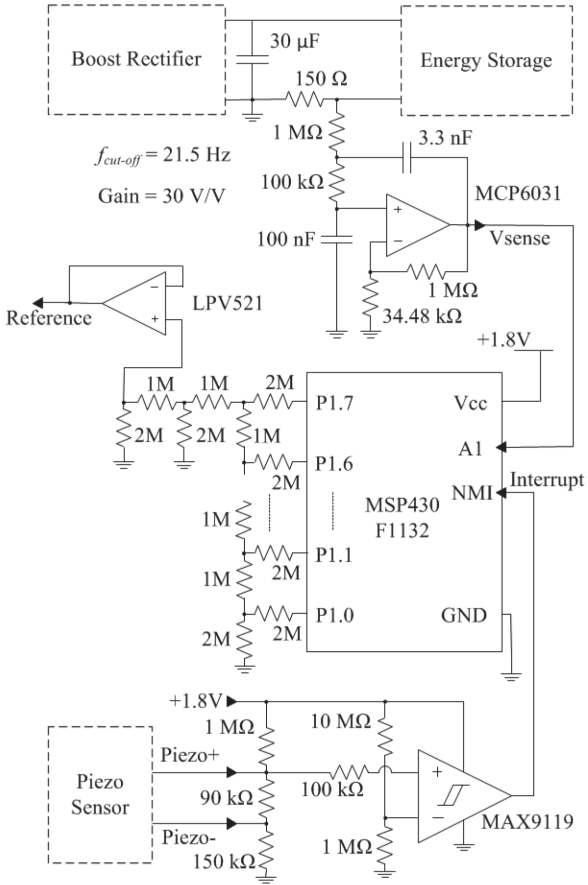

Fig. 3: MPTT control circuit implementation.

An 8-bit R-2R ladder architecture, connected to a full output port of the microcontroller provides the reference voltage of the gate drive circuit, and consequently controls the duty ratio of the boost rectifier. The buffered output stage of the low-power digital-to-analogue converter has an output range of 0 – 450 mV with a resolution of 1.75 mV/LSB, which corresponds to 0.6% step in the duty ratio δ.

MPTT Control Algorithm

A perturb-and-observe algorithm is implemented; the microcontroller adjusts the power converter's duty ratio in discrete steps, and monitors the resulting change in the average output power via the current measurement circuit. If the output current decreases, the direction of the perturbation is reversed for the next adjustment, otherwise, the direction remains the same.

The step changes occur every 15 displacement cycles (around 350 ms), synchronised by the interrupt generator to the zero-crossing point of the generated voltage. The execution of the sampling, determining the next duty ratio, and the updating of the reference voltage output, takes 58.7 µs, 25 µs of which is the ADC conversion time at 5 MHz clock frequency. The microcontroller is in power-down mode for over 99.9% of the perturbation period, reducing the average power consumption to 750 nW. The total current drawn by the MPTT circuitry is 3 µA at 2V, resulting in a total quiescent power overhead of the power conditioning system of 44 µW at 2V output.

EXPERIMENTAL RESULTS

Transient start up

Zero stored energy start up is demonstrated in Fig. 4 under a constant excitation of 4 m·s^{-2} at 43.6 Hz. The passive full-wave quadrupler circuit [5] charges the supercapacitor to 1.8 V in approximately 215 s. At this point, the outputs of the linear regulators are enabled, initiating the turn-on of the ancillary and control circuits. The MPTT control quickly brings the duty ratio from the initial 80% down to below 70% at 1.8V output, and continuously adjusts it as the output voltage carries on rising. The output voltage reaches 3.2 V 500 seconds after the start.

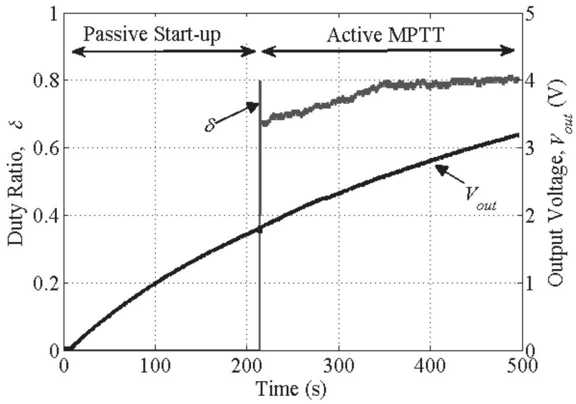

Fig. 4: Zero energy start-up: voltage across the 68 mF supercapacitor, and the variation in the duty ratio.

Steady-state results

The optimum duty ratio, corresponding to the maximum transfer power P_{store}, is a function of the output voltage in boost rectifier based power conditioning systems, as shown in Fig. 5. In order to evaluate the tracking effectiveness of the MPTT control, the duty ratio perturbations are monitored over the output voltage range of 2 – 4.5 V. The transfer power falls away gradually as the duty ratio deviates from the optimum point, resulting in a relatively broad region of duty ratios (Fig. 5) that allow over 99% of the maximum power to be transferred to the energy storage and the load.

During the test, the output voltage is regulated by a low-power shunt regulator (LM-4041). Starting from 4.5 V, the output voltage is reduced in discrete steps, whilst a fixed excitation of 4 m·s^{-2} at 43.6 Hz is maintained. At each voltage level, 100 measurements are captured to account for the effects of the continuously varying duty ratio that result from the MPTT algorithm's perturbations. The 100 measurement points represent a statistical sample of the duty ratio as controlled by the MPTT algorithm. The modal value of the recorded points δ_{mode} represents the duty ratio that the power converter is operated with the most. The duty ratio samples fall within ± 0.025 from the modal value, with a typical standard deviation of around 0.0175.

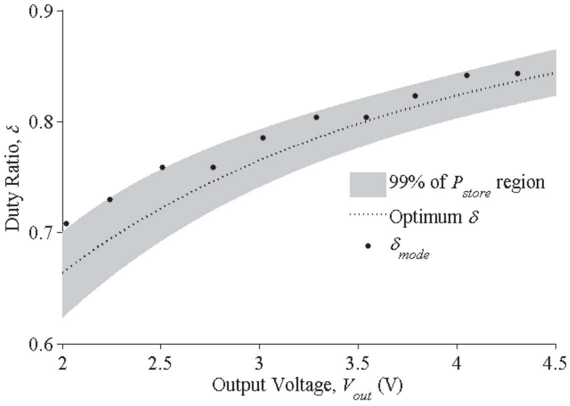

Fig. 5: The modes of the groups of 100 duty ratio samples recorded at each output voltage compared to the optimum and the 99% output power duty ratio range.

Along with the duty ratio, the displacement cycle averaged input power $P_{generated}$, quiescent power $P_{quiescent}$, and the transferred power P_{store} are also recorded over the output voltage range. The average values of these, calculated from the 100 recorded samples, compared against the energy harvester's maximum extractable power P_{max} for the given excitation, are shown in Fig. 6.

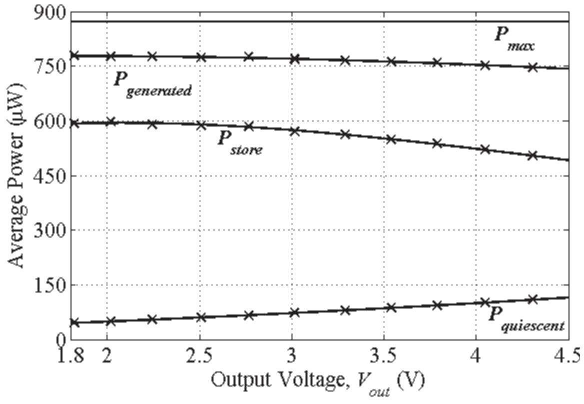

Fig. 6: Average power levels, Pgen, Pstore, and Pquies, compared to the generator's maximum output power Pmax

The quiescent power consumption is at its minimum at low output voltages because of the conversion efficiency of the linear regulators that supply the ancillary and control circuits. As the output voltage increases, the quiescent overhead approach 120 µW, this, in turn, decreases the power available to the load. The average generated power remains approximately constant over the output voltage range, corresponding to a harvester utilisation of 83 – 88.5%.

DISCUSSION

The MPTT control effectively tracks the changing output voltage conditions by adjusting the duty ratio of the power converter, as demonstrated during the transient charge-up and the quasi-steady-state measurements. The modal value of the duty ratio samples fall close to the optimum points, thus ensuring that close to the maximum potential power is transferred to the energy storage and the load.

The period between perturbations is an important design parameter presenting a potential trade-off: shorter periods may result in the instability of the control algorithm as mentioned in [1], whilst longer periods lead to slower feedback response, and consequently increased time for the algorithm to converge to an optimum point. The latter effect also limits the validity of the assumption of a constant output voltage, thus influencing the accuracy of the output power measurements.

Despite the fact that the algorithm is designed to maximise the output power of the converter, and not the power extracted from the energy harvester directly, the harvester utilisation remains high over the entire output voltage range. This is because the conversion efficiency of the converter is relatively constant, in the region of 75 – 80%, and is only a weak function of the duty ratio near the optimum point. The quiescent losses increase significantly with the output voltage, which means that the peak overall system effectiveness is achieved at the lower end of the output voltage range. Up to 69% of the energy harvester's maximum extractable power can be transferred to the supercapacitor at 2V output, dropping down to 57% at 4.5V.

CONCLUSION

A complete power conditioning system with maximum power transfer tracking control is presented with quiescent power consumption as low as 44 µW at $2V_{DC}$ output. The perturb-and-observe algorithm implemented in a low-power microcontroller is shown to be capable to track the optimum duty ratio point over the output voltage range by relying solely on the output current measurements.

The system is capable of providing up to 69% of the maximum available generated power to the load, after accounting for all the power penalties, whilst providing rectification and level boosting of the generated voltage, and actively maximising the power transferred to the energy storage element.

Future work will investigate the trade-off presented by the selection of the perturbation period, and will focus on further reducing the quiescent current consumption of the power condition system.

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