Optimization of Passive Voltage Multipliers for Fast Start-up and Multi-voltage Power Supplies in Electromagnetic Energy Harvesting Systems

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Abstract. This paper demonstrates the use of passive voltage multipliers for rapid start-up of sub-milliwatt electromagnetic energy harvesting systems. The work describes circuit optimization to make as short as possible the transition from completely depleted energy storage to the first powering-up of an actively controlled switched-mode converter. The dependency of the start-up time on component parameters and topologies is derived by simulation and experimentation. The resulting optimized multiplier design reduces the start-up time from several minutes to 1 second. An additional improvement uses the inherent cascade structure of the voltage multiplier to power sub-systems at different voltages. This multi-rail start-up is shown to reduce the circuit losses of the active converter by 72% with respect to the optimized single-rail system. The experimental results provide insight into the multiplier’s transient behaviour, including circuit interactions, in a complete harvesting system, and offer important information to optimize voltage multipliers for rapid start-up.

1. Introduction

A significant challenge for an energy harvesting (EH) system with an active switched-mode converter between the harvester and main storage element is cold start [1], i.e., start-up with no previously stored energy. The most common cold-start solution is to use a parallel passive converter, e.g., a voltage multiplier, to charge the storage capacitor to the point where the converter’s control circuits can be activated and supplied from this capacitor [2], as illustrated by the dashed arrows in Figure 1. This period of sub-optimum operation can take several minutes or even longer for sub-milliwatt harvesting, especially if the harvester is excited intermittently as is the case in many real environments [3].

This work presents a considerably faster start-up scheme: rather than charging the millifarad main storage capacitor to the required $V_{\text{store}}$, the start-up voltage multiplier output $V_{\text{cap}}$ powers up the control of the active converter directly, as indicated by the bold arrow in Figure 1. The multiplier is optimized for rapid start-up, only having capacitances of microfarads as required to power the microwatt control circuits. Once the main converter has charged up the main energy storage, this becomes the supply for the converter’s control circuits, thereby improving robustness.

For electromagnetic energy harvesting, voltage multipliers have been described in the literature for the main power extraction circuits [1], and optimized design described under specific load conditions. Typically the optimization includes minimizing the multiplier’s output impedance at the harvester excitation frequency [4] and holding the output voltage constant at a value where the harvester is operating close to its maximum power point. By contrast, this paper investigates optimum multiplier design with rising output voltages, and the principal purpose is to make the charging time to reach a
pre-defined supply voltage as short as possible. The multiplier is thus open-circuited at the output during this period. We demonstrate further improvements by using the inherent cascade architecture (Figure 2a) of a voltage multiplier to supply several rails at different voltages.

The electromagnetic harvester used in this work produces a nominal 110 µW into a matched (360 Ω) load under a sinusoidal excitation of $1.5 \text{ m}\cdot\text{s}^{-2}$, at its resonant frequency of 44 Hz. Its full details have previously been published and can be found in [5].

![Figure 1. Improved start-up of active control of power conditioning subsystems.](image)

![Figure 2. (a) Typical voltage multiplier, and (b) a single stage rectifier as its basic building block.](image)

### 2. Analysis and optimization of voltage multipliers for fast start-up

#### 2.1. Analysis of start-up time

For a given stored energy $E_{\text{store}}$, the start-up time $t_{\text{start}}$ of a voltage multiplier (Figure 2a) is

$$E_{\text{store}} = \frac{1}{2} C_{\text{out}} V_{\text{DD}}^2 = \int_{t_{\text{start}}}^{t_{\text{out}}} [P_{\text{in}}(t) - P_{\text{out}}(t)] \, dt,$$

where $C_{\text{out}}$ is the multiplier output capacitance and $V_{\text{DD}}$ is the required start-up voltage; the difference between the input power $P_{\text{in}}$ and loss $P_{\text{loss}}$ represents the charging power (i.e., $P_{\text{out}}$ in Figure 2a). While $P_{\text{loss}}$ is associated with the multiplier’s constituent devices, e.g., the diode voltage drop and number of diodes, $P_{\text{in}}$ is determined by the harvester loading condition, which varies continuously during start-up.

Here we present a simplified analysis of the dynamic loading by considering a single-stage rectifier as the basic building block, Figure 2b. The rectifier draws current $i_{\text{IN}}(t)$ from a sinusoidal input voltage source $v_{\text{IN}}(t) = V_{\text{IN,A}} \cdot \cos(\omega t)$. Thus, the diode current (exponential) is $i_{\text{D}}(t) = I_{S} \cdot \exp(V_{\text{D}}/n\phi - 1)$, where $I_{S}$ is the diode saturation current, $\phi$ is the thermal voltage, and $n$ is the slope factor. The diode’s voltage drop is $v_{\text{D}}(t) = V_{\text{IN,A}} \cdot \cos(\omega t) - V_{\text{cap}}(t)$, and the resistance emulated by the rectifier is governed by

$$r_{e}(t) = \frac{v_{\text{IN}}(t)}{i_{\text{IN}}(t)} = \frac{V_{\text{IN,A}} \cdot \cos(\omega t)}{I_{S} \cdot \exp(V_{\text{IN,A}} \cdot \cos(\omega t) - V_{\text{cap}}(t))/n\phi - 1).$$

It follows that the resistance $r_{e}(t)$ varies not only within every input cycle but also as the capacitor is charged during start-up and $V_{\text{cap}}(t)$ increases. This relationship becomes more complicated when the input source in Figure 2b is replaced by the actual harvester-generated voltage, since this voltage now dependent on the loading represented by $r_{e}(t)$ and with time-varying amplitude. The slower the rate of change of the dynamic loading condition, the closer this condition approximates the optimum steady-state loading condition of the harvester, as demonstrated in [5]. This suggests the use of large multiplier capacitances ($C_{\text{VM}}$ in Figure 2a) to maximise the input power, because the larger the capacitance, the more slowly $V_{\text{cap}}(t)$ increases during start-up, and thus the more slowly $r_{e}(t)$ increases in equation (2). Larger capacitances, however, result in longer changing time for each multiplier-stage. A good trade-off is thus required here to minimize start-up time.

#### 2.2. Component selection to minimize start-up time

Start-up of the gate-drive control (Figure 1) occurs at 0.9 V corresponding to the minimum operating voltage of a TS3001 low-power pulse-width-modulation (PWM) generator used here. As suggested by equation (1), the lower the required rail, the shorter the start-up time. A multiplier-output capacitance
of \( C_{\text{out}} = 47 \, \mu\text{F} \) is used through the optimization, as this storage is suitable for microwatt loads. The default magnitude of the harvester’s excitation is \( 1.5 \, \text{m} \cdot \text{s}^{-2} \) corresponding to a maximum harvestable power \( P_{\text{max}} = 110 \, \mu\text{W} \). During low-voltage start-up, the diode’s forward-voltage drop is the primary source of power loss. This points towards the use of low-threshold diodes, but typically the lower the threshold is, the higher the leakage is. Four different Schottky diodes are thus evaluated through PSpice simulation: RB411D, BAT760, BAT754, and 1PS79SB30. Despite the RB411D diode having the highest leakage (2.5 \( \mu\text{A} \) @ 1 V), the benefit of its low voltage drop of \( -90 \, \text{mV} \) for 100-\( \mu\text{A} \) forward current outweighs the drawback of high leakage and results in the fastest start-up. It is thus selected.

Figure 3. Simulated start-up times for \( V_{\text{cap}} = 0.9 \, \text{V} \) versus multiplier capacitance \( C_{VM} \) for different stage numbers \( N \).

Figure 4. Simulated start-up times of optimized combinations of \( N \) and \( C_{VM} \) for \( V_{\text{cap}} = 0.9 \, \text{V} \) and 1.5 V, against harvester excitation.

Figure 5. Dual-rail \( (V_{\text{cap}_L, H}) \) start-up topology of a voltage multiplier.

2.3. Multi-rail start-up
The single-rail start-up system suffers from a trade-off, where choosing a lower rail voltage shortens the start-up time but also increases the circuit loss of the main converter due to insufficient headroom above the gate threshold voltage. This trade-off can be improved through the powering up of different subsystems with different voltage rails. Fortunately, the voltage multiplier readily provides different
internal voltages, see Figure 5, where, during start-up, the rails $V_{\text{cap\_L}}$ and $V_{\text{cap\_H}}$ rise simultaneously with $V_{\text{cap\_H}} > V_{\text{cap\_L}}$. The resulting system is illustrated in Figure 6. The majority of the control circuits are powered by the lower rail $V_{\text{DD\_L}}$, which reduces the total quiescent power consumption, and permits these circuits to be triggered sooner via an under-voltage-lockout (UVLO). The higher rail $V_{\text{DD\_H}}$ powers only the gate-drive buffer to provide sufficient headroom above the gate threshold voltage of the main switching device $M_1$, thereby achieving low on-state resistance and conduction loss. Improved trade-offs between start-up speed, quiescent power overheads of active control, and power-conversion efficiency can thus be expected. In the circuit of Figure 5, the choice of $C_H$ affects the start-up speed of $V_{\text{cap\_L}}$, because the larger capacitance $C_H$ is, the more power $P_H$ is drawn from stage $N=4$, and therefore less power $P_L$ is available to charge $C_L$. Using a small $C_H$ improves the start-up speed while the actual required $C_H$ is small as it is only used to power the gate-drive buffer.

3. Experimental results

3.1. Measurements of transient power during start-up of single-rail system

As suggested in equation (1), the start-up time is determined by the varying input power and power loss. The input and output transient power (averaged over every excitation cycle) of the voltage multiplier of Figure 2a is measured during a start-up event and plotted in Figures 7, 8 and 9, as a function of $C_{VM}$, showing that these powers vary dynamically. Figure 7 shows that larger capacitances $C_{VM}$ improve the harvester loading, as seen by the higher input powers, but also increase the power loss, which results in an optimal $C_{VM}$ at 12 µF yielding the highest output power.

Figure 8 shows that the output powers peak at different output voltages for different stage numbers $N$. A higher $N$ shifts the power peak to the higher voltage, as it provides higher voltage-boosting. This also improves the harvester loading, as each multiplier-stage draws power from its preceding stage so that charging the first stage takes more time. The resulting loading changes slowly and approaches the optimum steady-state loading condition, as noted in Section 2.1. Higher $N$ with more diodes, however, results in higher loss. Thus, the optimal $N$ is 4, whose corresponding output power peaks at the rail 0.9 V. With $C_{VM}=12$ µF, it offers the shortest start-up time for $P_{\text{max}}=110$ µW as shown in Figure 3.

Figure 9 shows that different excitation magnitudes (whilst $N=4$, $C_{VM}=12$ µF) not only change the power peaks but also their voltage locations. Since higher excitations and hence input power levels $P_{\text{max}}$ result in higher voltages at which the powers peak, lower $N$ is required to shift the peak from a low voltage level to the targeted rail, in order to achieve the fastest start-up, as shown in Figure 4.
The system is compared with its single-rail counterpart using the circuit shown in Figure 2a with $V_{DD} = V_{cap}$. Figure 10 shows the steady-state measurement results. The higher the single-rail $V_{DD}$ is, the higher the quiescent power consumption $P_q$ is, and the lower the converter’s conduction loss $P_{cond}$ is, since the rail regulates the gate-drive signal swing. This results in an optimal $V_{DD}$ at 1.2 V corresponding to the lowest total power loss $P_{loss}$. By contrast, even lower $P_{loss}$ is achieved by the dual-rail system with $V_{DD_L}$ at 0.9 V for low $P_q$ and $V_{DD_H}$ at 1.5 V for low $P_{cond}$. These results, together with the measured start-up times, are summarized in Table 1. The single-rail 0.9 V start-up offers the shortest time but results in much higher $P_{loss}$. An improved trade-off is achieved here by the dual-rail system using small capacitances $C_H$ in Figure 5; the total power loss is reduced by about 72%, whilst the optimized start-up time is ~1 s, as opposed to the 148 s presented in [2], under similar conditions.

**Table 1.** Comparative summary of the single-rail and dual-rail power-supply systems.

| Power Supplies | Power Losses (relative to max. harvestable power) | Start-up Time ($C_{vm} = C_L = 47 \mu F$) |
|----------------|-----------------------------------------------|----------------------------------------|
| Single-rail of $V_{DD} = 0.9$ V | Quiescent, $P_q$ 5.8% Conduction, $P_{cond}$ 37.8% Overall, $P_{loss}$ 43.6% | 0.94 @ $C_{vm}$ = 12 \mu F (optimum) |
| Single-rail of $V_{DD} = 1.2$ V | 9.6% 5.4% 15% | 1.39 @ $C_{vm}$ = 10 \mu F (optimum) |
| Dual-rail of $V_{DD_L} = 0.9$ V, $V_{DD_H} = 1.5$ V | 8.8% 3.2% 12% | 1.03 @ $C_H = 2.2 \mu F$, $C_{vm} = 12 \mu F$ |
| | | 1.13 @ $C_H = 4.7 \mu F$, $C_{vm} = 12 \mu F$ |
| | | 1.2 @ $C_H = 6.8 \mu F$, $C_{vm} = 12 \mu F$ |

4. Conclusion

For microwatt electromagnetic harvesting systems, start-up using passive voltage multipliers can be shortened by selecting stage numbers and capacitances to achieve peak output power at the targeted rail voltage for given input power levels. Furthermore, by using the proposed multi-rail multiplier topology which distributes supply rails to various subsystems, an improved trade-off between start-up speed and active power conversion efficiency is found, resulting in a ~1 second start-up and a ~72% reduction in power loss with respect to the single-rail system.

**References**

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