An Up-conversion Management Circuit for Electrical Field Energy Harvester

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Abstract. This paper presents a high-efficiency management circuit using a maximum power point tracking (MPPT) matching circuit for power-line electrical energy harvesting. Due to small internal capacitor of the transducer and heavy load, the traditional circuit of the electrical energy harvesting at a low working frequency of 50Hz has a low transducer efficiency, and cannot be used in both low power-line voltage and heavy load. Besides, the matching impedance varies with the charging voltage. In order to achieve maximum output power during whole charging process, an up-conversion MPPT matching circuit is developed. Higher charging power, and larger ultimate charging voltage in a power-line voltage of 4000V can be obtained by using the MPPT up-conversion matching circuit. In order to drive the wireless sensor with a higher consumption power, an instantaneous discharging circuit is developed. The management circuit can drive wireless sensor with an output power of 60mW.

1. Introduction
Wireless sensor networks (WSN) have been used for monitoring the operation state of the power line and electrical devices [1]-[4]. Because WSN nodes are distributed in high-voltage environments, replacement of batteries is dangerous. Sensor nodes with the limited battery energy hardly work for long time. Energy harvesting technology provides an energy supplement method [5]-[8].

Electrical field energy sources are ubiquitous near power lines and electrical devices. The electrical field energy harvesting method may have many advantages in power line state monitors [1][3][4]. Electric field energy harvesting with a power of 47μW for wireless sensors in smart grid is designed [9]. Low-cost electric field energy harvester for an MV/HV asset-monitoring smart sensor obtains 17mW at 35kV [10]. A management circuit with up-conversion oscillation technology for electric-field energy harvesting can obtain 663μW at 10kV [1]. But the matching impedance varies with voltage of storing capacitor, and the management circuit hardly obtains the maximum power.

A MPPT method for low-power solar energy harvesting has a high efficiency with 92% at 100mW. But this circuit has a long tracking time of 1s and high power consumption of 350μW [11]. An efficient electromagnetic energy harvesting using MPPT with 0.35μm CMOS process can obtain an efficiency of 50% at a power consumption of 10μW [12]. A maximum power transfer tracking for ultralow-power electromagnetic energy harvesters attains an efficiency of 70% at a power consumption of 44μW [13].
low-power self-powered piezoelectric energy harvesting system with MPPT with an efficiency of 72% and a power consumption of 408μW is designed [14]. However, many conventional MPPT management circuits need large power consumption (44μW-100mW) due to using MCU and complex control circuit.

We proposed a high-efficiency up-conversion management circuit based on electrical field energy harvesting with low power consumption. The conjugate impedance matching is designed for a capacitive internal impedance transducer. Because the matching impedance of the maximum charging power varies with voltage of storing capacitor, a new MPPT matching circuit with low-power consumption is proposed. The feedback signal can turn on/off the up-conversion matching switch by varying the duty cycle, and the maximum power can be obtain in whole charging time by using a new MPPT hardware circuit with low power consumption. The management circuit of the energy harvesting can continuously gather and accumulate weak energy from the electrical field in long period, and provide a high-power output in a very short cycle to drive the wireless sensors at a long distance.

2. Electrical field energy harvesting
The hollow aluminum cylinder (Fig.1) is a passive electrical field transducer around power line. The isolative high-voltage materials separate transducer from power line. \( C_p \) and \( C_{tg} \) are capacitances between power line and transducer, and between transducer and ground, respectively. \( C_p \gg C_{tg} \). Thus, the capacitor \( C_p \) can be used as the energy harvester for scavenging the high-voltage electrical field energy across 50Hz power lines. \( r=10\text{mm}, \ r_1=18\text{mm}, \ r_2=20\text{mm}, \ l=300\text{mm}, \ h=93\text{cm} \).

\[
C_p = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(r_1/r)} = 28.5\text{pF}, \ C_{tg} = \frac{2\pi\varepsilon_0l}{\cosh^{-1}(h/r_2)} = 3.6\text{pF}.
\]

The output power of less than 1nW can be obtained at a direct charging circuit for a storage-energy supercapacitor of 0.1F. Thus it is difficult to acquire large output power by using the direct connection with a heavy load. For the traditional matching circuit, a very large inductance of over 10000H is necessary due to a small \( C_p \) of 28.5pF. Therefore, the MPPT conjugate matching circuit with the up-conversion circuit is necessary for maximum power output at a high capacitive internal resistance.

3. Management circuit of electrical field energy harvesting

3.1. Management circuit principle
The management circuit of electrical field energy harvesting is composed of an up-conversion matching circuit, two rectifier circuits, a charging current detecting circuit, a storage-energy circuit, a MPPT circuit, a burst generator and an instantaneous pulse discharge circuit, as shown in Fig. 2. The capacitive energy harvester harvests the low-frequency (50Hz) electrical field. In order to obtain the maximum power and decrease the matching coil size, the bilateral switching up-conversion matching circuit is used, as shown in Fig. 3. The up-conversion resonant circuit with bidirectional analog switch can convert 50Hz signal into a higher frequency (32.768 kHz) signals. The bidirectional switch consists of two switches with a small conduction resistance (120mΩ). Rectifier 2 (Fig. 2) transfers ac signal into dc signal for the capacitor \( (C_c) \) of the subsidiary power supply. Because the matching circuit of the electrical field energy harvester under a low power-line voltage (\( \leq 10\text{kV} \)) does not directly drive the wireless sensor with a higher consumption power of 60mW, an instantaneous discharging circuit is developed for the weak energy harvesting. The instantaneous discharging circuit (Fig. 2) can continuously accumulate weak power from the energy harvester for a long period, and provide a higher power output in a very short time. The burst generator can produce a burst signal. Because voltage across the storage energy capacitor cannot suddenly change, the maximum charging power point is the same as the maximum charging current point. The current detecting circuit can find the maximum charging
power point by detecting maximum charging current point. The MPPT circuit can produce different pulse control signals with changeable duty cycles into the control input of the up-conversion matching circuit. The output power of the auxiliary power supply is above 10μW. By using the proposed MPPT circuit and the up-conversion matching circuit, the maximum charging power can be obtained.

3.2. MPPT circuit with up-conversion matching

The feedback control circuit can match the impedance of the electrical field energy harvester by using a higher frequency and a larger duty cycle for the switching control signal, as shown in Fig.3. In the charging duration, the maximum power point varies with the charging voltage. To obtain maximum power from electric field energy harvesting, a MPPT circuit with up-conversion matching is necessary. The maximum power point can be found by detecting charging current maximum point due to no sudden voltage change of storage-energy supercapacitor. The automatic duty cycle change of the up-conversion circuit can track the maximum current/power point. The consumption of the MPPT circuit has a 6μW at a voltage of 5V and a current of 1.2μA.

The average output current in the up-conversion output loop can be expressed as

\[ I_2 = \frac{L_2(1 + e^{-\beta/\omega R})}{2\pi[1 + (\beta_2 / \omega R)^2]} \frac{\omega C}{2\pi} \]  

The output power can be calculated by

\[ P(V_{rect}, D) = \frac{V_{rect}^2 D (\omega C L_2 + DT_2 / 2L_2)(1 + e^{-\beta/\omega R})}{2\pi[1 + (\beta_2 / \omega R)^2]} \frac{\omega C}{2\pi} V_{rect}^2 \]  

T is the period of the switch S. D is duty cycle. \( V_{rect} \) is charging voltage in storage-energy supercapacitor. There is a maximum charging power point for the change of the charging voltage and the duty cycle.

Setting \( dP(V_{rect}, D)/dV_{rect} = 0 \) and \( dP(V_{rect}, D)/dD = 0 \), conditions of maximum charging power are

\[ D_0 = \frac{\omega C L_2}{4T(1 + (\beta_2 / \omega R)^2)} \]  

\[ V_{rect} = \frac{V_{rect}^4 2 \omega C L_2 (1 + e^{-\beta/\omega R})}{4T[1 + (\beta_2 / \omega R)^2]} \]  

The maximum charging power at \( V_{rect} = V_0 \) and \( D = D_0 \) can be expressed as

\[ P(V_0, D_0) = \frac{V_0^4 2 \omega C L_2 (1 + e^{-\beta/\omega R})^2}{32\pi^2[1 + (\beta_2 / \omega R)^2]} \]  

The maximum charging power can be obtained from (6). The duty cycle and the charging voltage at the maximum charging power can be expressed as (4) and (5), respectively.

4. Experiment

4.1. Up-conversion of electrical field energy harvesting

In experimental hollow aluminum cylinder, the radius of the transmission line, the inner and outside surface of aluminum foil cylinder transducer are \( r=10\text{mm}, r_1=18\text{mm} \) and \( r_2=20\text{mm} \), respectively. The axial length of cylinder and the distance between the lowest point of a cylinder and the earth are...
\[ l=300\text{mm} \text{ and } h=93\text{cm}, \text{ respectively.} \]

\[ C_P=2\pi \varepsilon_0 \varepsilon_r / \ln(r_1/r_2)=28.5\text{pF}. \]

\[ C_{tg}=2\pi \varepsilon_0 l / \cosh^{-1}(h/r_2)=3.6\text{pF}. \]

The matching inductance and resistance in the primary coil of the transformer are 0.7349H and 56.2Ω, respectively. The inductance, resistance and the matching capacitance in the secondary coil of the transformer are 10.723mH, 6.4Ω and 2200pF, respectively. The storage-energy supercapacitor \( C_{rect} \) is 0.1F. The voltage amplitude of the power line with a frequency of 50Hz is 4000V.

The management circuit is shown in Fig. 3. In the up-conversion circuit, the frequency and the duty cycle of the up-conversion switch are 32.768kHz and 20%, respectively. Fig. 4 shows the up-conversion voltage waveforms across the secondary inductance \( L_2 \) of transformer at a switching period of 30.518\( \mu \)s. In the secondary loop of the transformer, \( \omega_0=1/\sqrt{L_2C_5} \) is the resonant angular frequencies of the secondary loop. The main component in secondary loop is resonant frequency signal. An undamped resonant signal (6V p-p) can be obtained because the switching frequency is equal to the resonant frequency (32.768kHz).

**4.2. Comparison of MPPT Matching Charging Circuit and Direct Matching Charging Circuit**

Fig. 5 shows the charging process of the traditional direct matching charging circuit and the MPPT matching charging circuit. The charging voltages in the storage-energy supercapacitor are increased with exponential curve. At a charging time of 40 minutes, charging voltages of 370mV and 260mV can be obtained for the MPPT matching charging circuit and the direct matching charging circuit, respectively. The MPPT matching charging circuit acquires a 42.3% larger voltage than the direct matching charging circuit.

Fig. 6 shows charging powers of the MPPT matching charging circuit and the traditional direct matching charging circuit in different charging voltages. The maximum charging powers of the MPPT matching charging circuit and the direct matching charging circuit are 19\( \mu \)W and 7.5\( \mu \)W at a charging voltage of 0.32V and a charging time of 36 minutes, respectively. The MPPT matching charging circuit increases a 153% stronger maximum charging power than direct matching charging circuit. In initial charging time, the duty cycle of the up-conversion switch is 50%. Then, the duty cycle of the control switch automatically is varied by the MPPT feedback circuit in order to obtain the maximum charging current/power in the detecting resistance (Fig. 5), and the electrical-energy harvester is matched with up-conversion circuit. For a charging voltage of 0.32V, the maximum charging power can be obtained at a duty cycle of 20%.
4.3. Wireless sensor node with MPPT energy harvesting

A voltage of 4000V with a frequency of 50Hz in an electrical power line is produced. The designed electrical field energy harvester is installed around the power line. A storage-energy supercapacitor with a capacitance of 0.1F is used. The wireless sensor node is composed of sensor units (DS600, made by MAXIM company), a high-speed lower-power microprocessor with a low-power 2.4G transceiver (nRF24L01) and a 3.3V power supply generated by the energy harvester with management circuit. The times of the receiving and transmitting data of the wireless sensor is 400ms and 4ms, respectively. The powers of the receiving and transmitting data is 18mW and 60mW, respectively.

The necessary minimum energy of the sensor node in a working cycle is

\[ W = PT = 18 \times 0.25 + 60 \times 0.004 = 4.74\text{mJ}. \]  \hspace{1cm} (6)

While the charging voltage across the storage-energy supercapacitor at a charging time of 200 minutes is 1.1 V, the voltage across the storing supercapacitor decreases to 1.0 V at a short time of 250ms. The discharging energy of the instantaneous discharging circuit provided by the storing supercapacitor at one discharging period is

\[ E = \Delta U^2 C / 2 = (1.1^2 - 1.0^2) \times 0.1 / 2 = 0.5\text{mJ}. \]  \hspace{1cm} (7)

From (6) and (7), the provided energy of the instantaneous discharging circuit is larger than the necessary minimum energy of the sensor node in a working cycle (E>W). The energy from the instantaneous discharging circuit can drive the operation of the wireless sensor.

In experiment, wireless sensor nodes with energy harvesting supply are placed in an open field. The electrical energy harvester with the high-efficiency management circuit under a voltage of 4000V can drive wireless sensors with an output power of 60mW at a distance of over 35m.

5. Conclusion

In this paper, a low-power-consumption high-efficiency up-conversion MPPT matching management circuit for the electrical energy harvesting is proposed. By changing the duty cycle of the up-conversion matching switch, the maximum charging power is tracked during the charging process, and higher charging power and ultimate charging voltage can be obtained compared with the traditional direct matching charging circuit. The developed instantaneous discharging circuit can continuously accumulate weak energy from the power-line transducer for a long period, and provide a higher power output in a very short time. The electrical energy harvester with the MPPT up-conversion matching management circuit can provide the enough power for the wireless sensor, and drive wireless sensors at a long distance.

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References

[1] Zhang J, Li P and Wen Y 2016 IEEE Trans. Power Electron. 31 5515
[2] Li P, Wen Y, Zhang Z and Pan S 2015 IEEE Trans. Ind. Electron. 62 6327
[3] Moghe R, Iyer A, Lambert F and Divan D 2014 IEEE Trans. Smart Grid 5 2002
[4] Gutierrez A, Dopico N, Gonzalez C, Zazo S, Jimenez J and Raos I 2013 IEEE Trans. Ind. Electron. 60 3176
[5] Li P, Wen Y, Jia C and Li X 2011 IEEE Trans. Ind. Electron. 58 2944
[6] Li P, Wen Y, Yin W and Wu H 2014 IEEE Trans. Ind. Electron. 61 3349
[7] Kempiati A, Borca D and Hella M 2013 IEEE Trans. Ind. Electron. 59 456
[8] Li P, Wen Y, Liu P and Li X 2010 Sensor. actuat. A-Phys. 157 100
[9] Chang K, Kang S and Park K 2012 J. Electron. Eng. Technol. 7 75
[10] Moghe R, Iyer A and Lambert F 2015 IEEE Trans. Ind. Appl. 51 1828
[11] López O, Penella M and Gasulla M 2010 IEEE Trans. Ind. Electron. 57 3129
[12] Maurath D, Becker P and Spreemann D 2012 IEEE J. Solid-St. Circ. 47 1369
[13] Szarka G, Burrow S and Proynov P 2014 IEEE Trans. Power Electron. 29 201
[14] Kong N and Ha D 2012 IEEE Trans. Power Electron. 27 2298