Research and Design of Conditioning Units for Wireless Energy Harvesting Device in Smart Grid

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ABSTRACT

With the rapid development of Chinese power industry, the wireless sensor technology has become an important part of realizing the intelligent construction of the power grid. However, the problem, that how to convert the energy collected by wireless storage device into stable DC output for wireless sensors, has limited the large-scale of wireless sensor. Therefore, it is an urgent need to design conditioning units for wireless energy harvesting device. According to the actual situation of the substation and the lower efficiency of traditional energy harvesting device, this research has proposed a new type of spherical capacitive energy converters topology, and designed energy collected and accelerated circuit and the PWM double-loop controlling and conditioning circuit with rectifier, storage and voltage regulation function. Besides that, the main parameters have been determined by theoretical calculation, and the conditioning circuit is simulated by PSIM simulation software. The simulation results verify the effectiveness of the mentioned topology and parameter selection method.

Keywords: wireless sensor, conditioning unit, energy collected and accelerated circuit, isolated fly-back conditioning circuit.

INTRODUCTION

Advanced sensing and measurement technology is required to accomplish the normal operation of intelligent monitoring and diagnosis in smart grid. However, the energy supply problem has become the main barrier which hinders it to further develop. The high voltage substation and transmission line in the power grid are rich in electromagnetic energy[1]. Thus, it is necessary to develop a wireless energy harvesting device that can collect stray energy in the surrounding environment of a substation, and a conditioning unit that converts the collected power to DC power for wireless sensor. The energy collection unit converts the spatial electromagnetic energy in the substation into electric energy. In this article, a new type of spherical capacitive energy converter topology is proposed to collect the electric field.
energy in each direction. The conditioning unit is used to make the energy collected carry on rectification, storage, voltage stabilization and other operations. However, the electromagnetic field distribution in the actual substation is rich in harmonic components, and is susceptible to interference from the external environment. Therefore, the output voltage of the wireless energy harvesting device often fluctuates greatly. Moreover, due to the current collected technology is not very efficient, there is less electromagnetic energy collected by the wireless energy harvesting device. But, wireless sensors used in smart grid requires a stable DC voltage to work properly. Therefore, in order to solve the conflict between the unstable voltage output on the harvesting device’s side and the need for stable DC voltage on the sensor’s side, the optimal design of the conditioning unit used for the wireless energy harvesting device becomes necessary. The traditional conditioning units used for harvesting devices have many shortcomings, which are low energy transformational efficiency and unstable output voltage. Considering that, first, optimal conditioning units should achieve a stable DC output in the case of unstable voltage generated by wireless energy harvesting device. Secondly, it should have a higher conversional efficiency to meet the power requirements of wireless sensor. Therefore, the research of stable and efficient conditioning circuit topology and its optimal analysis method, effectively solve the practical problems about wireless energy devices supplying for the wireless sensor. It is also of great significance to achieve energy self-sufficiency of wireless sensors.

**PRINCIPLE AND CHARACTERISTICS ANALYSIS OF SPHERICAL CONVERTER**

A new type of spherical capacitive energy converters topology is proposed to collect the electric field energy in each direction[2]. Upper and lower metal hemispherical shells have made up the capacitive bipolar plates, filling with the insulating medium.

![Figure 1. The model of ball harvesting device under spherical coordinate.](image)

The mathematical analysis model of the ball harvesting device built in spherical coordinate system is shown in Figure 1. The original point is located at the center of spherical shell, a is the radius of sphere and the space potential equation of any point $P \,(r, \theta, \phi)$ satisfies Laplace’s equation:

$$\nabla^2 u = 0$$  \hspace{1cm} (1)

In spherical coordinate system, it is:

$$\nabla^2 u = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial u}{\partial r} \right) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial u}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 u}{\partial \phi^2} = 0$$  \hspace{1cm} (2)

The general solution of potential is expressed as:

$$u(r, \theta) = \sum_{n=0}^{\infty} \left( A_n r^n + B_n \frac{1}{r^{n+1}} \right) P_n(\cos \theta)$$  \hspace{1cm} (3)
The capacity of ball harvesting device is:

\[ C = \frac{Q}{U} = \frac{Q_0}{2V} = \pi R \sum_{n=1,3,5} \frac{(n+1)(2n+1)}{2} \left[ \int_0^\pi P_s(\cos \theta) \sin \theta \, d\theta \right] \tag{4} \]

The capacitance, as its own characteristic parameter, is a fixed value and the relational expression between the output voltage and the strength of external field of the ball harvesting device is:

\[ U = \frac{3RE \cos \delta}{\sum_{n=1,3,5} \frac{(n+1)(2n+1)}{2} \left[ \int_0^\pi P_s(\cos \theta) \sin \theta \, d\theta \right]^2} \tag{5} \]

And \( \delta \) is the included angle between the uniform field strength at any direction and z axis of changeover. So, it is easy to obtain that the output voltage of ball harvesting device is determined jointly by spherical radius and strength and direction of field according to Equation (5). Spherical radius and external field can be considered comprehensively, when the maximal output voltage of the harvesting device is set to be the goal of optimization; when external field is fixed, the longer the radius of sphere is, the higher the output voltage is, and the optimization constraint turns into volume restriction.

Although the electric field in the substation is rich and complex, the main component is the frequency alternating electric field. The output voltage of the capacitive harvesting device is synchronously followed by the external alternating electric field[3]-[5]. In order to simplify the theoretical analysis of the conditioning circuit, AC voltage source can be used to approximate the capacitive energy unit.

Wireless sensor generally has complex compositions, including sensing, data processing and controlling, communication and other units. However, this article focuses on the conditioning topology and the characteristics of capacitive energy converters supplying for the sensor load. Therefore, it is reasonable to use an equivalent resistance to approximate the wireless sensor load.

**DESIGN AND ANALYSIS OF ENERGY COLLECTED AND ACCELERATED CIRCUIT**

In order to overcome the shortcomings that the traditional conditioning unit can not effectively transfer the energy collected, higher frequency switch is used to generate intermittent pulse current and speed up the charge flow. So the transmission efficiency of electric power has been improved by the high frequency of switch on and off. The topology of Energy Collected and Accelerated unit is shown in Figure 2:

![Figure 2. The topology of Energy Collected and Accelerated unit.](image)

For example, the resistance of the load is 300\( \Omega \), input power is 350mW, input voltage is 10V, the value of duty cycle is 0.5 and then the value of inductance is 0.03mH. The output voltage of the conditioning unit is shown in Figure 3 under 5KHZ.
The simulation results show that the output voltage will stabilize at 11.6V after 5ms, and there is less obvious pulsation compared with the output voltage waveform of the traditional conditioning unit. The quality of waveform is greatly improved.

Similarly, the start-up of the conditioning unit under different electric field strength is tested. The converter is still a plate-type capacitive converter with a radius of 10 cm. The time, that the voltage of storage capacitor reaches 3V, has been tested in different electric field strength. [6] The experimental results are shown in the Table 1. It can be concluded from the experimental results that the start time of Energy Collected and Accelerated unit is greatly reduced compared with the traditional conditioning unit.

Table 1. Start Time of Energy Collected and Accelerated Unit in Different Electric Field Strength.

<table>
<thead>
<tr>
<th>Electric field strength (kV/m)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time(min)</td>
<td>&gt;15</td>
<td>15</td>
<td>15</td>
<td>11.5</td>
<td>7.5</td>
<td>5.5</td>
<td>3.8</td>
<td>2.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

In summary, the inductor and the high frequency switch used in Energy Collected and Accelerated unit is set on the AC side. As the output voltage of the energy harvesting device is susceptible to the influence of the spatial electromagnetic environment in the substation, the inductor can filter out the AC harmonics and reduce the damage caused by the sudden change of the current in the circuit to the electronic device. However, the inductor and high-frequency switch in Boost converter is on the DC side, with different working mode and role from Energy Collected and Accelerated unit.

In addition, Energy Collected and Accelerated unit can speed up the transfer of power from the converter to the load, through the switch on and off and the pump up role of the inductance. But the unit only uses one more inductance and switch compared with traditional circuit. Therefore, its structure is relatively simple, and easy to meet the application requirements. The circuit can be used as the preferred topology of conditioning units.

**SELECTION AND OPTIMIZED DESIGN OF CONDITIONING CIRCUIT**

**Selection of Conditioning Unit**

The input voltage of the conditioning circuit designed in this paper is equal with the output voltage of the collected energy converter, 100V and the output power is low power. Electricity power collected by the energy harvesting device is related to the intensity of the external electric field. [7] Since it is difficult for prior technology to collect high power, the
study decides to design a fly-back type circuit to fit requirements of conditioning unit. In addition, because of the instability of the external electric field and the complexity of the external magnetic environment of the transformer substation, the conditioning circuit is easily interfered, which mostly reduces the quality of output voltage. So it is reasonable and preferable to isolate the AC voltage input side from the DC voltage output side. Because the buck converter and the boost converter are non-isolated without transformer, they are not considered. Forward converter transformer is not able to store energy, additionally more strict requirements to MOSFET. Fly-back circuit is able to isolate the output side and the input side, relatively simple, with low price and dynamic adjustment range.[8]-[9] It is usually used for transforming small power. Therefore, considering above reasons, the conditioning circuit should be designed to use commutated and voltage-stabilizing circuit followed by isolated fly-back converter.

The Principle of Fly-back Conditioning Circuit

The schematic diagram of Fly-back conditioning circuit is shown in Figure 4: the MOSFET will be conducted with the current flow $I_p$ through the primary side, $N_p$, as the PWM signal is in a high level. The primary winding has stored the energy. Meanwhile, the negative polarity of the output voltage in the secondary winding $N_s$ is above on the positive pole, so diode will be cut off with no signal output. On the contrary, the MOSFET will be cut off with no current flow through the primary side as the PWM signal is kept in low level. According to the principle of electromagnetic induction, the induced voltage $U_o$ will be produced in the primary winding side and $U_s$ will be generated in the second winding side. Positive polarity of $U_s$ is above on negative pole. Due to the power flowing through diode and capacitance, the output voltage is stable. The output voltage will basically achieve a stable level to meet our requirements, because of the high switching frequency.

![Figure 4. Basic principles of fly-back conditioning circuit.](image)

The Design of Isolated Fly-back Conditioning Circuit

Performance indicators of Fly-back conditioning circuit:
(1) Standard input voltage: AC 100V, 50Hz.
(2) Input voltage range: 90-110V.
(3) Operating frequency: 80KHz.
(4) Output voltage: 3.3V
(5) Operating temperature: -25 °C ~ 80 °C.
(6) Output voltage accuracy: ≤ 3%.
(7) Voltage regulation: ≤ 3%.
(8) Output ripple: ≤ 150mV.
(9) Ripple coefficient: ≤ 2%
(10) Efficiency: 80%.
The Overall Design of Fly-back Conditioning Unit

The system mainly includes follow components: input bridge rectification filter circuit, converter (including power switch, buffer absorption circuit and high frequency transformer), output filter circuit, control circuit. The AC voltage input of the system is 100 V. AC is transformed to DC through the bridge rectification filter circuit and then DC flows through the voltage conversion of fly-back converter and rectification filter circuit to achieve stable DC voltage output, 3.3 V, for the wireless sensor power supply. When the input voltage fluctuates, the research needs to adjust the voltage feedback to ensure the output stability. Feedback signal is used to control chip UC3842 to adjust the PWM pulse wave output width. After sampling, comparison and other steps, the PWM pulse wave output width will control the switch tubes’ duty cycle, to achieve a stable voltage.

![Figure 5. The overall design of fly-back conditioning circuit.](image)

SIMULATION RESULTS AND ANALYSIS OF UC3842 FLY-BACK CONDITIONING CIRCUIT

The simulation diagram of the output voltage $U_{out}$ is as follows:

![Figure 6. DC output voltage in 100V AC input.](image)

As the output voltage of the energy converter is consistent with the external electric field, the output voltage is inevitable to fluctuate. In order to determine whether the stabilized performance of the fly-back conditioning circuit meets the standards, it is necessary to get the DC output voltage $U_{out}$ simulation diagram under the situation that the AC input voltage changes suddenly from 90V to 110V at 0.5s. The diagram is shown in Figure 7:

![Figure 7.](image)
Figure 7. DC output voltage under AC input voltage changing from 90 to 100V.

Figure 8. Ripple diagram of output voltage $U_{out}$.

Figure 9. FFT diagram of output voltage $U_{out}$.

Figure 6, Figure 7 and Figure 8 shows that $U_{out}$ almost has no disturbance even at sudden changing of AC input voltage. Meanwhile, as the voltage is maintained at the level of about 3.3V DC voltage to supply the wireless sensor, it is found that the conditioning circuit works well with better performance of voltage regulatory. Moreover, it is able to deal with the actual situation that the output voltage of the converter easily fluctuates. Besides that, the ripple of the output DC voltage is always kept wispy, which is about 0.5%, even when the input AC voltage fluctuates greatly. Figure 9 shows that the output voltage has no high-frequency voltage components basically, and the amplitude of low-frequency voltage component is small. So the output voltage is able to maintain stability.

CONCLUSION

In this article, the practical problem about capacitive energy converters operating in the high voltage substation has been put forward and analyzed. In order to collect the electric field energy in each direction, a new type of spherical capacitive energy converters topology
is proposed. According to the case, energy collected and accelerated unit and isolated fly-back conditioning circuit are proposed and researched in detail. Experiments show that energy collected and accelerated circuit can improve the efficiency of energy conversion and the starting speed significantly. In addition, a fly-back conditioning circuit composed of single-ended output current control PWM driving chip UC3842 is simulated and designed by power electronic simulation software PSIM. Through checking the simulation results of the start circuit of the conditioning circuit, PWM control and drive circuit, DC output circuit, it has met the design requirements the above mentioned. Compared with traditional conditioning circuit, this conditioning unit is able to cope with the unstable electromagnetic environment in the substation efficiently with higher rate of power conversion, better regulation and anti-jamming capability.

REFERENCES