Design of Energy Harvester Circuit for a MFC Piezoelectric based on Electrical Circuit Modeling

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Abstract—**In this paper, the characteristic of the piezoelectric material, Macro Fiber Composites (MFC), has been investigated by comparison between the electrical equivalent circuit based simulation and the experimental result. The operational factors such as internal impedance and frequency which affect the maximum power output of the piezoelectric are systematically determined. The effect from the characteristic of the capacity after the rectifier circuit of the energy harvesting circuit in order to achieve the suitable energy storage is also mentioned. Some basic characteristic are tested and measured based on standard energy harvest kit and commercial MFC.**

Keywords-component; Piezoelectric; Equivalent circui;, Energy harvesting; Macro Fiber Composites.

I. INTRODUCTION

With the high growth of electronics industry recently, electronics circuit has been applied widely in every place and the certain energy supply source is an inevitable component in those systems or applications. Basically, in these applications, a conventional electrochemical battery has been mainly used as energy storage. However, there are various disadvantages or problem, such as limited capacity and lifecycle, weight and size limitation as well as leakage of the chemical solution. Also the problem about the continuously maintenance and reliability becomes seriously, especially for some applications on security monitoring. In order to solve these problems, the energy harvesting or energy scavenging circuit is also one research topic which is widely interested by the researchers around the world. Among various types of energy harvester equipments, a piezoelectric material is one effective component to convert the surrounding mechanical vibration energy into the electrical energy directly. From prior literature during these decades the piezoelectric materials have long been used as sensors and actuators. Although the mechanical vibrations take place in most of the structures, but the possible harvested performance of the piezoelectric material is not high and the level of the energy is very low in micro-watt or milli-watt order [1]. However with some improvement on the piezoelectric material and fabrication process as well as the low energy consumption of the electronics circuit design makes the possibility for using the piezoelectric in more wide range applications. Basically, it could be used to harvest and supply the energy for numerous applications, such as medical implanted devices [2], diagnosis equipment for large power plant [3], power source for remote wireless sensing nodes [4-5], ultra low power ubiquitous applications [6] and in low frequency application such as prosthetic hand [7]. A Macro Fiber Composite (MFC) is an alternative piezoelectric material which offers high performance and flexibility in a cost-competitiveness. It has very unique features, such as readily embeddable, flexible and durable structure.

In order to optimize the performance of whole energy harvesting circuit which usually composes of mechanical part and electrical part, the characteristic of each part including the whole system have to be analytically determined. Basically, the evaluation of the performance of the piezoelectric based on different electromechanical platform and model. Those models considered the complex decoupling effect between mechanical part and electrical part simultaneously while some characteristic, especially the electrical characteristic of the MFC piezoelectric itself was not clearly mentioned. In this paper, with the fixed electrical parameter, i.e. output voltage of the tested MFC, an evaluating method based on only electrical equivalent model is focused in this article. The commercial energy harvesting kit is used as a testing platform. Both the experimental and simulation results focused on the maximum power point of the MFC at each testing condition are investigated. Furthermore, the effect from the internal resistance in selected capacitor within the energy harvesting circuit is also considered in this paper.

II. ELECTRICAL EQUIVALENT CIRCUIT MODEL FOR MFC

In principle, the Macro Fiber Composite (MFC) can be represented as an ideal energy source (voltage or current source) with internal resistance. In case of linear source and load, in principle the Maximum Power Point (MPP) will be occurred only at the operating point which the external load resistor (R_L) equals to the internal resistor (R_i) in piezoelectric material. However, it was also reported that this MMP values will be changed due to operating frequency.

Fig. 1 indicates the proposed electrical equivalent circuit of the MFC where R_i and C_i are the open circuit value of internal resistant and internal capacitance of the MFC, respectively which can be simply measured their values by RLC meter at real operating frequency region.

The energy source represents by the ideal AC sinusoidal voltage source connected directly to the R_i and C_i. Basically, the maximum power point will be occurred when the external impedance equals to internal impedance. Hence only load resistor R_L is connected to the equivalent circuit of MFC and the maximum power point is determined. Therefore, from the equivalent circuit in Fig. 1, the total internal impedance, Z_{In_Total} can be expressed as the relation between impedance from resistance, $Z_R= R_i$ and impedance from capacitance, $Z_C=1/\omega C_i$ as following equation.

$$Z_{In\_Total} = \frac{Z_C Z_R}{Z_C + Z_R} = \frac{R_i}{1 + R_i C_i * 2\pi f} \tag{1}$$

The maximum power point will be changed at each corresponding operating frequency. The higher the operating frequency, the larger value of impedance of capacitance which cannot be neglected, so from (1) at high operating frequency region, the value of the load resistance that cause the maximum power point R_{L_peak} can be approximated as following equation. Its value will be change inversely to the operating frequency and the value of capacitance.

$$R_{L\_peak} = Z_{In\_Total} = \frac{1}{C_i * 2\pi f} \tag{2}$$

III. EFFECT FROM CAPACITOR IN HARVESTING CIRCUIT

The energy harvesting circuit is used to store the energy to the energy storage or it may be supply directly to the load upon to the design of each application. Fig. 2 indicates a basic conventional energy harvesting circuit. The AC power generated by the MFC is rectified by the full bridge rectifier circuit, after the certain period of time the energy will be accumulated into the capacitor, the stored energy can be expressed as following equation.

$$w(t) = \frac{1}{2} c v^2(t) \tag{3}$$

The stored energy directly depends on the value of selected capacitor, so it is a key factor related to the capability of the energy harvesting circuit to supply for each application. However, the value of voltage level also affect the stored energy, therefore the capacity to maintain the high output voltage is also one factor to be carefully considered.

In this paper, not only the value of the capacitor, the type of those capacitors, such as Tantalum, Electrolyte capacitor and

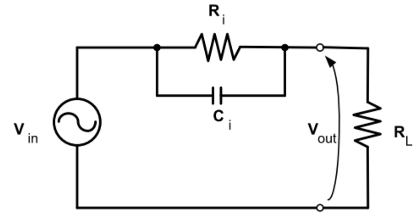

Fig. 1 Equivalent circuit of MFC

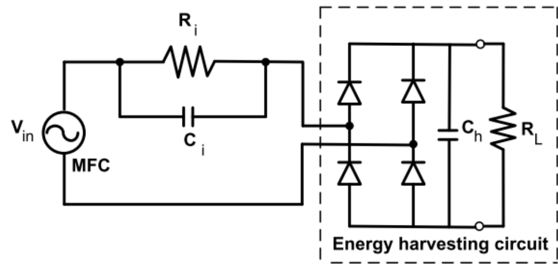

Fig. 2 Conventional energy harvesting circuit

Niobium oxide etc., also be considered. Since each capacitor also has different internal impedance which will be also directly affect to the leakage current or the capacity for maintaining the high output voltage, so the harvesting circuit designer have to carefully consider.

Fig. 3 shows the voltage waveforms across the MFC and C_h. When the energy harvesting circuit is connected to the MFC, the voltage across C_h will increase continuously to some certain level. The response of the output voltage across C_h will be faster when the frequency of the voltage waveform of the MFC is high. Also, with larger value of internal resistance in C_h, the voltage across C_h will also increase faster. Therefore in some application liked energy harvesting in prosthetic leg which the frequency only 1-2 Hz, the larger value of internal resistance in C_h is preferable, since the output voltage could be accumulated to the required level before it would be leaked out or be discharged to the load. With different type, value and voltage rating of each capacitor, the internal impedance will be different. Consequently, the leakage current will also be different.

The internal resistance of each capacitor can be determined from the simple test. The capacitor and the load resistance which is connected in parallel to C_h will be charged to any certain voltage level by energy circuit or DC supply. Then at any time, the input is switched off in order to let the stored energy in C_h discharge to the load resistance as shown in Fig. 4. The decreasing ratio of the output voltage or the time constant that output voltage decreases from same certain voltage level, can be defined by its capacitance value and internal resistance as following equation.

$$R = \frac{-t}{C * \ln(\frac{v(t)}{V})} \tag{4}$$

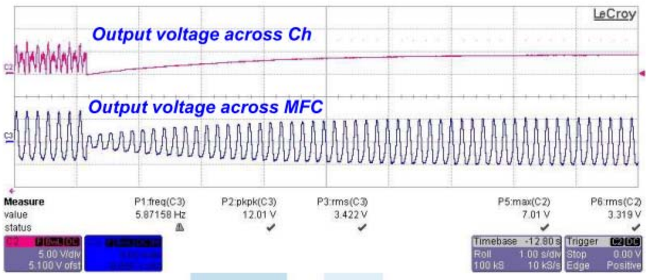

Fig. 3 Output voltage across MFC and capacitor in energy harvesting circuit.

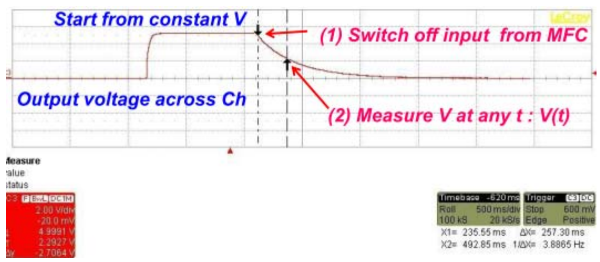

Fig. 4 Output voltage across capacitor in energy harvesting circuit for measuring internal resistance value.

IV. Experimental and Simulation results

A. *Specification of tested MFC*

Table. I. Specification of tested MFC

Model	MFC 8528
Type	P2 (d31 mode)
Size	8.5*2.8 cm
Maximum operational positive voltage	+ 360 V
Maximum operational negative voltage	- 500 V
Operational bandwidth	< 10 kHz

In this paper, a P2 type d31 coupling mode as shown in Fig. 5 is used as a specimen. Although the coupling efficiency of this type is lower than the other modes, it is one commonly used since it is most efficient for the small force and low vibration level environment. In this type, a force is applied in the direction perpendicular to the poling direction. The tested MFC model MFC8528 is mounted on the flexible arm and connect to the energy harvesting kit.

B. *Specification of Energy Harvesting Kit*

Fig. 6 shows the experimental setup where the commercial Smart energy harvester development kit from Smart material Corp is used. It composes of a shaker which its frequency can be adjusted from 0 to 60 Hz and control system for adjusting the testing conditions. The end of the flexible arm with MFC on the top is clamped to the periodical moving pole in the central point of the harvesting kit while on another end of the flexible arm, a 18 grams of weight is attached in order to keep the constant movement of the flexible arm and constant deforming of the MFC or a constant mechanical energy input condition.

Fig. 5 Tested MFC

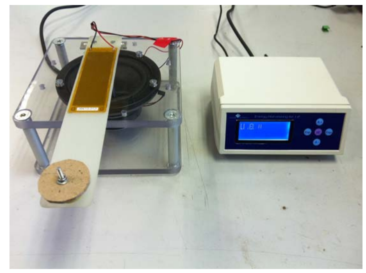

Fig. 6 Energy harvesting kit

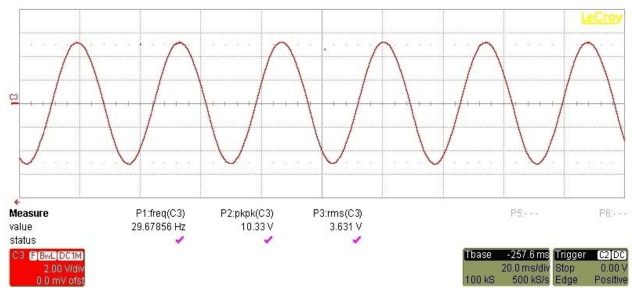

Fig. 7 Measured waveform of output voltage of MFC

C. *Basic characteristics*

The maximum power point at each operating frequency is determined by varying the load resistance in Fig. 1. The amplitude of movement of the shaking pole of the energy harvesting kit is adjusted in order to keep the output voltage from the MFC to be the same 10 Vpeak_peak. Fig. 7 indicates the waveform of the open circuit output voltage across the MFC. With the symmetrical bending of the flexible arm, the MFC is also symmetrically deformed up and down. It is seen that the open circuit voltage of a MFC is a pure sinusoidal function of time, so the voltage source in Fig. 1 could be represented by a usual sinusoidal function too.

In order to verify the effectiveness of the proposed equivalent circuit in Fig. 1, the simulation with the same testing condition such as open circuit voltage from MFC and frequency etc., has been investigated by PSCAD program and the results are compared to the experimental results. Fig. 8 shows the relation between the value of load resistance caused a maximum power point (R_{L_peak}) and frequency. It is found that the simulation results agree well to the experimental results. Furthermore, in the higher frequency region, with the effect from the impedance of capacitance, the value of R_{L_peak} becomes smaller than the value in lower frequency. With the operating frequency limitation of the energy harvesting kit about 60 Hz, the results in the higher operating frequency cannot be determined, therefore the equivalent circuit model

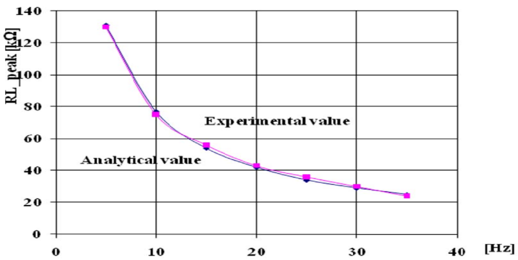

Fig. 8 Relation between R_{L_peak} and frequency (simulated and experimental results comparison)

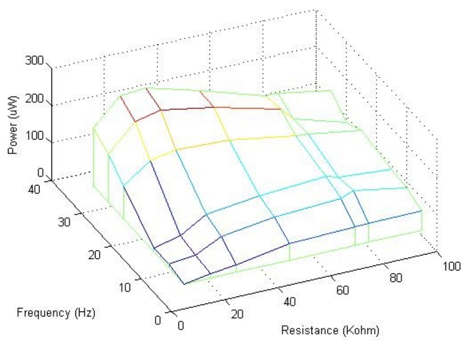

Fig. 9 Relation between R_{L_peak}, frequency and harvested power (experimental results)

will be useful for checking the operation in the other applications which have higher operating frequency.

Fig. 9 shows the relation among load resistance, power and operating frequency. The harvested power is calculated from the measured voltage value by digital oscilloscope and measured value of load resistance directly. It is seen that the higher the operating frequency, the higher the power that could be harvested from the MFC.

D. Internal resistance in capacitor of harvesting circuit

Table I shows the measured value of internal leakage resistance of the capacitor inside the energy harvesting circuit (C_h) as shown in Fig. 2. The Niobium oxide trends to have a larger value of internal resistance. Similarly, the internal resistance of each type of capacitor which have different capacitance value are also measured. From Table II, the internal resistance becomes larger when the value of capacitance is smaller. Finally, the internal resistance of the electrolytic capacitor that has different rating voltage is also measured. Its value will be also varied by the rating voltage.

V. CONCLUSION

The basic characteristics of the MFC piezoelectric has been investigated in this paper by comparison between electrical equivalent circuit based simulation and experimental results. Experiments have been carried out on commercial energy harvesting kit. The condition of maximum power point at each operating frequency was focused. With the effect from impedance of internal capacitor in the MFC, the value of the load resistance that causes the maximum power becomes smaller when the operating frequency becomes higher too. The effect from the capacitor in the harvester circuit is also considered. With the suitable selection of capacitor which has high internal impedance, the energy will be stored effectively with low leakage.

Table I. Measured value of internal resistance in each type of capacitor

Type	Neo Oxide	Electrolytic	Polypropylene	Niobium Oxide
Capacitor / Voltage Rating	4.7μF / 63V	4.7μF / 16V	4.7μF / 250V	4.7μF / 10V
Resistance (MΩ)	10.89	10.00	10.65	11.28

Table II. Measured value of internal resistance in different capacitance

Electrolytic	Capacitor / Voltage Rating	47μF / 100V	4.7μF / 100V	0.47μF / 100V	
	Resistance (MΩ)	8.82	9.34	10.01	
Niobium Oxide	Capacitor / Voltage Rating	47μF / 10V	10μF / 10V	4.7μF / 10V	2.2μF / 10V
	Resistance (MΩ)	9.91	11.27	11.28	12.09
Polyster Film (WIMA)	Capacitor / Voltage Rating	10μF / 63V	10μF / 63V	10μF / 63V	10μF / 63V
	Resistance (MΩ)	9.58	9.84	10.55	10.86

Table III. Measured value of internal resistance for different rating voltage

Electrolytic	Capacitor / Voltage Rating	4.7μF / 16V	4.7μF / 25V	4.7μF / 35V	4.7μF / 100V
	Rresistance (MΩ)	10.00	10.97	10.14	9.34

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