DC/AC Resonant Inverter with Current Limit Resistors for Detecting External Loads of Piezoelectric Resonators

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Abstract **– This paper gives the experimental and implementation results for a DC/AC resonant inverter with current limit resistors for detecting external loads of piezoelectric resonators. For electrical analysis of a given piezoelectric resonator, the equivalent circuit model was evaluated. To generate the high electrical energy required to vibrate a piezoelectric resonator, a modified DC/AC resonant inverter was proposed as an energy supply. For high energy conversion efficiency, the resonance matching algorithm was proposed. The current limit resistor in an inverter circuit makes a monitoring signal representing a status of external loads. Using this monitoring signal, the output energy loss can be detected and compensated by using PWM (Pulse Width Modulation) method. An inverter was implemented using current limit resistors and a dummy inductor. The DC input voltage was 25~30V and the output voltage was a non-sinusoidal AC wave with a peak value of 150V at an operating frequency of 28.675kHz.**

I. INTRODUCTION

The piezoelectric vibration resonator oscillating with its mechanical resonance frequency is based on the mechanical energy generation by ultrasonic vibrations. This energy is obtained by the converse piezoelectric effect which produces a traveling wave on an elastic material generated from AC signal. The supplied voltage wave of a piezoelectric resonator is an AC voltage which frequency is in the vicinity of mechanical resonance frequency. In this aim to get AC current, a conventional DC/AC resonant inverter can be used [1, 2]. However, there are two problems in utilizing this inverter. First, if the inherent capacitive load of a resonator is not eliminated, there always exist power losses due to non-zero phase angle in spite of same AC resonant frequency. Second, under the loaded condition, the power of mechanical vibration seriously decreases.

The objectives of this paper are three-folded, i) to present an analysis of a given piezoelectric resonator, ii) give two solutions about aforementioned problems using current limit resistors for detecting external load, and iii) show experimental results of an implementation.

II. ELECTRICAL ANALYSIS OF A PIEZOELECTRIC RESONATOR

The impedance properties of a piezoelectrically excited resonator can be represented near an isolated resonance by an equivalent circuit model, and the simplest form of that is shown in Fig.1. The static capacitance C_0 in an equivalent circuit represents the electrode capacitance of the resonator. The circuit branch consisting of motional capacitance C_m, motional resistance R_m, and motional inductance L_m is called the motional arm, and describes the specific properties of the resonance [3, 4].

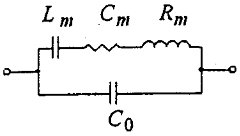

Fig.1 Equivalent circuit of piezoelectric element

To analyze the given piezoelectric resonator [5], we measured its impedance using HP impedance analyzer. Fig.2 shows measured impedance graph.

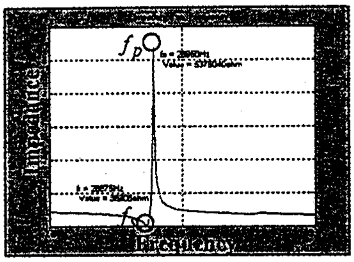

Fig.2 Measured impedance

We can obtain measured values, which correspond to maximum admittance at 28.675*kHz* and maximum impedance at 28.95*kHz*, respectively. These frequencies will be a series resonant frequency f_s and a parallel resonant frequency f_p in an equivalent circuit. From this data graph, following 4 values are obtained.

$$\omega_p = 2\pi f_p = 1.82 \times 10^5 [rad/\sec],\ \omega_s = 2\pi f_s = 1.82 \times 10^5 [rad/\sec]$$

$$|Z|_{\omega=\omega_p} = 53760.4[\Omega],\ |Y|_{\omega=\omega_s} = 2.71 \times 10^{-3} [1/\Omega]$$

The admittance and impedance characteristic of the resonator can be expressed as

$$Y(\omega) = j\omega C_0 + \frac{j\omega C_m}{1 - \omega^2 L_m C_m + j\omega C_m R_m} \qquad (1)$$

$$Z(\omega) = \frac{1 + j\omega R_m C_m - \omega^2 L_m C_m}{j\omega(C_0 + C_m) - \omega^2 C_0 C_m R_m - j\omega^3 C_0 C_m L_m} \qquad (2)$$

The specific frequencies at which the impedance reaches a minimum or a maximum are given with a good approximation by

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{L_m C_m}} \quad (3) \qquad f_p = \frac{1}{2\pi}\sqrt{\frac{C_0 + C_m}{L_m C_m C_0}} \quad (4)$$

The following parameters were calculated in our resonator sing 4 equations (1-4) and 4 values.

$$L_m = 1.25H,\ C_m = 24.7pF,\ R_m = 370.35\Omega,\ C_0 = 1.234nF$$

Ve simulated equivalent circuit model using calculated 4 arameters and showed its results in Fig. 3.

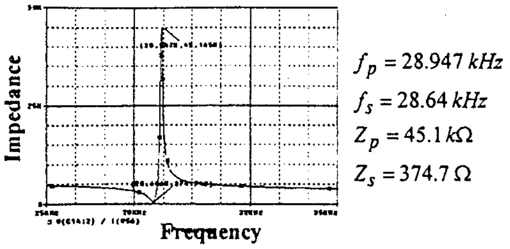

Fig.3 Simulated impedance graph of equivalent circuit model

To show how well this simulated results (Fig.3) fit to the neasured impedance graph (Fig.2), the correlation oefficient ρ was evaluated.

$$\rho_{X,Y} = \frac{COV(X,Y)}{\sigma_X\sigma_Y} = \frac{E[XY]-E[X]E[Y]}{\sigma_X\sigma_Y} = 0.973 \qquad (5)$$

Vhere, $COV(\,)$ is covariance matrix, $E[\,]$ is average value of given variable, σ is variance, and X, Y are variables of neasured and simulated data, respectively. In a sense of ngineering, correlation coefficient 0.973 indicates that two opulations of interest are almost identical.

III. RESONANCE MATHCHING

If the resonator is driven in resonance, even small electric ield strengths suffice to generate large mechanical ibrations. In non-resonant operation, same vibrations equire much higher electric field. Therefore, the frequency f AC driving signal should be tuned to the series resonant requency of piezoelectric elements in order to get a high esonator power. When a driving frequency is equal to series esonant frequency, the equivalent circuit can be simplified s the parallel circuit of motional resistance R_m and static apacitance C_0. This static capacitance C_0 is a part, which nakes imperfect resonance condition due to non-zero phase ngle.

$$Z(\omega_s) = \frac{R_m}{1+\omega_s^2R_m^2C_0^2} - j\frac{\omega_s R_m^2 C_0}{1+\omega_s^2R_m^2C_0^2} = R + jX \qquad (6)$$

Here, X represents reactance component and is not zero. So, phase angle θ is not zero. In this condition, it is ecessary to insert a dummy inductance L_{dummy} with series onnection to the equivalent circuit in order to satisfy perfect esonance conditions. This dummy inductance plays a role to emove the static capacitance C_0 in a R_mC_0 network. Fig. 4 hows the equivalent circuit with the inserted dummy nductance.

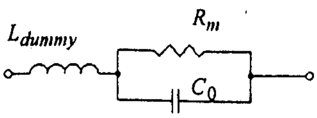

Fig.4 Equivalent circuit model with resonance matching method

The total impedance value of circuit in Fig.5 is

$$Z(\omega) = \frac{R_m}{1+\omega_s^2R_m^2C_0^2} + j\left(\omega_s L_{dummy} - \frac{\omega_s R_m^2 C_0}{1+\omega^2R_m^2C_m^2}\right) \qquad (7)$$

At $\omega = \omega_s$, the phase angle should be zero. Therefore, the calculated dummy inductance value is $0.168\,mH$. This procedure is called resonance matching.

IV. DC/AC RESONANT INVERTER WITH CURRENT LIMIT RESISTORS

A. Configuration and Principle of Operation

To drive a piezoelectric resonator, we need high power AC signal generator. Fig.5 shows a proposed circuit diagram of a DC/AC resonant inverter with current limit resistors. It consists of two MOSFETs (Metal Oxide Silicon Field Effect Transistor) with an anti-parallel diode that would normally allow the negative current to flow when the switch is OFF. Resistor R_{CL} is called current limit resistor, which plays a role to limit excessive current flowing in each switch, and protects the damage of MOSFET. T_{CT} is center-tapped transformer with turns ratio n and load is composed of dummy inductor Z_{dummy} and piezoelectric resonator. $i_{S1}(t)$ and $i_{S2}(t)$ are current flowing each current path in each half period and can be expressed as

$$i_{S1}(t) = \begin{cases} i_1(t), & for\ 0 < \omega t \le \pi \\ 0, & for\ \pi < \omega t \le 2\pi \end{cases},\quad i_{S2}(t) = \begin{cases} 0, & for\ 0 < \omega t \le \pi \\ i_1(t), & for\ \pi < \omega t \le 2\pi \end{cases} \qquad (8)$$

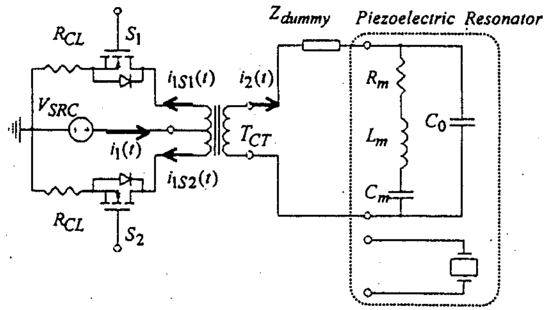

Fig.5 Circuit diagram of DC/AC resonant inverter with current limit resistors

When switch S_1 is OFF and S_2 is ON, the DC V_{SRC} input current $i_1(t)$ flows through switch S_2 and the bottom winding of transformer becomes primary. Hence, the current $i_2(t)$ through the piezoelectric resonator is $-i_1(t)/n$, where n is the transformer turns ratio N_2/N_1. On the other hand, when S_1 is ON and S_2 is OFF, the DC input current $i_1(t)$ flows through switch S_1 and the upper winding of the transformer becomes primary. Thus, the secondary current $i_2(t)$ is $+i_1(t)/n$. Therefore, in the secondary part, the driving voltage $v_2(t)$ can be represented by

$$v_2(t) = \begin{cases} +nV_{SRC}, & for\ \ 0 < \omega t \le \pi \\ -nV_{SRC}, & for\ \ \pi < \omega t \le 2\pi \end{cases} \qquad (9)$$

B. Detection of External Load using Current Limit Resistors

The operating piezoelectric resonator is seriously affected by external load, which reduces output power. When the user makes an external load by abrading the resonator with any object, the driving system has to compensate the power of resonator. For detecting external loads in a piezoelectric resonator, the current limit resistor can be used. This resistor R_{CL} makes the monitoring signal indicating the external load as well as prevents the damage of MOSFET. Under loaded conditions, the output power always varies due to resistance change inside a resonator. We can find this variation of output resistance by using the DC value of current flowing through resonator. This DC value is very sensitive to the resistance because of high quality factor (Q) value of resonator. If a resonator is unloaded, DC value is relatively high level, otherwise, it is low level. This value can be detected from voltage across the current limit resistor and is called monitoring signal $m(t)$ and is defined as

$$m(t) = m_1(t) + m_2(t) = K_s \cdot | i_1(t) | \qquad (10)$$

Here, $m_1(t)$ and $m_2(t)$ is voltage signal across current limit resistor R_{CL} in each current path in the inverter. K_s is a scaling factor that transforms current into voltage and $i_1(t)$ is AC-current that flows into transformer. The flowing current is not perfect rectangular shape since piezoelectric resonator carry only fundamental and some harmonics of generated rectangular signal. The simple RC network circuit obtains DC value of monitoring signal $m(t)$. We define this DC value of $m(t)$ as $m_{DC}(t)$ and it is represented as

$$m_{DC}(t) = \frac{1}{T_s}\int_0^{T_s} m(t)dt \qquad (11)$$

In Equation (10), K_s is proportional factor between voltage $m(t)$ and current $i_1(t)$. Therefore, we can replace K_s into current limit resistor value R_{CL}.

If an external load exists, the amplitude $m_{DC}(t)$ will be reduced. The primary current $i_1(t)$ is reflected from secondary current $i_2(t)$. Therefore, we can use the monitoring signal to detect the external load and its analysis provides us with load information. However, it is difficult to identify a specific loaded and unloaded state because the quantity of flowing current is always relative. Although the output power seems to be high, it is possible for the flowing current of resonator to have low value. Since the vibration fiction increases the temperature, this temperature variation also changes the internal resistance. To specify the loaded and unloaded condition, we apply to an average filter to a DC monitoring signal. The unloaded condition shows almost constant $m_{DC}(t)$ regardless of its amplitude. On the other hand, an external load makes a sudden drop down $m_{DC}(t)$. In this case, if the monitoring signal is subtracted from the average filtered signal, we can obtain the indication signal, which means time instances of the occurring external load. Fig.6 shows a block diagram to detect external load.

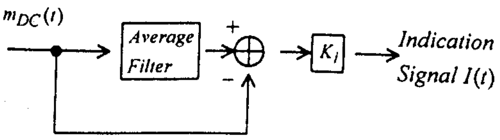

Fig.6 Indication signal of loads

The indication signal $I(t)$ is obtained by

$$I(t) = K_i \cdot [Aveage\{m_{DC}(t)\} - m_{DC}(t)] \qquad (12)$$

Where, K_i is a scaling factor whose value is high enough to increase non-zero value of the subtraction between $Average\{m_{DC}(t)\}$ and $m_{DC}(t)$. If the result of subtraction is less than $1V$, signal $I(t)$ will be nearly zero. Two cases indicate the loaded and unloaded conditions, respectively.

$$if \quad I(t) = 5V, \quad Load\ exists$$
$$if \quad I(t) = nearly\ 0V, \quad Load\ does\ not\ exist$$

According to the indication signal, we can compensate the power loss caused by external load. If the external load is detected, the duty cycle has to be 100%. On the other hand, if any load does not exist, the duty cycle is determined by user input below 100%. Table.1 can represent this process.

Load	**Duty Cycle**
Not Exist	User Control Duty Cycle (20% ~ 50%)
Exist	100%

Table.1 Duty cycle change table

V. IMPLEMENTATION AND EXPERIMENTAL RESULTS

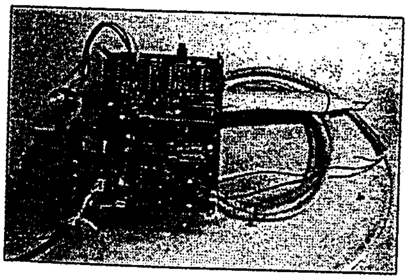

Fig.7 Implemented system

Fig.7 shows the picture of implemented system. It includes the common AC24V input transformer and DC/DC transform circuit. The system requires DC30V, DC12V and DC5V. The voltage regulators provide ICs with stable DC voltages. We can expect that waveforms of current $i_1(t)$ depend on the switching frequency. According to the switching frequency, the current flowing through each path of inverter may begin or end at different time. Improper switching time causes switching loss (Fig.8). Fig.9 shows DC monitoring signal $m_{DC}(t)$ obtained from voltage across current limit resistor. Its level depends on an external load. To identify the unloaded condition by using $m_{DC}(t)$, its magnitude has to be kept on average value. When the average filtered signal is greater than $m_{DC}(t)$, we can say that the external load occurs. Fig.10 shows DC monitoring signal $m_{DC}(t)$ and its average filtered signal. Fig.11 shows the detected load using indication signal. This signal changes the duty cycle of driving signal using PWM (Fig.12).

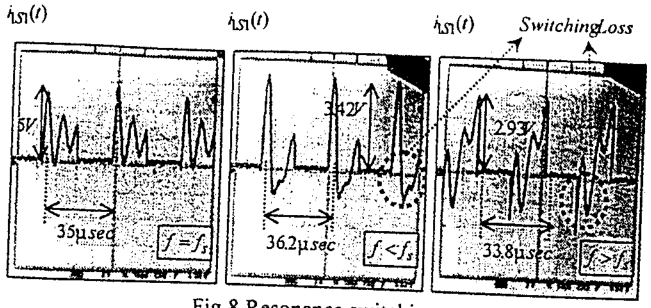

Fig.8 Resonance switching

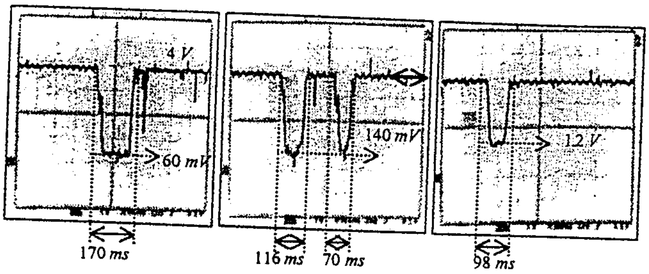

Fig.9 $m_{DC}(t)$ under various external loads

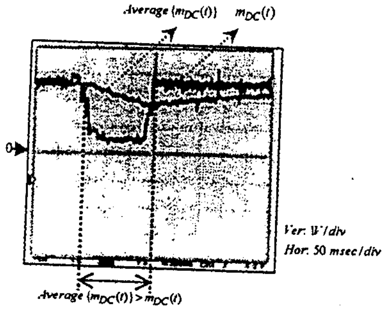

Fig.10 Average filtered signal

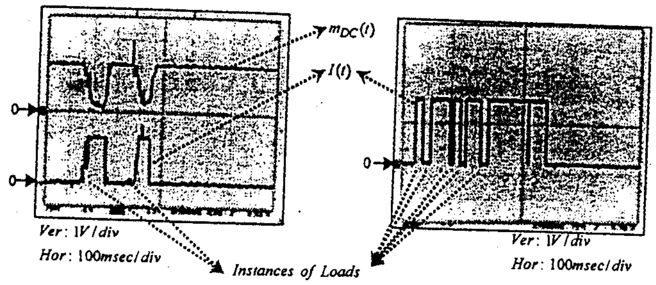

Fig.11 Load indication signal

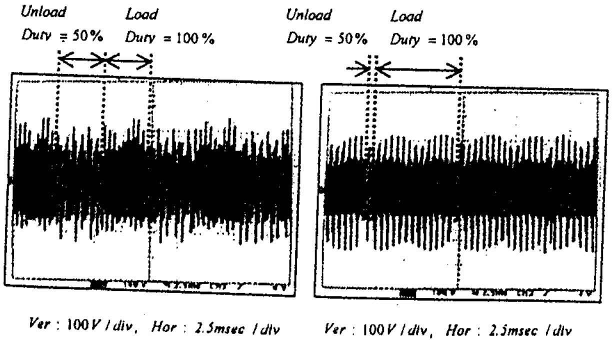

Fig.12 Power compensation by increasing duty cycle

VI. CONCLUSIONS

A modified DC/AC resonant inverter was proposed for driving a piezoelectric resonator and demonstrated by implementation. Since a piezoelectric resonator has its static capacitive load, we have to insert an inductive component to make perfect resonance condition. For detecting external loads, the current limit resistor is positioned in each current path of the inverter to make monitoring signal. This signal indicates external load as well as prevents the damage of switching device MOSFET. The whole system includes two MOSFETs (IRF630), two current limit resistors 5.6Ω and a center-tapped step-up transformer with turns ratio 1:5. The input voltage was DC25V~30V and the output was an AC signal with driving frequency $28.6\,kHz$ and peak value of 100V~150V. The variation of monitoring signal caused by external loads, and the load indication signal are obtained experimentally. They compensate power losses using PWM technology. Further details of the analysis and operation are mentioned in [7].

VII. ACKNOWLEDGMENTS

This work was supported in part by the Ministry of Education (MOE) through the Brain Korea 21 (BK21) project.

VIII. REFERENCES

[1] M. K. Kazimierczuk, "Class D Voltage-Switching MOSFET Power Amplifier," IEEE Trans. Solid-State Circuits, vol. 138, no. 6, pp. 285-296, Nov. 1991.

[2] M. K. Kazimierczuk, "Current-Source Parallel-Resonant DC/AC Inverter with Transformer," IEEE, pp. 275-284, Mar. 1996.

[3] Standards Committee of the IEEE, *An American National Standard: IEEE Standard on Piezoelectricity,* IEEE, ANSI/IEEE Std. 176, Mar. 1987.

[4] M. Schmid, E. Benes, W. Burger, and V. Kravchenko, "Motional Capacitance of Layered Piezoelectric Thickness-Mode Resonators," IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 38, no. 3, pp. 199-206, May 1991.

[5] M. Crivii, and M. Jufer, "Driver Circuit for Piezoelectric Motor," European Power Electronics Association, pp. 453-457, 1993.

[6] P. Emanuel, *Motors, Generators, Transformers, and Energy,* Prentice Hall, Inc., 1985.

[7] M. Chae, *Implementation of a DC/AC Resonant Inverter Circuit for Driving Piezoelectric Resonators,* M.S. Dissertation, Dept. of Information and Communications, Kwangju Institute of Science and Technology, June 2000.