'87 韓國自動制御學術會議論文集 1987. 10.16~17

A NEW ULTRASONIC POWER GENERATOR USING INSTANTANEOUS CURRENT RESULTANT CONTROL-BASED INVERTER AND ITS CONTROL SYSTEM

Kim,Donghee* Kim,Youngseok Yoo,Dongwook Kim,Yohee

KOREA ELECTROTECHNOLOGY RESEARCH INSTITUTE (KERI)
POWER ELECTRONICS LAB.

Abstract

The design of ultrasonic transducer energy processing systems requires highly reliable command featuring mechanical frequency tracking and constant velocity control of the ultrasonic transducer with an acoustic load. This paper presents a new conceptional instantaneous current resultant control base high-frequency inverter using self turn-off devices driving an electrostrictive ultrasonic transducer system and its optimum control technique, which is implemented by feedback of the ultrasonic transducer applied voltage and instantaneous velocity of the transducer vibrating system through a Phase-Locked-Loop control scheme.

The feedback voltage corresponding to instantaneous velocity is averaged over a half-period with respect to constant amplitude/constant velocity control strategy. Described are the theory of this signal detection technique and the experimental set-up.

1. Introduction

Recently, high speed thyristors, power transistors and various new type of semiconductor devices have been developed in the industrial fields.

In static high-frequency inverter technology suitable for ultrasonic transducer equipment applications, conventional configuration using thyristors are being upgraded by the utilization of self turn-off devices such as Bipolar Transistors, Power MOSFETs, SIT etc.

High power ultrasonic electrostrictive transducers of more than 1KW require highly reliable control strategy with adaptive tracking of the mechanical transducer resonant frequency. The use of high-frequency inverters applicable for driving electrostrictive transducers guarantee high-efficiency as well as high output level, but problems arise because the electrostrictive transducer characteristics or the high frequency inverter load vary greatly with the transducer vibration amplitude, influencing strongly the mechanical work energy conversion efficiency; a wrong control mode pattern may even lead to break the mechanical energy transmission systems including the ultrasonic transducers.

2. System Description of Inverter Type Ultrasonic Generator

Figure 1(a) shows the typical circuit configuration of a Voltage-Fed resonant inverter using self turn-off devices.

Figure 1(b) shows the various steady-state operation modes obtained in the high frequency inverter shown in Figure 1(a).

.Mode(a): Switching frequency is

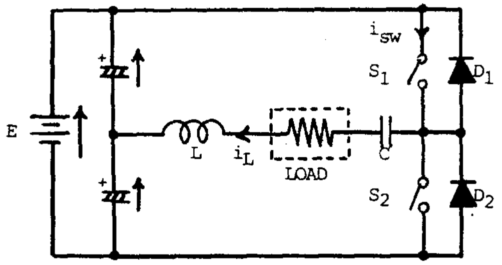

Figure 1(a). Voltage-Fed Series Resonant High-Frequency Inverter.

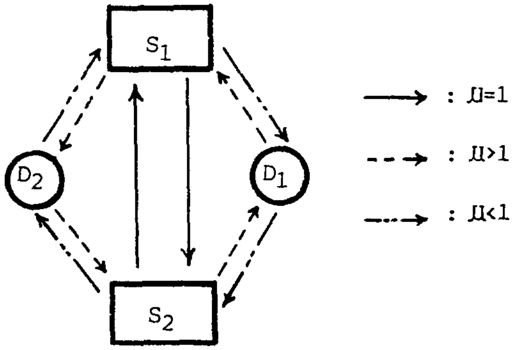

Figure 1(b). Steady-State Operation Mode Classification.

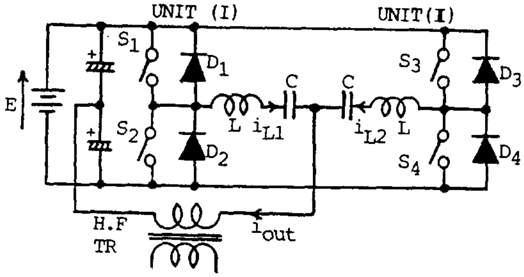

Figure 2. Proposed Instantaneous Current Resultant Cotrol-Based Resonant High-frequency Inverter.

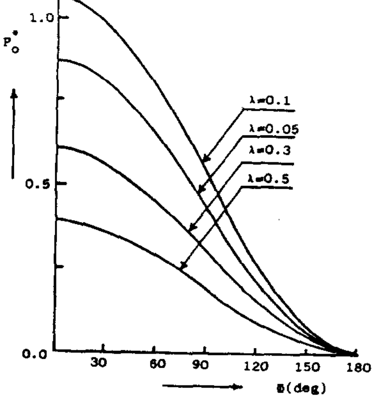

Figure 3. Output Power vs. Phase Angle Φ.

indential to the natural resonant frequency, i.e.

i_{sw}^{+0} at t=0 is null.

Mode (b): Switching frequency is higher than natural resonant frequency ,i.e. i_{sw}^{+0} at t=0 is negative.

Mode(c): Switching frequency is lower than natural resonant frequency ,i.e. i_{sw}^{+0} at t=0 is positive.

Figure 2 shows the inverter circuit newly proposed which is a combination of two resonant inverters represented in Fig. 1(a) connected to the same input DC voltage source; output current is given as the resultant phasor difference of individual resonant branch current.

Output power is therefore depending on the phase-shift angle value between unit inverter drive signals, allowing VVVF control. This inverter makes use of the latest SIT allowing high frequency high power conversion.

Fixing the normalized frequency value at μ=1.1(μ: L-C circuit resonant frequency / Switching frequency), the output normalized power is plotted in Fig. 3 where the phase angle Φ varies from 0^o to 180^o with the normalized load $\lambda = R/Z_s$ as a parameter, emphasizing the capability of total output power control when Φ is increased from 0^o(full output power) until 180^o(no power). Output current distortion factor versus phase angle shifting Φ is shown in Figure 4, demonstrating that phase shifting control technique does

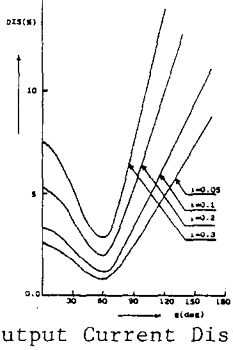

Figure 4. Output Current Distortion factor versus Phase Angle Φ

not penalize the output waveform distortion factor which can be kept low especially at higher power output level.

3. Analog Processing Sensor of Ultrasonic Transducer Velocity

3.1 Generalities

When driving directly an ultrsonic transducer system, the control circuit must both track the resonant frequency of the transducer and keep it at constant velocity. The purpose of the mechanical resonant frequency tracking system is to match optimally the inverter frequency with that of the mechanical ultrasonic transducer. The electrical, mechanical, and acoustic energy conversion efficiencies are best at the mechanical resonant frequency operation, as the losses generated by the ultrasonic transducer systems are the smallest and the mechanical work is most powerful.

This mechanical resonant frequency is however subject to varying factors as the transducer acoustic load, its temperature and the supplied operating power level, emphasizing the need for a fast-response resonant frequency tracking system.

Thus, the control processing command must include special sensors of which output is proportional to either the transducer.

3.2 Magnetostrictive Ultrasonic Transducer Sensor

Shown in Figure 5 is a detection circuit which provides an output proportional to the instantaneous velocity of the ultrasonic transducer. Using the notation in Figure 5, we can obtain,

$$\dot{V}_L = \frac{j\omega L\dot{I}}{P} \qquad (1)$$

$$\dot{V}_N = \frac{j\omega L_d}{N}\dot{I} + \frac{\dot{A}\dot{v}}{N} \qquad (2)$$

Subtracting Equation (1) from Eq.(2),

$$\dot{V}_p = \dot{V}_N - \dot{V}_L = j\omega\left(\frac{L_d}{N} - \frac{L}{P}\right)\dot{I} + \frac{A\dot{v}}{N} \qquad (3)$$

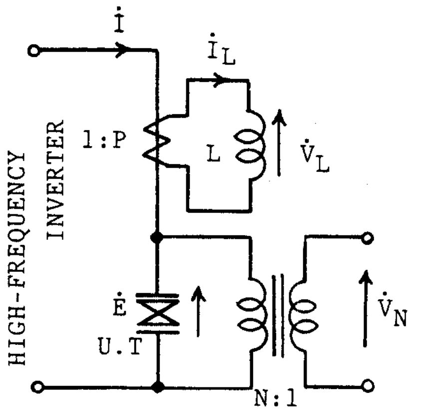

Figure 5. Detection Circuit of Magnetostrictive Transducer Velocity.

Values of P and N are chosen such that,

$$(L_d/N) - (L/P) = 0 \qquad (4)$$

Eq.(3) becomes,

$$\dot{V}_p = (\dot{A}\dot{v}/N) \qquad (5)$$

The fundamental equations of the magnetostrictive ultrasonic transducer are:

$$\begin{aligned} \dot{E} &= \dot{Z}_d\dot{I} + \dot{A}\dot{v} \\ \dot{F} &= -\dot{A}\dot{I} + \dot{Z}_b\dot{v} \end{aligned} \qquad (6)$$

Replacing $\dot{F} = -\dot{Z}_a\dot{v}$ in Eq.(6), we obtain:

$$\dot{v} = \frac{\dot{A}}{|\dot{Z}_a + \dot{Z}_b|} e^{-j\phi}\,\dot{I} \qquad (7)$$

Assuming $\dot{A}$ is real number, Eq.(5) becomes:

$$\dot{V}_p = \frac{A^2}{N}\frac{\dot{I}}{|\dot{Z}_a + \dot{Z}_b|} e^{-j\phi} \qquad (8)$$

Eq.(8) dictates the control method of the inverter, requiring the $\dot{V}_p$ and $\dot{I}$ to be in phase.

3.3 Electrostrictive Ultrasonic Transducer Sensor

Shown in Figure 6 is a simple detection circuit which provides an output voltage proportional to the instantaneous velocity of the ultrasonic power transducer. The voltage $\dot{V}_c$ across the secondary of the current transformer C.T. is function of the turn ratio P and of the value of the capacitor as expressed in equation (9):

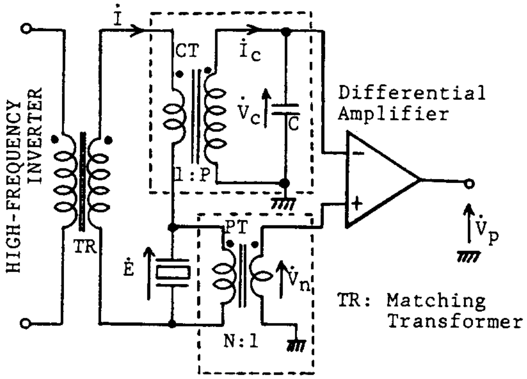

FIgure 6. Detection Circuit of Electrostrictive Transducer Velocity.

$$\dot{V}_c = \frac{Cd}{CP}\dot{E} + \frac{A\dot{v}}{j\omega CP} \qquad (9)$$

Where,

$\dot{E}$: terminal voltage of ultrasonic transducer

C_d: damping capacitor value

A : force factor

$\dot{v}$: instantaneous vibration velocity

: angular frequency of electrical power source

Next, the voltage $\dot{V}_n$ across the potential transformer P.T. of turn ratio N is $\dot{V}_n = \dot{E}/N$; $\dot{V}_n$ and $\dot{V}_c$ is the input of differential power amplifier of which the output is amplified by factor K.

We obtain,

$$\dot{V}_p = K\left(\frac{Cd}{CP} - \frac{1}{N}\right) + \frac{KA\dot{v}}{j\omega CP} \qquad (10)$$

Let us take $C_d/C_p=1/N$ in order to cancel the left hand term in Eq.(10),

$$\dot{V}_p = \frac{KA}{j\omega CP}\dot{v} \qquad (11)$$

If KA/ C_p is real number, its value does not have any effect of the phase of $\dot{V}_p$ and $\dot{v}$; thus, a phase of $\dot{V}_p$ is 90^o lagging with respect to the phase of $\dot{v}$.

$\dot{V}_p$ obtained from Eq.(11) is then a signal proportional to the instantaneous velocity of the ultrasonic transducer.

The fundamental equations of the electrostrictive ultrasonic transducer in electrical, acoustic and mechanical terms are;

$$\begin{aligned}\dot{F} &= -A\dot{E} + \dot{Z}_b\dot{v}\\ \dot{I} &= \dot{Y}_d\dot{E} + A\dot{v}\end{aligned} \qquad (12)$$

where: $\dot{Z}_b$: mechanical impedance

$\dot{Y}_d$: damping admittance

From Eq.(12), the realtionship between the ultrasonic transducer velocity $\dot{v}$ and its terminal voltage $\dot{E}$ is,

$$\dot{v} = (A/|\dot{Z}_a+\dot{Z}_b|)e^{-j\phi}\dot{E} \qquad (13)$$

where, Z_a : acoustic impedance

Rewriting the Eq.(11) using Eq.(13) yields,

$$\dot{V}_p = \frac{KA^2}{CP(|\dot{Z}_a + \dot{Z}_b|)} e^{-j(\frac{\pi}{2} + \phi)} \dot{E} \qquad (14)$$

The phase angle value between $\dot{V}_p$ and $\dot{E}$ is given by the term $\exp(-j(\pi/2+\phi))$.

In order to track the ultrasonic transducer at its resonant frequency, the high frequency inverter is adaptably driven such a control strategy that the detected voltage $\dot{V}_p$ always keeps 90^o lag with the transducer terminal voltage $\dot{E}$.

3.4 Velocity Control of Ultrasonic Transducer

As can be seeing from Eq.(10), if the inverter output frequency slips by a small amount, the effect of ω on $\dot{V}_p$ is very small so the term $KA/CP\omega$ can be assumed to be constant. Now, let us assume that the transducer velocity $\dot{v}$ is sinusoidal, that is $\dot{v} = v_a \sin\omega t$ and compute the average of $\dot{V}_p$ over a half-period is given by,

$$V_{pm} = (2KAV_a/\omega CP) \qquad (15)$$

By maintaining V_{pm} constant in Eq.(15), v_a becomes costant allowing the control of the transducer vibration speed $\dot{v}$ at a fixed value.

4. Power/Frequency Adaptive Control

4.1 Drive Signal Generating Circuit

Figure 7 illustrates the block diagram of the phase shifting control circuit (control block I) and mechanical resonant frequency tracking control circuit(control block II). Control block I generates the phase-shifted MOSFET drive signals synchronized by a Phase Locked Loop(PLL)

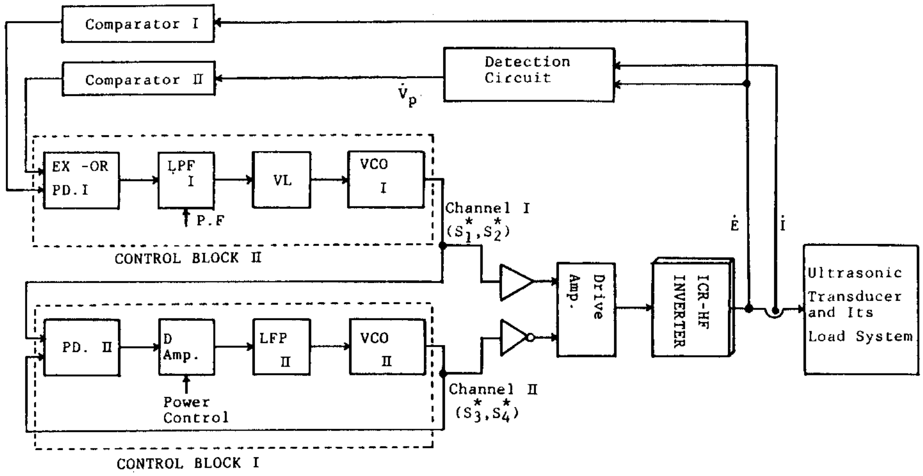

Figure 7. Block Diagram of Signal Generator for Phase-Shifting Angle and Resonant Frequency Tracking Control System.

circuit. Channel I transmits the reference drive signals $S_1^*(S_2^*)$ and Channel II carries the shifted signals $S_3^*(S_4^*)$ for power control.

4.2 Mechanical Resonant Frequency Tracking Control

The frequency control procedure explained above is concretely realized using a Phase-Locked-Loop control circuit to command the inverter output frequency.

The mechanical resonant frequency tracking controller(CONTROL BLOCK II) is represented in Figure 7. Applied voltage and current of transducer system are fed back through the detection circuit into a phase detection which is part of the frequency control phase locked loop. Whole system is locked when transducer voltage $\dot{E}$ is in quadrature phase relation between $\dot{V}_p$.

Plotted in Figure 8 is the phase relation between $\dot{V}_p$ and $\dot{E}$.

The control block II operation is now explained when the load characterstics change: if the inverter frequency is higher than the resonant frequency of the transducer f_r as for point "b" in Fig.8, the phase between $\dot{V}_p$ and $\dot{E}$ becomes higher then 90^o, increasing the Phase Detector (PD.I) output voltage. This voltage polarity is inverted by Low Pass Filter (LPF I), then throgh the Voltage Controlled Oscillator(VCO I) drives the inverter at a lower frequency. The inverter operating frequency will finally reach the stable point "a" corresponding to the mechanical resonant frequency of the transducer.

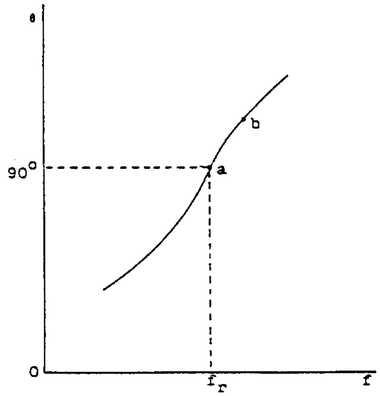

Figure 8. Phase Relation between $\dot{V}_p$ and $\dot{E}$

5. Conclusions

The compulsory features of the adaptive electrostrictive ultrasonic transducer power controller which includes new type of high frequency resonant inverter using MOSFETs have been explained and verified from an experimental point of view. The instantaneous velocity detection circuit of two transducer systems in order to track the transducer mechanical resonant frequency has been analyzed and its practical implementation has also been demonstrated concretely presented.

The control scheme which consists of a Phase-Locked-Loop strategy including the MOSFET inverter and using the mechanical velocity detection circuit has been described in detail.

A promising semiconductor ultrasonic power generator with a highly effecient electro-mechanical and acoustic energy conversion, as well as extremely stable operation of the ultrasonic transducer equipments even in various acoustic loads were ascertained with the experimental work.

References

1). Kazumi Sano, Hatuso Morishita:"Ultrasonic Oscillation by using Power SIT" ,Tokin Techical Review,Vol.9, No.1,(1983)

2). L.Jack Smith:"Use of Phase-Locked-Loop Control for Driving Ultrasonic Transducer",NASA TN D-3567, August(1966)

3). Someshwar Gupta:"Phase-Locked-Loop", Proceeding of the IEEE,Vol.63, No.2,February,pp.291-303(1975)

4). Hiroshi Shimizu, Shigemi Saito:" Methods for Automatically Tracking the Transducer Resonance by Rectified Voltage Feed Back to VCO", Faculty of Engineering, Tohoku Uni. US 78-37 (1978)