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Research Article

RESONANT FREQUENCY TRACKING CONTROL BY IZL (INTEGRATED ZERO LOOP)

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ABSTRACT
This paper presents a novel resonant frequency tracking control method for the full bridge type high frequency inverter. The proposed method uses only one ac current transformer though a general PLL as a frequency control method uses 2 current or potential transformers. Furthermore, the high frequency inverter system does not need to employ an active converter to control the DC bus voltage for the output power regulation although the inverter system using PLL has to have an active converter.
Accordingly, the inverter that installs the proposed control method can control the operation frequency adequate and regulate the output power by one converter system. Hence, the high frequency inverter that is used for changing reactance load like an induction heating load can be simplified by introducing the proposed frequency control method. He operation principle is illustrated with a sample of block diagram. Simulation is implemented to estimate the control method and its results shoe a good performance for tuning the operation frequency to the resonant frequency. In addition, the control method is installed in an actual inverter for high power induction heating application. Observed and measured results verify the performance of the proposed frequency control method.

***Keywords**: Esonant Frequency IZL, Integrated Zero Loop, High Frequency Control*

INTRODUCTION
Phase shift-PWM full bridge inverter (figure 1) achieves a soft switching state by tuning the operation frequency at the resonant frequency (Hiroyasa *et al.,* 2004). Its power can be regulated from a rated power to several % while the soft switching state is kept and the operation frequency is fixed.
Operating the inverter at the resonant frequency leads that the output total power factor of the inverter is close to 1, which reduces conduction loss in the switching devices and the passive components that is accrued by the reactive current. In general, PLL (phase locked loop) as a resonant frequency tracking control method is utilized for tuning the operation frequency at just or close to the resonant frequency (Atushi *et al.,* 2007; Mu-Ping *et al.,* 2001).

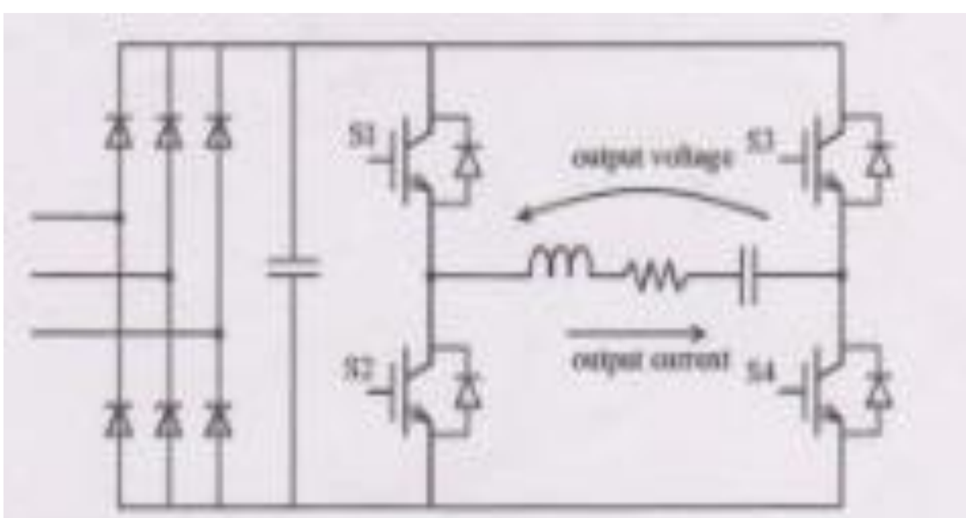

Figure 1: Full bridge inverter with series load resonant circuit

PLL controller consists of two zero-cross detectors, a compartor, and an oscillator. Zero cross detectors observe the zero cross points of the voltage and current of the passive components in main frequency so that the phase difference is measured. The oscillator maintains the inverter operation frequency so that the phase difference is fixed to constant or zero. PLL controller is convenient because a number of PLL controller ICs has been supplied by lots of supplier. It is necessary to pay attention that a noise in detected voltage and current might affect a performance of zero cross detector.

However PLL a frequency control method interferes with phase shift-PWM as a power regulation method, because the principle of PLL is to fic the phase of output voltage and current although phase shift-PWM changes the phase to regulate the output power.

PLL and shift-PWM are not compatible in a control method scheme of high frequency power source uses the combination of PLL and PAM control. In these cases, the system needs to have not an inverter but also a buck chopper or an active AC-DC converter. The high frequency inverter is controlled on PLL principle and its frequency keeps in the resonant frequency. The buck chopper or the active AC-DC converter performs PAM function to regulate power by changing DC bus voltage to the high frequency inverter. It is so called a 2-converter system and it tends to be bulky and heavy. The power loss on the switching devices increases inevitably because the number of active switching devices such as thyristor or IGBTs in the PAM controlled converter.

To simplify his inverter system, CTBL (conduction time balanced loop) as a frequency control method has been presented (Hiroyasu *et al.,* 2004). CTBL provides the resonant frequency tracking control function same as PLL for phase sift-PWM high frequency inverter, CTBL controller consists of two current detectors for switching devices that is used in the high frequency inverter, a comparator, and an oscillator. CTBL scheme uses not information of phase or zero –cross point of output voltage and output current but the time length that the current flows through the switching devices. The oscillator maintains the inverter operation frequency so that two measured time length become in balance with same length. As a result, the inverter can operate at just the resonant frequency.

In other words, the phase difference of output current to output voltage caused by the power regulation of phase shift-PWM and the resonant frequency tracking control by CTBL are compatible in one high frequency inverter. Then the buck chopper or the active AC-DC converter for power regulation can be omitted.

But CTBL scheme needs to observe the current flowing through power switches, and a couple of hall-effect sensors have to be installed between the DC bus to the power switch. Thus there are problems that stray inductance in series with the power switch increases inevitably. This stray inductance enlarges the voltage stress across the power devices and increases switching loss. In addition, hall-effect sensors are expensive compared with CT. To improve them this paper presents a novel resonant frequency tracking control method by using just one AC current transformer for phase shift-PWM high frequency inverter.

Principle of Novel Resonant Frequency Tracking Control Scheme

The proposed resonant frequency tracking control scheme focuses attention on the output current same as PLL. Figure 2 shows the each waveforms of phase shift-PWM full bridge inverter with a series resonant circuit when the inverter operates at the resonant frequency. The current doesn't include DC component because the series resonant circuit has a series capacitor. vg1 to vg4 are gate pulse signal for s1 to s4. The output current waveform is assumed as a sinusoidal waveform because it flow through the resonant circuit. The wave form of the output voltage has 2 level.

It can be confirmed that an integral value of the output current when the inverter outputs zero voltage becomes zero (refer figure 2 a). And it is same in any duty of the power regulation if the output current is sinusoidal waveform (see figure 2 b).

On the other hand, the output current phase becomes lead when the inverter operation frequency is lower than the resonant frequency (figure 3 a).

In this condition, the integration value of the output current becomes negative. Conversely, the integration value of current becomes positive when the operation frequency is higher than the resonant frequency (figure 3 b). The current phase becomes delay.

a. ***Higher Power***

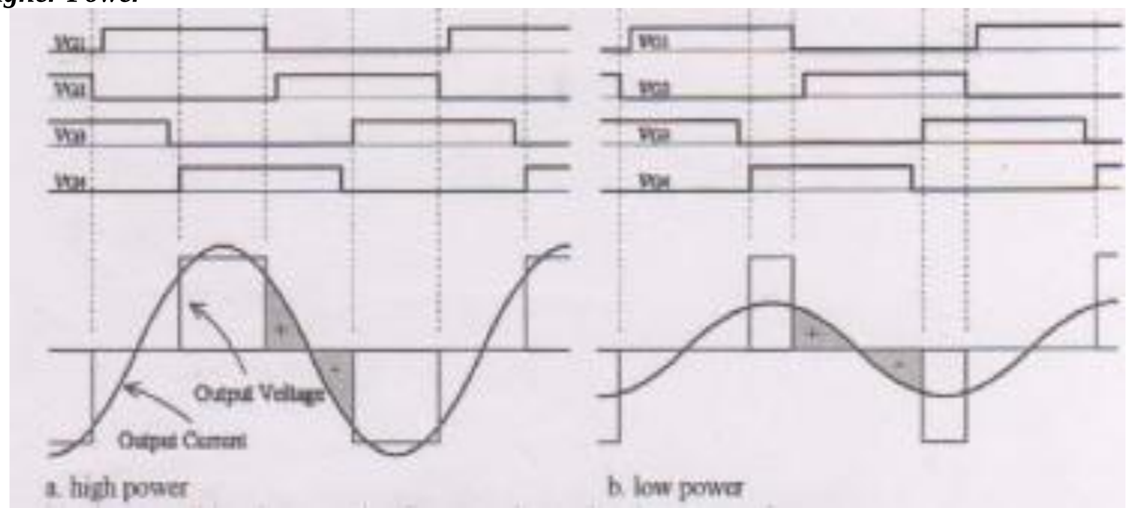

Figure 2: A condition that operation frequency is tuned to the resonant frequency

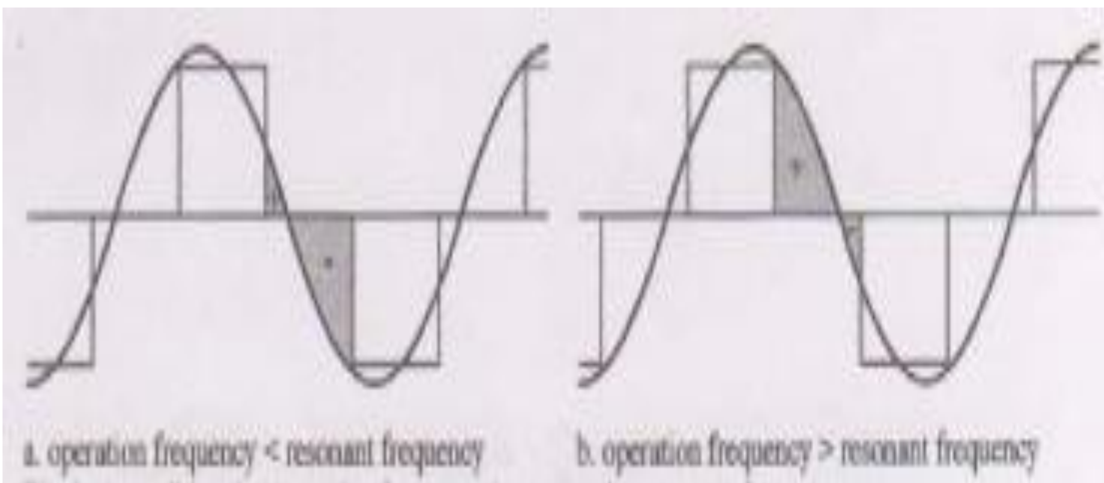

Figure 3: A condition that operation frequency is not tuned to the resonant frequency

From these considerations, the integration value of the output current in a period that the inverter outputs zero voltage can be used as information for controlling operation frequency. It is clear that the inverter can track the resonant frequency while the operation frequency is controlled so that the integration value becomes zero. The period that the inverter outputs zero voltage is known by the gate signal vg1 and vg3. Therefore only AC current transformer is necessary to implement this integration zero loop (IZL) for tracking the resonant frequency. Figure 2 tells that IZL as the tracking resonant frequency scheme can be compatible with sahift-PWM as the power regulation method in one high frequency inverter.
Furthermore, IZL has a possibility to be robust than PLL because zero cross detectors are not used for the control method.

Frequency and Power Controller

Figure 4 shows the block diagram of inverter's controller including both the proposed frequency regulator IZL and the power controller PS-PWM. Each function is described as follows.

Power Controller

The inverter output power is controlled by phase shift-PWM. This gate pulse modulation is applied to the gate pulse signals for s3 and s4. The dead time is given to all gate pulse signal s1 to s4 in order to prevent short of each bridges.

Frequency Controller

1) To start the inverter operation, an initial voltage is given to the frequency controller in short period. The VCO (voltage controller oscillator) starts to oscillate and its frequency becomes the inverter operation frequency at a start-up condition.
2) The output current waveform is obtained by the AC current transformer and it is converted to low voltage waveform.
3) A NOR gate receives the gate pulse signal for s3 and s1. The NOR gate outputs high level in the period that the inverter outputs zero voltage.
4) The waveform signal input into a bi-directional switch. The bi-directional switch is controlled by and output of the NOR gate. The bi-directional switch chops off the waveform signal in a duration that the NOR gate outputs los level.
5) The taken out signal by the bi-directional switch is integrated.
6) A sample old circuit keeps the level of integrator's output voltage. If the voltage of the sample hold circuit is positive, the inverter operation frequency should be higher than a previous state. On the contrary, if the voltage is negative, the controller makes the operation frequency lower frequency.
7) The hold timing is determined at the end of vg3,
8) The VCO oscillates the operation frequency. The frequency is controlled by the input voltage is tuned to the resonant frequency by a gradual process.

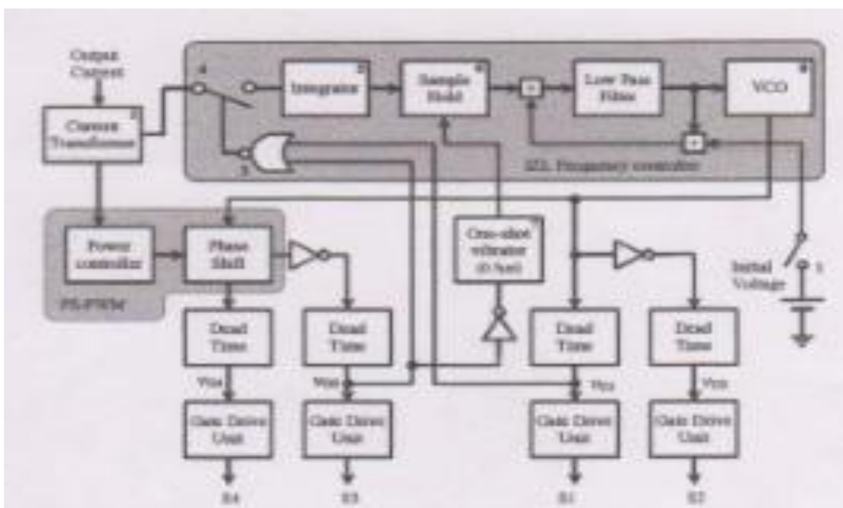

Figure 4: Block diagram of frequency and power controller

Estimation Using Simulation

To estimate the proposed frequency control method IZL, the simulation was implemented by using software PSIM in a condition shown in table 1. A main circuit consists of a rectifier that converts 3-phase utility voltage to DC bus voltage, a DC bus voltage, a DC bus capacitor, IGBTs (ideal devices) man inductive load as an induction heating load, and a series resonant capacitor.

Table 1: Condition

3-phase utility voltage	**200v**	**DC bus capacitance**	**3mf**
Series resonant capacitance	1.5mf	inductance	36mh~52mh
Load resistance	1,75mf	Intial operation frequency	19,6KHz

Equivalent load resistor and the equivalent inductor. This high frequency inverter controlled by IZL and PS-PWM is assumed to be applied to a large induction heating cooker for business use. It is well and known that the equivalent inductance changes with temperature of the heated material. Therefore, the resonant frequency is changed from 18.0 KHz to 21.7 KHz by changing the inductance in this simulation the inductance is changed 2Mh by 2Mh from 52mh to 36 mh.
Figure 5 shows a simulation results. The inductance changes 2mh per 1ms. As a result, the resonant frequency is also changed and is shown as the gray line. A black line indicates the operation frequency controlled by IZL. Actual equivalent inductance doesn't change so drastically and rapidly.
Accordingly, it is clear that IZL has enough performance to tune the operation frequency at the resonant frequency for the induction heating applications.

Figure 5: Tracking the changing resonant frequency

Furthermore the power factor of the inverter output side is researched by the simulation. There is no regulation about the power factor on the inverter's output side. However, It is expected that the conduction losses can be decreased on each semiconductor devices and other components in main circuit when its power factor is high. Figure 6 indicates the simulation results about the total power factor.

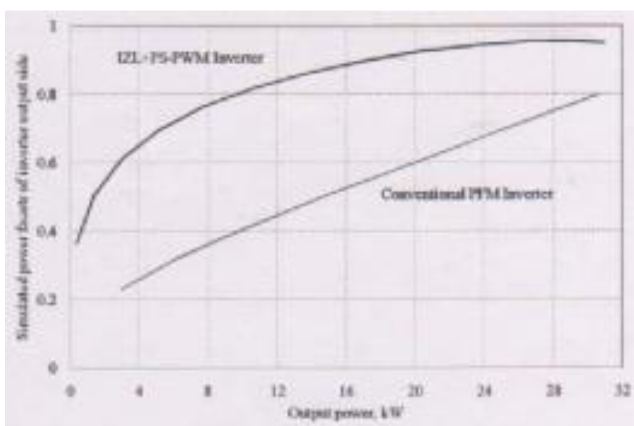

Figure 6: Simulation results of the total power factor of inverter output side

A gray line shows the total power factor of the conventional full bridge inverter that output power is controlled by PFM (pulse frequency modulation). The power factor is 0.8 approximately when the inverter outputs even the rated maximum power. On the other hand, the black line shows the total power factor of the proposed frequency controlled inverter. The total power factor is maintained high in any power control condition because the inverter operates at the resonant frequency.

Observation Results of High Power in Induction Heating Application

The proposed frequency controller was installed in a PS-PWM high frequency inverter for a high power induction heating application in order to demonstrate its performance. An operating condition of the actual inverter is same as the simulation shown in table 1. Figure 7 shows the observed waveforms that the inverter with IZL controller output a rated power. A black line that is similar to sinusoidal wave is the output current and a gray line is the output voltage. The current phase is conformed to the output voltage well because the proposed controller tuned the operation frequency to the resonant frequency. The measured power was about 29.5KW.
The total power factor of the inverter's output side is maintained high in any power regulation condition in the same way of the simulation results. As the results, IZL is verified that it has enough performance to track the resonant frequency and it realizes high total power factor of the inverter output terminal. The operation frequency is not influenced by PS-PWM. Hence, it was confirmed that the proposed frequency control method and the PS-PWM as the power regulation are not influenced each other. IZL enables the inverter to control the frequency adequate and to regulate the output power by one converter system.

CONCLUSION

This paper presents a novel frequency control method to tune the operation frequency to the resonant frequency by using just one AC current transformer. The principle of the control method is simple. A key of the proposed frequency control method is integration value of the output current in the period that output voltage is zero. If the integration value is positive of the output current in the voltage. Therefore, it can be known that the operation frequency should be low so that the inverter operates in the resonant frequency. On the other hand, the current phase is lead to the voltage if the integration value of the current is negative. Hence the operation frequency should be high in order to keep high total power factor. In this paper this frequency control is named IZL (integrated zero loop) because the inverter operates in the resonant frequency by tuning the frequency so that the integration become value becomes always zero. IZL does not need to observe the phase of output voltage and current for controlling the frequency in a similar way of CTBL. Accordingly IZL is compatible with PS-PWM as the power regulation, and the high frequency inverter system does not need to employ an additional active converter for the power regulation. As a result, the high frequency inverter system can be simplified.
Several simulations were performed to demonstrate IZL as the frequency control. It was clarified that the inverter with IZL tracks the changing resonant frequency quickly. Furthermore, the total power factor of the inverter's output terminal can be maintained high in the range from a rated maximum power to the low power condition.
From these considerations, on may well conclude that the proposed resonant frequency tracking control method is highly suitable for the high frequency inverter of the high power induction heating applications.

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