Induction Heating System Using Self Oscillating Driver

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Abstract*—A high frequency induction heating system (IHS) has been developed for the heating of small quantities of metal for laboratory and diamond applications. The IHS load forms part of a resonant circuit whose frequency is determined by the electrical characteristics of the work-piece placed inside the heating coil. The dynamic nature of the IHS load is such that it causes a shift in the natural resonant frequency of the load circuit. Self oscillating driver (SOD) control for the power sources enable continuous operations at the resonant frequency of the tank circuit, resulting in a high conversion efficiency due to dead time switching and maximum power transfer to the load at all times. This paper describe SOD control system for the prototype IHS. Some basic design criteria as well as the actual implementation of the system are presented. Simulation is obtained for proposed SOD using MATLAB software. Experimental results are presented to illustrate the effectiveness of the self oscillating driver (SOD)control system.

Index Terms – Self oscillating driver, Dead time , Induction heating system, Zero voltage switching,High frequency inverter

I. INTRODUCTION

In recent years, with great advances of power semiconductor switching devices, the electromagnetic induction current based heat energy processing appliances using high frequency power conversion circuits have attracted special interest for consumer food cooking and processing applications. The high frequency IHS appliances have been developed for consumer home use and business-use food cooking mass production [1],[2]

One of the most common topologies for resonant power supplies is the series resonant converter,as shown in Fig. 1a. The circuit utilizes a simple resonant tank and, when operated slightly above resonance, can offer zero voltage switching (ZVS) for the MOSFETs. Since the maximum device voltage is clamped to the supply voltage, lower voltage MOSFETs with a smaller channel resistance can be used, limiting the conduction losses. The operating frequency can be a significant fraction of a kHz [4]-[5]. However, the MOSFETs have to commutate all of the current in the work piece which, in the absence of an impedance matching transformer. It can be in the order of amperes.

The alternative is to use a parallel resonant tank in a current-fed inverter configuration [6],as shown in Fig. 1b. The current commutated by the transistors is comparatively small, and the conduction losses are kept under control, but the switches are exposed to the peak resonant voltage which may be much larger than the supply voltage. The problem is exacerbated for applications requiring high-frequency operation, where the quality factor of the parallel resonant tank can be very large. IGBTs are usually employed, as they can block much larger voltages than MOSFETs. However, the maximum operating frequency of these devices is well below that achievable with MOSFETs.

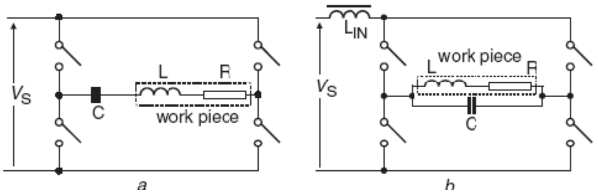

Fig. 1. Conventional resonant inverters for induction heating

To reduce the switching voltage in the parallel inverter or the switching current in the series inverter, a matching transformer is used to modify the impedance of the work piece, reducing the device ratings to manageable levels. Alternatively a higher-order resonant tank can be used to perform impedance matching, thereby removing the high-frequency transformer [7]-[9]. An inverter configuration in which the switching voltage is clamped to the supply voltage (as in the series resonant inverter) and the commutated current is only a fraction of the work piece current (as in the current-fed inverter) is published in [10]. This is achieved by using a parallel resonant tank supplied through an inductor, which matches the impedance of the tank and the impedance that can be handled by the inverter poles. An additional advantage of the circuit is the ability to share the commutated current between a number of inverter poles. The immediate benefit is the capability to use a number of poles to supply a large current to the parallel portion of the resonant tank, yet with begin requirements for the device current and voltage ratings.

The power throughput of resonant inverters is usually regulated either through control of the DC link voltage or by varying the operating frequency. DC link control is undesirable since a dedicated controlled rectifier is required, processing the entire power supplied to the inverter, thereby reducing the overall system efficiency. Furthermore, for operation above KHz, the operating frequency needs to be fixed in order to control pollution from emissions [11],[12]. The legally allowed operating frequency bands are fairly narrow and this precludes the use of variable frequency control.

The cost effective IHS cooking appliances using high frequency inverter topologies have some advantageous points such as energy saving, clean environment, rapid heating process, easiness of temperature control. The latest developments of IHS power supplies for consumer applications are more and more significant from the view points of environment and energy saving. Under these backgrounds, high frequency inverter (HFI) type power supplies are indispensable for consumer IHS appliances.

This paper deals with novel type of a HFI, which converts utility frequency AC power into high frequency AC power. This HFI composed of single phase diode bridge rectifier, non-smoothing filter, half bridge soft switching PWM,HFI , and induction heated load is proposed.It operating principle is presented by using the equivalent circuits. Operation at resonance also has the advantage of ensuring reduced switching losses in the power source, thereby allowing high conversion efficiencies. The workpiece geometry, conductivity and permeability of different metals tend to change the inductance of the heating coil when inserted into it. Considering the fact that the resonant capacitance is fixed, the tank circuit is driven to its new resonant frequency by changing the switching frequency of the power source. The SOD control system implemented has an operating range of 5KHz - 300 KHz . The control system presented is capable of monitoring the input power of the tank circuit and respond accordingly by adjusting the driving frequency of the power source in order to keep the IHS load at resonance throughout the heating cycle.

II. INVERTER OPERATIONS

SOD control ICs are monolithic power integrated circuits capable of driving low side and high side MOSFETs or IGBTs from logic level, ground referenced inputs. They provide offset voltage capabilities up to 600 V$_{DC}$ and, unlike driver transformer. It can provide super clean waveforms of any duty cycle between 0 - 99%.

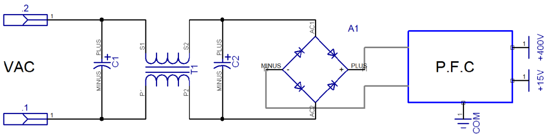

Fig. 2. Power Supply

These drivers provide the designer with self oscillating or synchronized oscillation functions merely with the addition of external V$_{R1}$ and C$_3$ components as shown in Fig 3. They also provide an internal circuitry which provides a nominal $1.2\mu s$ dead time between outputs and alternating high side and low side outputs for driving bridge power switches.

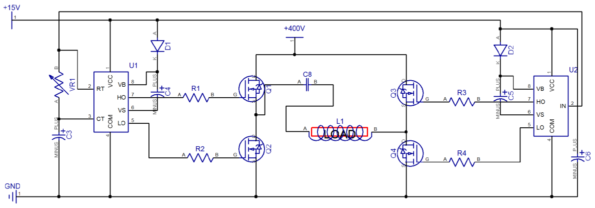

Fig. 3. Schematic Diagram

When used in the SOD mode the frequency of oscillation is given by:

$$f = \frac{0.714\,29}{C_3\,(75\Omega + V_{R1})} \tag{1}$$

These drivers are intended to be supplied from the rectified AC input voltage and for that reason they are designed for minimum quiescent current and have a 15V internal shunt regulator so that a single dropping resistor can be used from the DC rectified bus voltage.

It can readily be seen, therefore, that to charge and discharge the power switch input capacitance, the required charge is a product of the gate drive voltage and the actual input capacitance and the input power required is directly proportional to the product of charge and frequency and voltage squared:

$$Power = \frac{QV^2}{2} \times f \tag{2}$$

The above relationship suggest the following consideration when designing an IHS circuit:

1) Select the lowest operating frequency consistent with minimizing inductor coil size.
2) Select the smallest die size for the power switches consistent with low conduction losses (this reduces the charge requirements).

Some applications require higher voltages which may be too high for the simple half bridge topology. By using four power MOSFETs in full bridge circuit, the output voltage may be doubled without increasing the MOSFET current. A full bridge circuit automatically doubles output power and this topology can be implemented with the U1 master oscillator driving an U2 slave circuit as shown in Fig 3.

The slave driver U2 is driven from lead 2 of U1 and provide an inversion of its input signal at lead 2 to the LO drive waveform at lead 4. U1 does not have this inversion feature so its LO waveform is in phase with pin 2. When driven in this fashion, it is apparent that Q1 and Q4 conduct together and in the other half cycle Q2 and Q3 conduct together. The resultant output square wave has the same RMS value as the DC bus voltage. The IHS circuits are resonant at the self oscillating frequency if U1 determined from equation 1.

III. LOAD CIRCUIT

The load circuit parameters dictate the operating frequency range of the frequency control system. The frequency response of the load circuit was measured for three conditions namely: with no load, with a copper work-piece and with a steel work-piece.

Fig.4 shows the resonant frequencies, f_0 for an unloaded coil, f_1 for a copper work-piece and f_2 for a steel work-piece placed in the coil. The unloaded coil resonates at approximately 148kHz, and has a Q of approximately 18.

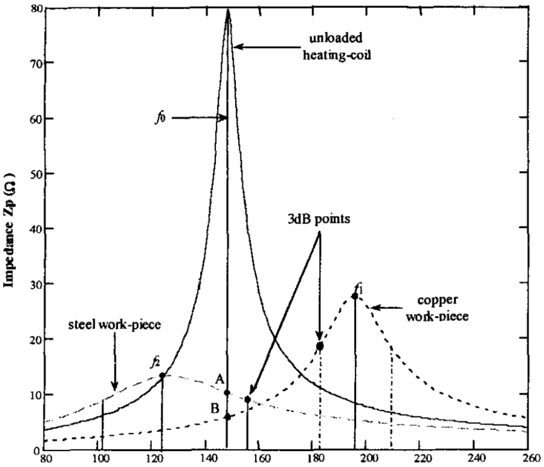

Fig. 4. Frequency response for the IHS tank circuit. The unloaded coil has a relatively high Q (approximately 18). When the coil is loaded the Q tends to decrease (8.25 for copper and 2.56 for steel). The resonance locked loop tracks the operating points f_0, f_1 and f_2 for different load conditions and therefore maintains maximum real power transfer to the load throughout the heating cycle

When a steel work-piece is inserted into the coil, the inductance of the coil increases, changing the Q of the tank circuit as well as its resonant frequency. If the induction furnace were to run in open loop, at frequency f_0 with a steel workpiece, the system would be operating at point A on the steel work-piece curve. Operation at point A results in a reduction of power transfer to the load, since point A is relatively close to the 3dB (1/2 power) point on this curve. When a copper work-piece is inserted into the coil, the system operates at point B on the copper work-piece curve. With no frequency-tuning present, operation at point B would result in very little power transfer to the copper work-piece.Another drawback of operating at points A (steel) and B (copper) is that significant switching losses develop in the power source when driving a load off resonance [14], [7] and [15]. The resonance locked loop therefore tracks the optimum operating points f_0, f_1, and f_2 for different loading in the coil [13].

IV. CONTROL SYSTEM

The implementation of SOD for this application requires the monitoring of the phase relationship between the driving voltage and driving current of the power source. The switching elements in the inverter drive the load at a frequency determined by the power MOSFETs [14]. Ideal waveforms of the driving voltage (V_{LOAD}) and driving current (I_{LOAD}) are shown in Fig.5.

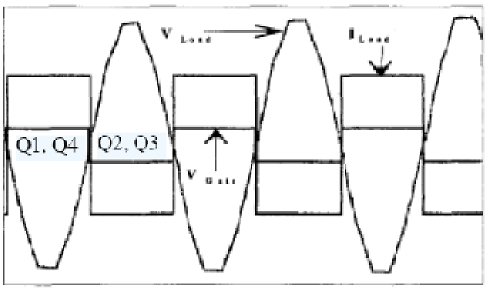

Fig. 5. Ideal waveforms of the driving voltage and current to the load circuit. It is apparent that the gate control signal (VGE) is an approximate phase representative of the driving current

Due to the principal of force commutated switching, it can be seen that the gate control signal (V_{GATE}) is an approximate phase representative of the driving current fed to the load circuit [13]. This concept is treated in an ideal sense and omits the propagations delay in the power MOSFET and drive circuitry, which is usually in the order of several hundred nanoseconds.

In order to choose the proper value and rating of the high voltage dropping resistor, it is important to understand all the SOD and surrounding component currents which contribute to the total current flowing through R. These contributions are

1) The quiescent current (I_{QCC}) of the SOD.
2) The current required to switch the gate of the power MOSFETs (dQ_G/dt).
3) The current sourced into the V_{R1} resistor by the chip (V_{CC})
4) The high voltage level shifting currents within the SOD and.
5) The additional current required to properly regulate the voltage o the SOD internal supply to ground zener clamp diode.

The first of the these considerations is the quiescent current of the U1, which is typically 400mA at room temperature. This current has a low temperature coefficient (less than -1000 ppm^{o}C) , so the (I_{QCC}) drops by less than 10% as the junction temperature rise from 25^{o}C to 125^{o}C. In addition to its temperature coefficient , the production variation of this current needs to be considered (these two sources of variation are included in the electrical characteristics within the data sheet). The SOD quiescent current is also relatively independent of the supply voltage, for $UVCC+ < V_{CC} < V_{CLAMP}$, where V $_{CLAMP}$ is the internal supply to ground zener clamp voltage (typically 15.4V at room temperature).

V. SIMULATION RESULTS

Sample circuit parameters are given by Table I .The switching frequency can be calculated from Eq. 1 and shown in Fig. 6. The power rating of the switch can be calculated from Eq. 2. Fig. 7 and Fig. 8 shows graph of the gate charge vs power rating of the switch and total gate charge vs power rating of the switch (MOSFET), respectively. Primary side of the isolation transformer, no load voltage and secondary side of the isolation transformer coil current are shown in Fig.9. Both steel and copper, load voltage and current are shown in Fig. 10 and Fig. 11, respectively. Simulation summaries are given in Table II.

TABLE I
CIRCUIT PARAMETER

Parameter	Value
Utility	230 / 50H$_Z$
N_1/N_2	1
f_{sw}	5-300 kH$_Z$
P_{out}	400 Watt

TABLE II
SIMULATION SUMMARIES

Parameter	Value	Remark
Z_L	80	No load impedance
f_{sw}	148 kH$_Z$	
Z_{LS}	14	For steel
f_{sw}	124 kH$_Z$	
Z_{LCu}	27	For copper
f_{sw}	191 kH$_Z$	

TABLE III
SIMULATION RESULTS

Load	Pri. voltage in volt	Coil current in ampere	P_{out}
No load	219.9999	2.7491	60.4801
Steel	219.9998	8.1481	179.2578
Copper	219.9996	15.7142	345.7117

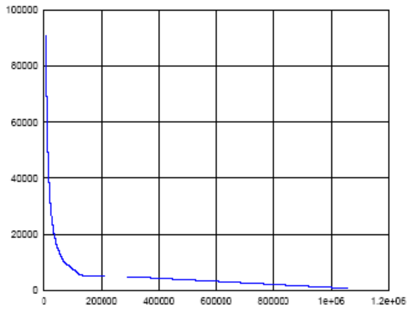

Fig. 6. frequency vs variable resistance

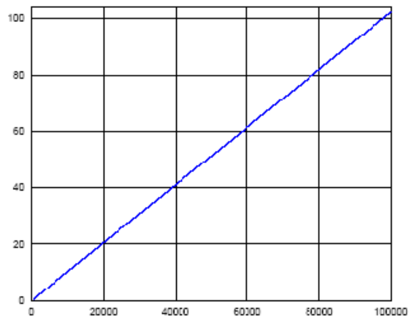

Fig. 7. Gate-Drain Charge/Gate-Source Charge Vs Switch Power Rating

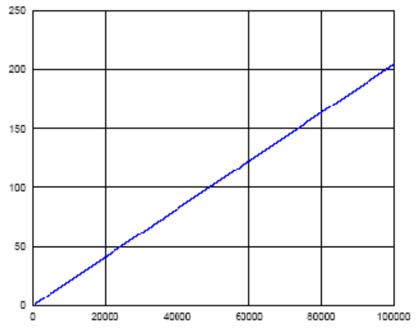

Fig. 8. Total Gate Charge Vs Switch Power

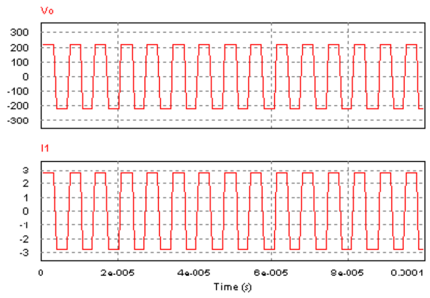

Fig. 9. No Load

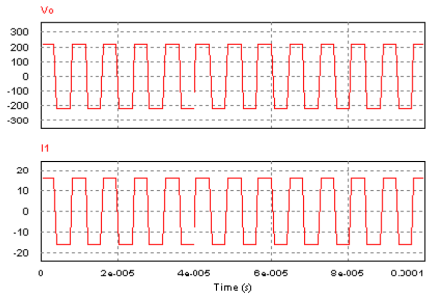

Fig. 10. For steel

VI. EXPERIMENTAL RESULTS

The SOD system was tested on the IHS in an experiment of steel and copper were heated respectively. The load circuit comprised a multi turn induction heating coil, Which formed part of a high Q parallel resonant circuit. When a steel work piece is placed inside the coil the inductance of the tank

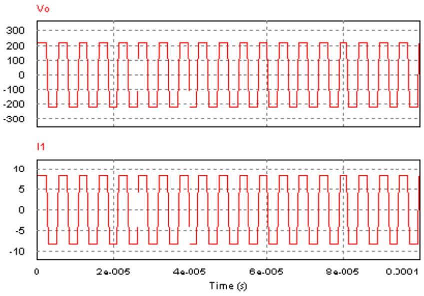

Fig. 11. For Copper

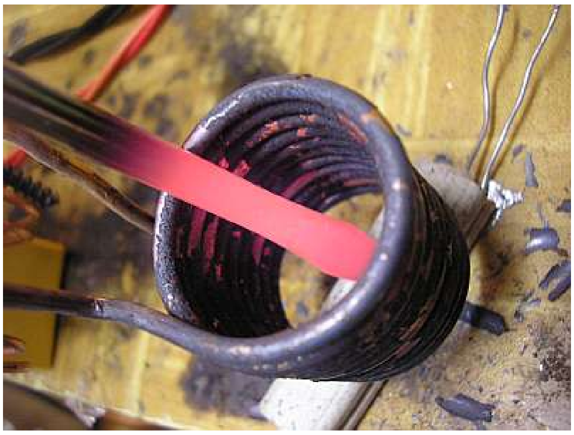

Fig. 12. SOD Experiment

circuit increase. This effect makes the tank circuit capacitively reactive as shown in figure 13.

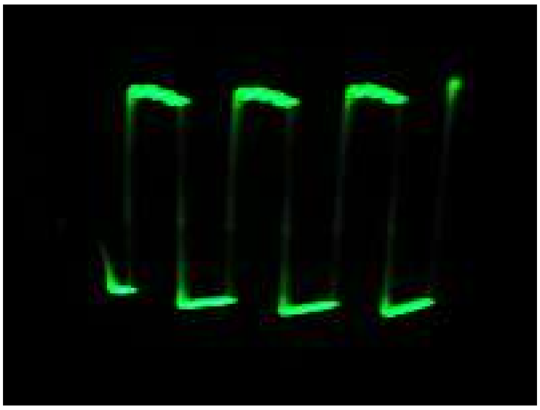

Fig. 13. Tank circuit at its natural resonant frequency by the power source. The SOD system is controlling the inverter switching frequency, thereby holding the load circuit in resonance at all times.

When transients increase dramatically in amplitude as the power is increased. This often results in the necessity to use special snubber circuitry to prevent MOSFET destruction.

Figure 14 and 15 shows the implementation of SOD to the IHS. It is evident that the ZVS occurring in every cycle. They are not present over voltage transients. With the SOD system in operation the gate signal is always zero crossing points of the tank circuit voltage.

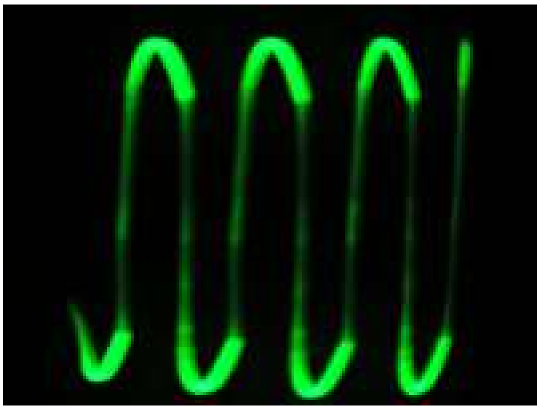

Fig. 14. Experimental waveform For Steel

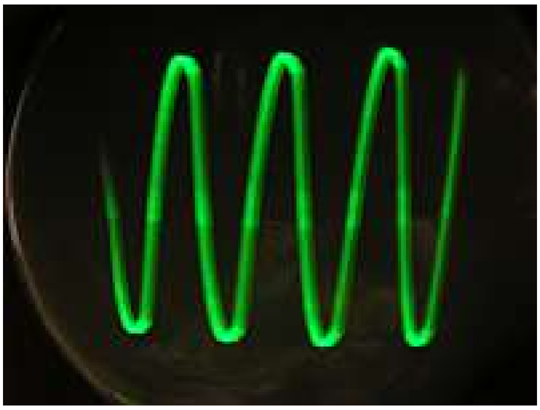

Fig. 15. Experimental waveform For Copper

VII. CONCLUSION

A SOD control system for a miniature high frequency control IHS has been developed. The system was proven to have a number of advantage as mentioned earlier. The implementation of the actual circuit utilities a minimum number of components and therefore provides a relatively cost effective approach for frequency control. The implementation of SOD has optimized the inverter performance. The ZVS achieved has eliminated the need for snubber circuitry and also allows the MOSFET switches to be driven to their maximum voltage rating.

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