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Induction heated metal hydride tube for hydrogen storage system

Hidrojen depolama sistemi için indüksiyon ısıtmalı metal hidrür tüp

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Abstract

In this study, the metal tube is heated up to a certain temperature by induction heating method so that the hydrogen stored by metal hydride method in it can be discharged. The voltage fed series resonant inverter (SRI) is used in the power stage of the system and the power switches are turned on under soft-switching conditions. The closed loop controlled 300 W SRI is designed to set the temperature of the tube to the reference temperature of 250 °C. The power control of SRI is realized by frequency control. The temperature of the tube is controlled by hysteresis on-off control due to its simple structure and easy applicability. 16-bit DSPIC33FJ16GS502 is used in the control of the system.

Keywords: Induction heating, Series resonant inverter, ZVS, Soft-switching, On-Off control, Metal hydride.

Öz

Bu çalışmada metal tüp, içerisine metal hidrür yöntemi ile depolanan hidrojenin deşarj edilebilmesi için indüksiyon ısıtma yöntemi ile belirli bir sıcaklığa kadar ısıtılmıştır. Sistemin güç katında gerilim beslemeli seri rezonans inverter (SRI) kullanılmış ve güç anahtarları yumuşak anahtarlama şartlarında iletime geçirilmiştir. Metal tüpün sıcaklığını referans sıcaklığı olan 250 °C'e sabitlemek için kapalı çevrim kontrollü 300 W'lik SRI tasarlanmıştır. SRI'nın güç kontrolü frekans kontrol tekniği ile gerçekleştirilmiştir. Tüpün sıcaklığı, basit yapısından ve kolay uygulanabilir olduğundan dolayı histerezis on-off kontrol ile denetlenmiştir. Sistemin kontrolünde 16-bit DSPIC33FJ16GS502 kullanılmıştır.

Anahtar kelimeler: İndüksiyon ısıtma, Seri rezonans evirici, ZVS, Yumuşak anahtarlama, On-Off control, Metal hidrür.

1 Introduction

Induction heating (IH) is used in many industrial and domestic applications such as surface hardening, melting, tempering, and cooking. This is because IH has advantages over conventional heating systems (resistance, flaming, etc.). These advantages include short process times, no heat dissipation in the environment, high efficiency, no combustion, and explosion. In addition, there is no waste at the end of the IH process [1]-[5]. All of these advantages demonstrate that induction heating is a reliable method for the heating process.

In IH systems, AC current, which is used to generate the electromagnetic field, is obtained with many different DC-AC inverter structures [6]-[19]. Among these structures, single-switched class-E, half-bridge and full-bridge inverters are frequently used in induction heating systems. When determining the converter structure, factors such as input voltage, control capability (suitability for different control techniques), efficiency, operating power, cost, simplicity of structure, ease of application and operating frequency are taken into consideration. The full-bridge is preferred because it is suitable for high power applications and the application of different control techniques. However, the disadvantages of this structure are the complex structure requiring a large number of elements and difficulty in obtaining the switching signals [6]-[9]. Class-E and half-bridge inverters are preferred for low and medium power applications [10]-[19]. The switch voltage of the half-bridge inverter, which has a simple and compact structure, is as much as the input voltage. Although the simple structure and ease of application of class-E inverter are particularly suitable for low power applications, the switch peak voltage is quite high compared to other inverter structures used in induction heating systems. This situation makes switch selection difficult and increases cut-off losses [16]-[19]. The half-bridge SRI is used as the power stage of the IH system because of the power ratio, switch voltage level and a fewer number of elements required for its assembly [10]-[15]. Soft-switching techniques are used to reduce switching losses. ZVS is mostly preferred for driving the MOSFETs in high-frequency applications. Thus, the MOSFETs are turned on under soft-switching conditions and the capacitance and leakage inductance are inserted into resonant elements [20].

Batteries used for the storage of electrical energy have negative aspects such as size, cost, low energy density and environmental problems. Hydrogen, however, is described as an energy carrier of the future because it is environmentally friendly and can be used wherever fossil fuels are used. These positive properties of hydrogen make it an alternative to the battery [21]-[23]. There are many methods used in hydrogen storage [23]. In the metal hydride-based hydrogen storage method, which is one of these methods, hydrogen can be chemically stored as hydride in metals and alloys [24]. The tube should be heated so that the hydrogen stored in the metal

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hydride tube to be discharged and ready for use. The temperature value required for discharge varies according to the metal hydride used. In the study [24], where the traditional heating method is used, the tube placed in the furnace or resistance heater is heated up to 250 °C and hydrogen is discharged. In this study, the induction heating method is preferred for heating the tube, unlike resistance heater. In order to verify the validity of the study, the experimental setup of the system, which is analyzed and designed, is established. In the system controlled in the closed loop, a digital signal controller (DSC) is used because of its low-cost, easy accessibility and simple use. The temperature of the tube is fixed to the reference temperature so that the hydrogen stored in the tube can be discharged. Thus, the heating process is carried out with the system that is simple in structure, easy to apply and low-cost. Moreover, unlike the study [24], a device such as a furnace is not used to heat the tube.

2 The power stage of the induction heating system

The operating principle of the induction heating system can be explained by the ideal transformer equivalent circuit given in Figure 1. In the figure, the heating coil and workpiece can be represented as the ideal transformer with conversion ratio n and the output load resistance R_{WP}.

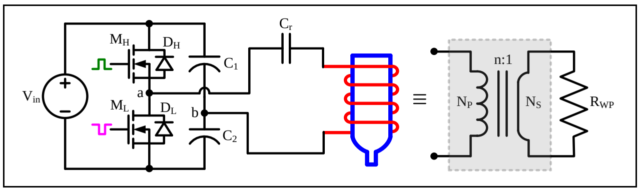

Figure 1. The half-bridge SRI IH system.

The V_{ab} pulse source with peak value $V_{in}/2$ is obtained by switching the input voltage. In IH systems, the loaded work coil can be expressed by an equivalent coil L_{eq} and resistance R_{eq} shown in Figure 2 [7].

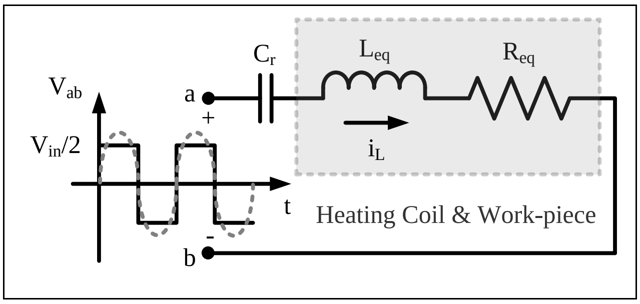

Figure 2. The series RLC equivalent.

When the resonant circuit behaves like a filter, the circuit can be analyzed by assuming that only the fundamental component of V_{ab} pulse source transfers power to the load. As a result of this assumption, the fundamental component of the pulse source is given as:

$$v_{1(t)} = V_m sin\omega_s t = \frac{2V_{in}}{\pi} sin\omega_s t \quad (1)$$

In Equation (1), ω_s is the switching angular frequency. The impedance of the resonant circuit is

$$|Z_{eq}| = \sqrt{R_{eq}^2 + (\omega_s L_{eq} - \frac{1}{\omega_s C_r})^2} \quad (2)$$

From Equation (2), it is clear that the impedance of the resonant circuit is a function of switching frequency (f_s). Therefore, one way to implement power control is changing f_s. Equation (3) gives the current equation of the lagging resonant circuit. ϕ is the phase angle between voltage $v_{1(t)}$ and current $i_{L(t)}$.

$$i_{L(t)} = I_m sin(\omega_s t - \phi) = \frac{\frac{2V_{in}}{\pi}}{|Z_{eq}|} sin(\omega_s t - \phi) \quad (3)$$

In order to reduce the capacitive turn-on losses of the MOSFETs, ZVS is used as a soft-switching technique, so the control variable (f_s) is selected greater than resonant frequency (ω_r) [20]. Figure 3 gives the operation modes and current-voltage waveforms of the converter above the resonant frequency. There are 4 different operation modes of the converter for above the resonant frequency $(f_s > f_r)$. One of the active (M_H and M_L) and passive (D_H and D_L) power switches in each of these modes is in conduction, the others are in insulation.

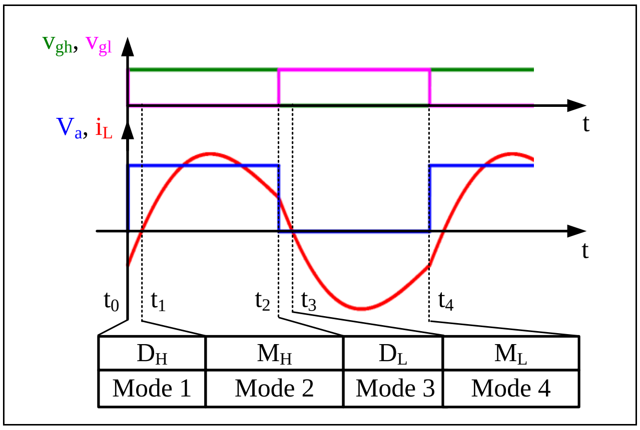

Figure 3. The operation modes and current-voltage curves of the converter for$f_s > f_r$.

It is assumed that all elements are ideal and the values of C_1 and C_2 are enough large so that they behave like a constant voltage source. Considering these assumptions, the operations of these modes are explained.

Mode I ($t_0 \le t < t_1$): When M_L is turned off at t_0, body diode D_H of M_H is conducted by negative i_L. Thus, M_H is clamped to the voltage of body diode D_H and the ZVS of M_H is obtained.

Mode II ($t_1 \le t < t_2$): As soon as D_H is turned off at t_1, M_H is turned on under ZVS conditions. In this mode, the resonant current i_L is positive.

Mode III ($t_2 \le t < t_3$): This Mode is similar to Mode 1. When MH is turned off at t_2, body diode D_L of M_L is conducted by positive i_L. Thus, the ZVS condition of M_L is established during this time.

Mode IV ($t_3 \le t < t_4$): This Mode is similar to Mode 2. As soon as D_L is turned off at t_3, M_L is turned on under ZVS conditions. In this mode, the resonant current i_L is negative.

Thus, the operation of the converter completes in 4 different modes. After t_4, operation modes of converter repeat from mode I to mode IV in the same way.

3 The configuration of the induction heating system

The IH system shown in Figure 4 consists of the power, control and measuring circuit. The input voltage V_{in} of the half-bridge SRI is fed by the rectified mains. The resonant circuit consists of the resonant capacitor C_r, heating coil and workpiece. The MOSFETs are used as the power switches in the converter due to the low switching losses at high frequencies. The temperature of the tube, which is the controlled output of the system and at the same time the feedback of the system, is tried to be fixed at 250 °C on average by hysteresis on-off control method. The error is obtained by subtracting the measured temperature T_M from the reference temperature T_R. Subsequently, the switching frequency, which is the control variable, is obtained by applying the error to the controller. Thus, if the error ($e = T_R - T_M$) is greater than 2 °C, the workpiece is started to be heated and if it is smaller than -2 °C, the heating process is stopped.

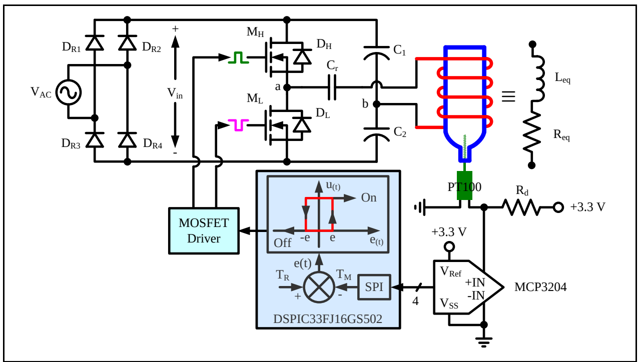

Figure 4. The induction heating system.

The DSPIC33FJ16GS502 DSC is used to digitally control the system and to generate control signals for the power switches. The DSC is specially developed for power electronic applications such as PFC, UPS, inverter, and converter. The two-end PT100 resistance temperature detector which is capable of temperature measurements from -200 °C up to 600 °C is used to sense the temperature. However, the PT100 is simply used by obtaining the voltage divider structure together with the resistor R_d. 12-Bit A/D Converters MCP3204 integrated circuit is used to digitize the temperature information from the PT100 by communicating with the DSC through a simple SPI interface. In addition, for faster analog-to-digital conversion and more accurate measurement, the supply voltage and the reference voltage of MCP3204 are selected to be 5 V and 3.3 V respectively.

4 The experimental study

In the storage method with a metal hydride system, hydrogen is stored in the space between the atoms of the granular metals. Hydrogen stored in the metal hydride tube is released by heating for use [23], [24]. The experimental setup given in Figure 5 is established to verify the validity of the IH system implemented to discharge the stored hydrogen by heating the metal hydride tube. To provide a high coupling factor between the heating coil and workpiece, the heating coil is designed depending on the physical properties of the metal hydride tube. The heating coil is wound in 53 turns. In addition, a data logger is used to display the temperature-time variation of the metal tube.

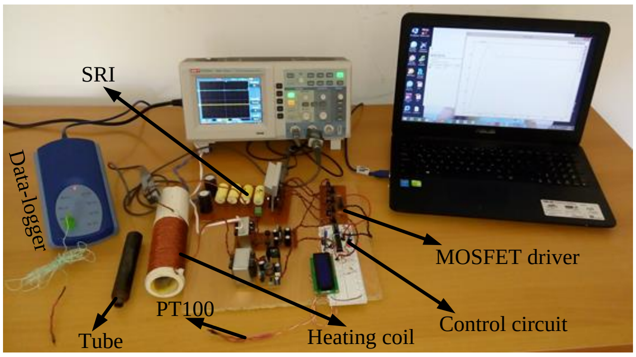

Figure 5. The experimental setup of the IH system.

By using the experimental test, L_{eq} and R_{eq} are determined as 76.7 μH and 5.62 Ω respectively. The value of the resonant capacitor is chosen as 400 nF and f_r is calculated as 28.73 kHz. The operating frequency of the IH system is chosen to be more than the resonant frequency to allow the power switches to be turned on under ZVS conditions.

The system is operated with the input voltage V_{in}, which is obtained by rectifying the mains voltage and has an average value of approximately 310 V, and the temperature-time graph given in Figure 6 is obtained by transferring the temperature values to the computer environment with the data logger. As can be seen from the graph, the tube which is an initial temperature of 26 °C is started to be heated at the 24th second and the temperature of the tube reaches the set value in a short time. The settling time of the system is approximately 133 seconds.

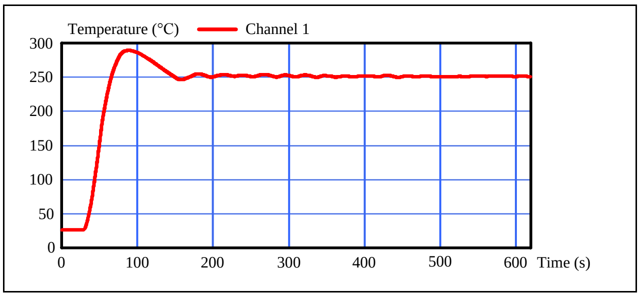

Figure 6. The temperature-time variation of the metal tube.

At the beginning, the SRI is operated with the minimum switching frequency of 50 kHz in order that the tube temperature could reach the desired temperature value at least as soon as possible. Then, as the temperature approaches the setpoint, the output power is decreased by increasing the switching frequency. Thus, the SRI is run at three different switching frequencies and the current and voltage curves of the resonance circuit for these frequency values are given in Figure 7.

As can be seen in Figure 6, the switching frequency is started at 50 kHz and is increased to 108 kHz and 217 kHz respectively as the temperature approaches the set value. When the set value is exceeded, the heating operation is stopped. Then, when the temperature is lower than the lower limit value of 248 °C, the inverter is operated at 217 kHz as floating power frequency and when the upper limit value of 252 °C is exceeded, it is stopped. This hysteresis band is repeated continuously, and the average temperature of the tube is fixed at 250 °C.

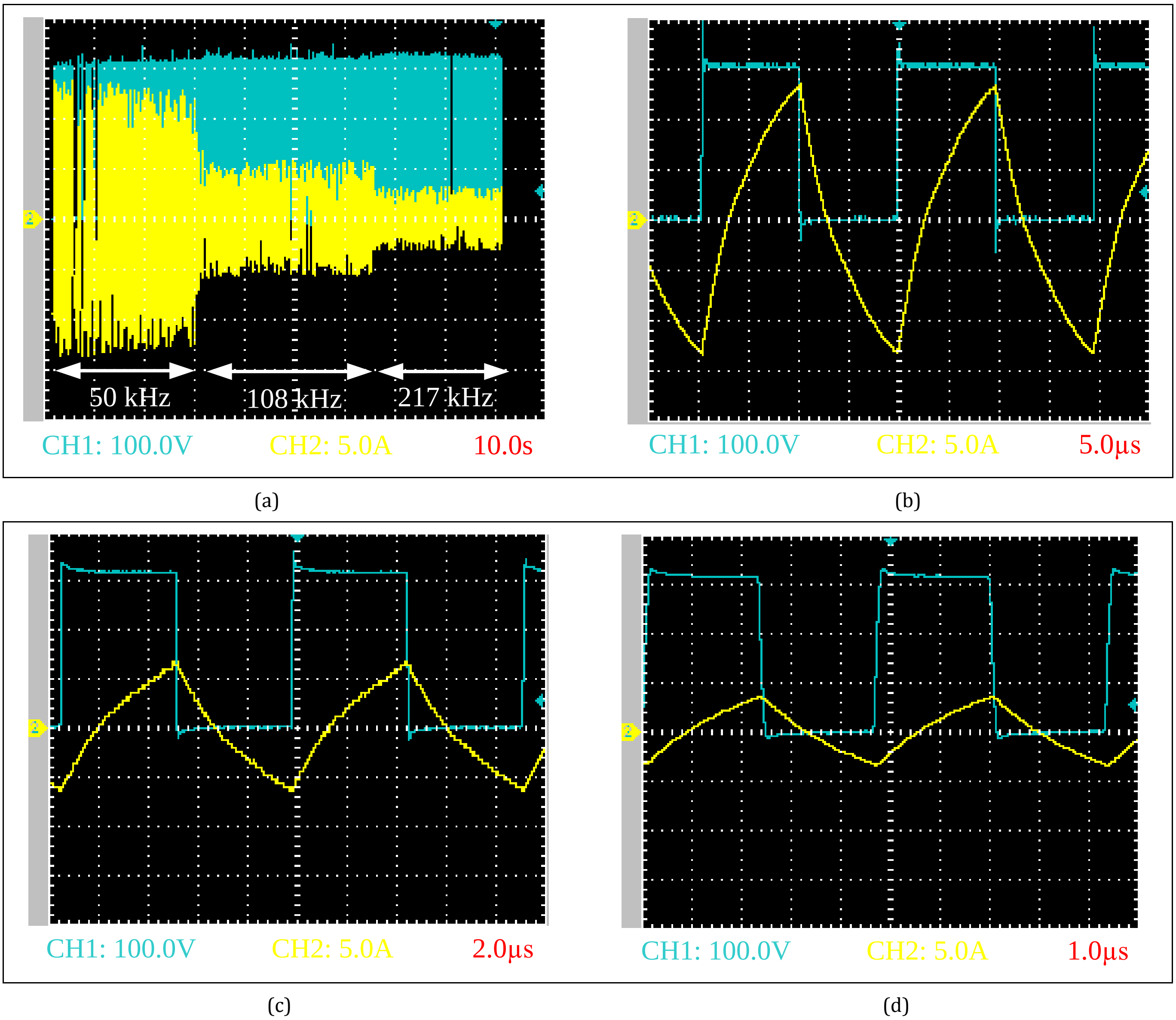

Figure 7. The current and voltage curves of the resonant circuit. (a): The current chancing via the switching frequency. (b): f_s=50 kHz. (c): f_s=108 kHz. (d): f_s=217 kHz.

5 Conclusions

Unlike resistance heating, by the IH method, the tube used in hydrogen storage is heated to 250 °C in a short time, such as 42 seconds. There are also no combustion residues and heat dissipation when hydrogen is discharged from metal hydride-based hydrogen storage. Thus, the heating process is carried out by the IH system, which is designed instead of a device such as a low-efficiency furnace used to heat the tube only. In order to increase the efficiency of the system and reduce the increasing switching losses with the frequency, the MOSFETs are switched on under ZVS conditions. Thus, turn-on losses are reduced. The temperature of the tube is maintained by the feedback control applied at the predetermined interval. However, in future studies, it is aimed to use advanced control techniques so that the reference temperature value is not exceeded too much, and the temperature of the tube can be fixed to the reference value in a shorter time and with fewer oscillations.

6 Author contribution statements

In the scope of this study, Selim ÖNCÜ contributed to formation of the idea, the design and supplying the materials; Muhammet KAYFECİ contributed to the design, literature review and supplying the materials; Salih NACAR contributed to the design, literature review and obtaining the results.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person/institution in the article prepared.

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