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Keywords

«Induction heating», «Autotuning», «Control methods for electrical systems», «Soft switching»

Abstract

Induction heating is the technique that heats the conductive material by high frequency large AC magnetic field. For efficient generation of the AC magnetic field, induction heating technique commonly utilizes the resonance between the heating coil and the resonating capacitor. The resonance is generally excited by applying the AC voltage of the resonant frequency. However, the resonant frequency is unstable because this frequency is susceptible to the disposition of the material to be heated. As a result, high efficiency high power induction heating system often suffers from unstable operation. This paper addresses this problem by proposing application of a simple automatic resonant frequency tuning circuit to the induction heating. This circuit can automatically achieve equivalent adjustment of the resonance frequency at the operating frequency without special control or the circuit sensing. In addition, this paper elucidated the control method of this tuning circuit to achieve the soft-switching operation in both of the inverter that drives the heating coil and the tuning circuit itself. The experiment revealed successful stabilization of the resonant frequency as well as satisfaction of the soft-switching condition both of the inverter and the tuning circuit, supporting effectiveness of the tuning circuit for induction heating.

Introduction

Induction heating is widely utilized in industrial [1–4] and home application [5–7] as a safe and convenient heating technique of conductive materials such as the metals. The induction heating does not require the frame for heating up the material to be heated. Furthermore, the induction heating generally has a simple mechanical construction, which can free the users from frequent maintenance.

In common induction heating systems, the inverter is employed to feed high frequency AC current to the heating coil. This AC current generates the AC magnetic field around the heating coil. As a result, the eddy current is induced inside the material to be heated, generating the heat by the ohmic loss inside the material. Therefore, effective heating requires large AC current of the heating coil for inducing large eddy current. However, the reactance of the heating coil may hinder the inverter from supplying sufficiently large AC current to the heating coil.

In order to solve this problem, the resonant capacitor is commonly attached to the heating coil, as shown in Fig. 1(a), particularly in high power induction heating systems [8–11]. If the heating coil is driven at the resonant frequency of this capacitor and the heating coil, the resonant capacitor cancels the reactance of the heating coil. Therefore, these systems are commonly driven at the resonant frequency, thus enabling large AC current to flow through the heating coil.

However, the resonant frequency is highly dependent on the inductance of the heating coil. This inductance is susceptible to the disposition of the material to be heated as well as the production tolerance of the heating coil. Furthermore, the production tolerance of the resonating capacitor also affects this inductance. Therefore, many induction heating systems have control circuits that adjusts the operating frequency of the inverter to coincide with the resonant frequency [12–18].

These control circuits detect the deviation of the resonant frequency from the operating frequency and adjust the operating frequency. However, the LC resonator of the heating coil and resonating capacitor often has high Q factor in many practical induction heating systems. Hence, the controller is required to generate the gate signal with sufficient frequency resolution so that the operating frequency can be accurately adjusted at the resonant frequency. This requirement may be severe particularly for controllers with microprocessors and FPGAs, which are commonly utilized in recent induction heating systems to implement fine and accurate control of the temperature of the material to be heated. The microprocessors and FPGAs operates based on the clock signal. Therefore, the frequency resolution of the gate signal is limited by the clock frequency, which may hinder accurate adjustment of the operating frequency.

As an alternative approach, this paper proposes application of an automatic resonant frequency tuning circuit to the induction heating systems. This tuning circuit can rather adjust the resonant frequency to the operating frequency of the inverter. This tuning circuit can adjust the resonant frequency without requiring fine frequency resolution of the operating frequency. The control of this circuit does not also need fine frequency resolution. Furthermore, the control of this circuit is straightforward and free from any sensing of the heating coil current or even the resonant frequency.

This tuning circuit is originally proposed for resonant inductive coupling wireless power transfer systems [19][20]. Hereafter, this paper refers to this tuning circuit as the automatic tuning assist circuit (ATAC) after the preceding works [19][20]. This paper investigates the effectiveness of the ATAC in comparatively high power application as induction heating systems. Particularly, the operating condition and the control method for the ATAC to achieve the soft-switching have been scarcely discussed in preceding studies, although the soft-switching is generally important for suppressing the switching loss in high power applications as many practical induction heating systems. Therefore, this paper elucidates the necessary control and the operating conditions for achieving the soft-switching.

The following discussion comprises three sections. Then next section briefly reviews the ATAC and analytically elucidates the operating condition, as well as the control method, for achieving the soft-switching. Then, the experiment is presented using the prototype induction heating system to verify the effectiveness of the ATAC. Finally, the conclusions are given.

Automatic Tuning Assist Circuit (ATAC)

Figure 1 illustrates the circuit diagram and the equivalent circuit of the conventional induction heating system without the ATAC. The conventional heating system comprises the inverter, the heating coil, and the resonating capacitor C_1. In the equivalent circuit model, the heating coil is

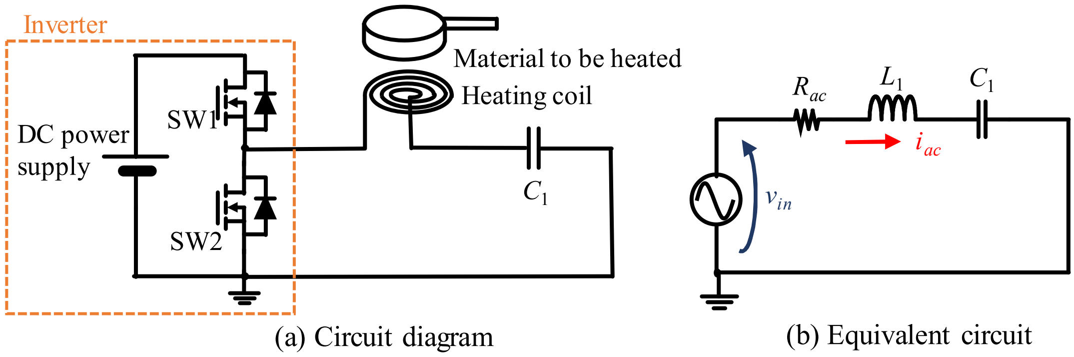


Fig. 1: Conventional induction heating system without the ATAC

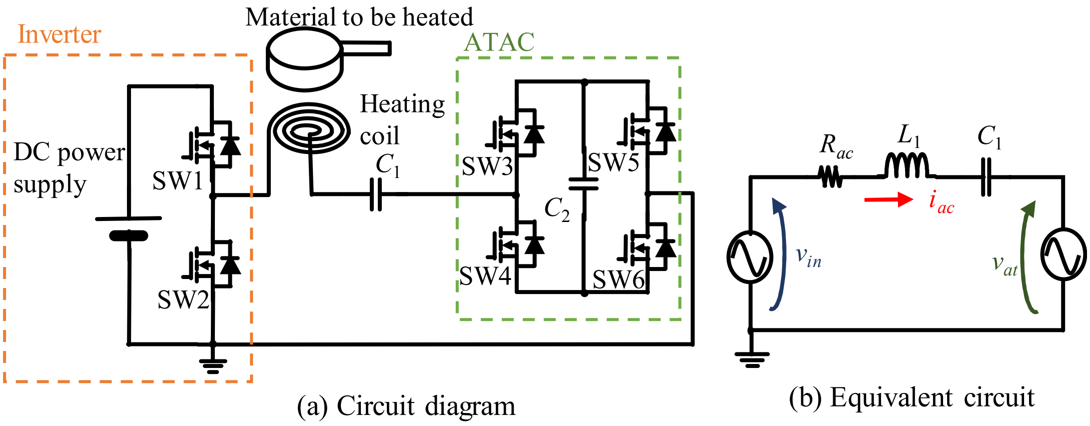


Fig. 2: Proposed induction heating system with the ATAC

replaced by the inductance L_1 and the AC resistance R_{ac}. The AC resistance R_{ac} is contributed by the power loss in the heating coil and that in the material to be heated. The inverter generates the AC voltage to excite the resonance between L_1 and C_1. Therefore, the inverter is commonly designed to operate at a frequency close to the resonant frequency. However, the resonant frequency is susceptible to the disposition of material to be heated and to the production tolerance of the heating coil and C_1; and therefore, the deviation of the operating frequency from the actual resonant frequency take various values and is generally difficult to observed by the controller of the inverter.

If the operating frequency exactly equals to the resonant frequency, the voltage drops at L_1 and C_1 completely cancel each other. Then, the inverter output voltage can be regarded to be fully applied to R_{ac}. This indicates that large AC current flows in the heating coil, leading to effective heating. However, if the operating frequency deviates from the resonant frequency, the voltage drop at the series resonator of L_1 and C_1 remains to hinder the AC current induction in the heating coil.

Figure 2 illustrates the circuit diagram and the equivalent circuit of the induction heating system with the ATAC. The ATAC is formed as a full-bridge circuit whose DC bus line is connected only to the smoothing capacitor C_2. Hence, the ATAC does not require any additional DC power supply. The full-bridge circuit of the ATAC operates at the same frequency as the inverter, which works as the AC voltage source, and with the predetermined constant phase difference with the inverter output voltage. Generally, the phase of the inverter voltage output coincides with the gating signals of the switches that incorporated in the inverter. Therefore, the ATAC does not require any sensing circuit nor complicated control circuit, as far as the ATAC and the inverter share the same controller.

The ATAC automatically generates the AC voltage that cancels the remaining voltage drop of the series resonator of L_1 and C_1, even if the operating frequency of the inverter deviates from the resonant frequency. As a result, the inverter output voltage is almost fully applied to R_{ac}, which is equivalent to adjusting the resonant frequency to the operating frequency of the inverter. The reason is briefly reviewed as below.

In order to simplify the discussion, the AC voltage generated by the inverter and the ATAC is approximated as the sinusoidal voltage v_{in} and v_{at}, respectively. (Hence, v_{in} and v_{at} represent the fundamental waves of the output voltage of the inverter and the output voltage of the ATAC, respectively.) As a result, the equivalent circuit is obtained as shown in Fig. 2(b). Based on this equivalent circuit, the heating coil current i_{ac} can be formulated as

$$\left(j\omega L_1 + \frac{1}{j\omega C_1} + R_{ac}\right) i_{ac} = v_{in} - v_{at}, \tag{1}$$

where ω is the angular frequency.

Note that the ATAC comprises only the switching devices and the capacitor; and therefore, the ATAC can receive no effective power under the steady operation. Therefore, if we denote the phase angle difference of i_{ac} from v_{at} as θ, we have $\theta=\pi/2$ or $\theta=-\pi/2$. Let V_{in} ,V_{at}, and I_{ac} be the effective voltage value of v_{in}, v_{at}, and i_{ac}, respectively; and let α be the phase angle difference of v_{at} from v_{in}. If we define the phase angle of vin as zero, the real and imaginary part of (1) can be expressed as

$$\begin{aligned} &-\left(\omega L_1-\frac{1}{\omega C_1}\right)I_{ac}\sin(\alpha+\theta)+R_{ac}I_{ac}\cos(\alpha+\theta) \\ &\quad=-\left(\omega L_1-\frac{1}{\omega C_1}\right)I_{ac}\cos\alpha\sin\theta-R_{ac}I_{ac}\sin\alpha\sin\theta=V_{in}-V_{at}\cos\alpha \end{aligned} \tag{2}$$

$$\begin{aligned} &\left(\omega L_1-\frac{1}{\omega C_1}\right)I_{ac}\cos(\alpha+\theta)+R_{ac}I_{ac}\sin(\alpha+\theta) \\ &\quad=-\left(\omega L_1-\frac{1}{\omega C_1}\right)I_{ac}\sin\alpha\sin\theta+R_{ac}I_{ac}\cos\alpha\sin\theta=-V_{at}\sin\alpha \end{aligned} \tag{3}$$

Eliminating V_{at} from (2) and (3) yields (4); and eliminating sinα from (2) and (3) yields (5):

$$I_{ac}=-\frac{V_{in}\sin\alpha}{R_{ac}\sin\theta}\,. \tag{4}$$

$$V_{at}=V_{in}\cos\alpha+\left(\omega L_1-\frac{1}{\omega C_1}\right)I_{ac}\sin\theta\,. \tag{5}$$

Because cosθ=0, sinθ must equal to either −1 or 1. The polarity of sinθ depends on the polarity of sinα. If sinα is positive, sinθ must be −1 because V_{in}, R_{ac}, and I_{ac} are positive in (4) according to their definition. On the other hand, if sinα is negative, sinθ must be 1. Furthermore, if we approximate that cosα is sufficiently small, the polarity of $\omega L_1-1/\omega C_1$ must equal to sinθ because V_{at} and I_{ac} are positive in (5).

Particularly, if α is set at π/2 or −π/2, (4) and (5) reduce to $V_{in}=R_{ac}I_{ac}$ and $V_{at}=|\omega L_1-1/\omega C_1|I_{ac}$. The former equation indicates the same relation as the conventional induction heating system in which the operating frequency exactly coincides with the resonant frequency. Therefore, the system with the ATAC operates as if the resonant frequency is automatically tuned at the operating frequency regardless to the value of $\omega L_1-1/\omega C_1$.

Conventionally, the effectiveness of the ATAC is investigated in comparatively small power applications such as wireless power transfer. Therefore, the control and design strategy of the ATAC has been only focused on the function of the automatic tuning of the resonant frequency. Accordingly, α has been simply set at π/2 or −π/2 depending on the polarity of $\omega L_1-1/\omega C_1$ [3][4]. However, in more high power applications such as induction heating, the ATAC should be controlled and designed to achieve the soft-switching in both the inverter and the full-bridge circuit of the ATAC for minimization of the switching loss.

In order to achieve the soft-switching in the inverter, the relation between i_{ac} and v_{in} should be inductive. Hence the phase angle of the output current, i.e. α+θ, must be slightly smaller than zero. (The angle α+θ should have small absolute value for large sinα, which results in effective heating by inducing large heating coil current I_{ac} according to (4).) In addition, in order to achieve the soft-switching in the full-bridge circuit of the ATAC, the relation between i_{ac} and v_{at} should be kept capacitive. Hence, θ should be π/2. As a result, we should set the parameter α at a value slightly

Table I: Specification of the experimental induction heating systems

DC power supply	63V
Heating coil	Diameter: 170mm Number of turns: 40T
Capacitor C_1	44.4nF
Capacitor C_2	17.6μF
Inductor L_1	98.8μH
Resonant Freq.	76kHz
Operating Freq.	76–91kHz
AC resistance R_{ac}	1.47–1.61Ω
SW1, 2	Infineon IRFP4668PBF
SW3–6	Toshiba TK62Z60X,S1F(S

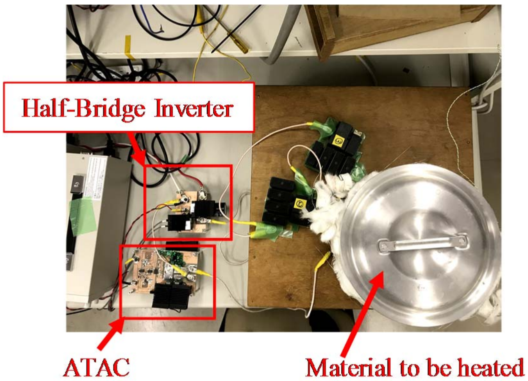


Fig. 3: Photograph of the experimental system with the ATAC

smaller than $-\pi/2$ and design $\omega L_1 - 1/\omega C_1$ to be positive. In other words, the resonant frequency of the series resonator of L_1 and C_1 should be lower than the operating frequency.

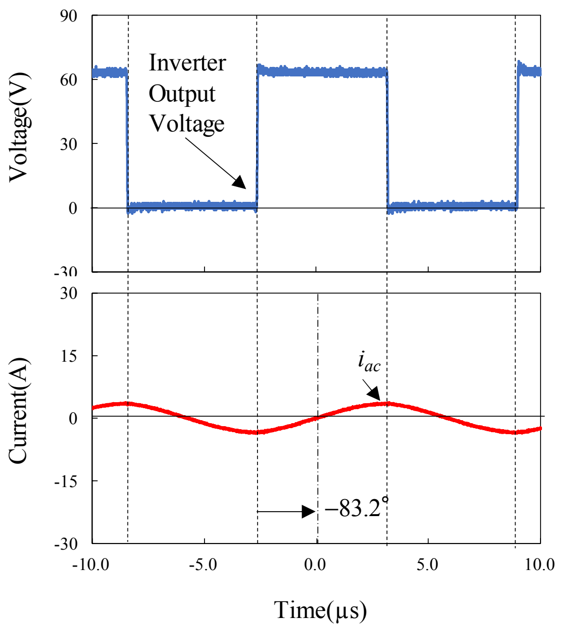
Certainly, the series resonator has been commonly designed to be inductive even in the conventional induction heating system without the ATAC. However, the ATAC can ensure the larger heating coil current because $\sin\alpha$ is always kept at a predetermined value close to the unity regardless to the reactance $\omega L_1 - 1/\omega C_1$, which may take large value depending on the disposition of the material to be heated and the production error of the heating coil and the resonating capacitor.

Experiment

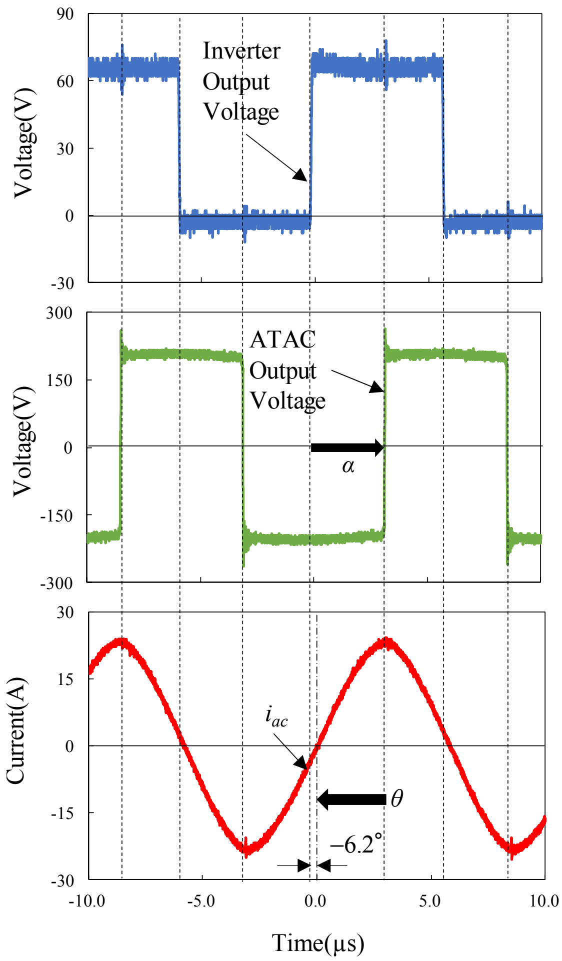
The effectiveness of the ATAC for the induction heating was evaluated experimentally by comparing the circuit operation between the induction heating systems with and without the ATAC. This experiment tested small-powered experimental induction heating systems constructed based on the circuit diagrams shown in Fig. 1(a) and Fig. 2(a). Fig. 3 shows the photograph of the prototype induction heating system with the ATAC. In this experiment, we utilized the aluminum pot with the diameter of 240mm as the material to be heated. Specifications of the experimental systems are shown in Table I. In this experiment, the operating frequency was ranged from 76kHz to 91kHz, which is equal or slightly higher than the actual resonant frequency of 76kHz.

First, we compared the operating waveforms between with and without the ATAC. For this purpose, we evaluated the voltage and current waveforms under operation at 86kHz, which is slightly higher than the resonant frequency. The phase angle α was kept at -95° in the prototype with the ATAC so that both of the inverter and the ATAC can achieve the soft-switching.

Figure 4 shows the result. Comparison between with and without the ATAC revealed that the amplitude of the heating coil current was greatly increased owing to the ATAC. The phase difference of the heating coil current i_{ac} from the inverter output voltage v_{in} was found to be -83.2° in the conventional system without the ATAC, which indicates that the heating coil current is mainly determined by the inductive reactance of $\omega L_1 - 1/\omega C_1$. On the other hand, the phase



(a)Without ATAC



(b)With ATAC

Fig.4: Experimental voltage and current waveforms (The operating frequency was set at 86kHz)

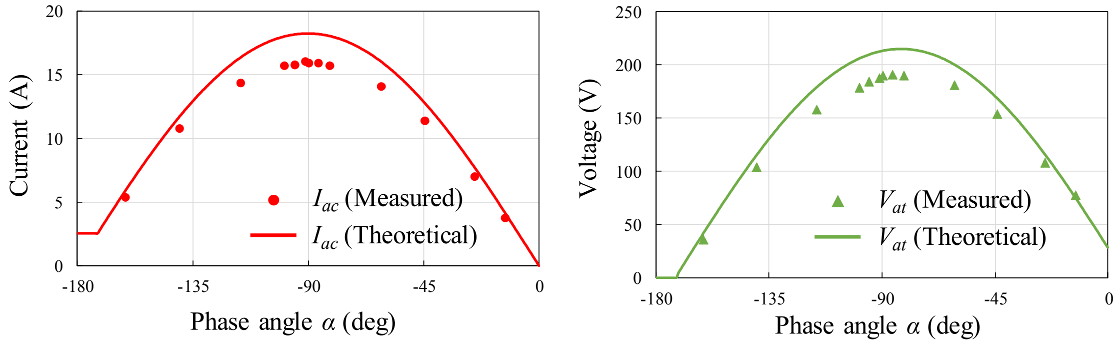
difference was found to be −6.2° in the system with the ATAC, as is consistent with the theoretical value of −5°. This phase difference indicates that the inverter can achieve the soft-switching. In addition, the phase difference between the heating coil current i_{ac} and the ATAC output voltage v_{at} also supported the soft-switching in the full-bridge of the ATAC.

In the proposed system with the ATAC, the effective value of the heating coil current, i.e. I_{ac}, was found to be 15.8Arms; and the effective value of the fundamental wave of the ATAC output voltage, i.e. V_{at}, were found to be 183.5Vrms. The experimental values for I_{ac} and V_{at} were found to be close to the theoretical values I_{ac}=18.1Arms and V_{at}=209.6Vrms, predicted using (4). (V_{in} was calculated as 28.4Vrms because V_{in} is the effective value of the fundamental wave of the inverter output voltage.) Slight discrepancy between the experiment and the theory can be explained as the result of the power loss in the ATAC. The power loss of the ATAC is included in R_{ac} in the equivalent circuit. Therefore, adding the ATAC to the induction heating system slightly increases R_{ac}, which may have caused slight decrease in I_{ac} and V_{at} in the experiment, as is inferred from (4) and (5).

Next, we evaluated the operating principle of the induction heating system with the ATAC. For this purpose, the dependence of I_{ac} and V_{at} on the phase angle α is evaluated using the prototype with the ATAC. In this evaluation, the operating frequency was set at 86kHz, which is slightly higher than the resonance frequency of 76kHz. Then, the experimentally evaluated dependence was compared with the theoretical prediction given as (4) and (5).

Figure 5 shows the results. The overall dependency of I_{ac} and V_{at} was found to be consistent with the theory. As predicted by the theory, I_{ac} took its maximum value at α=90°, supporting the theoretical prediction. Certainly, both of I_{ac} and V_{at} showed slightly smaller values in the experiment than the theoretical prediction. However, this discrepancy between the experiment and the theory can also be explained as the result of the power loss in the ATAC.

Finally, we confirmed the stability of I_{ac} against the impedance $\omega L_1 - 1/\omega C_1$. In the actual



(a) Heating coil current I_{ac} (b) ATAC output voltage V_{at}

Fig.5: Dependence of the I_{ac} and V_{at} on the phase angle α

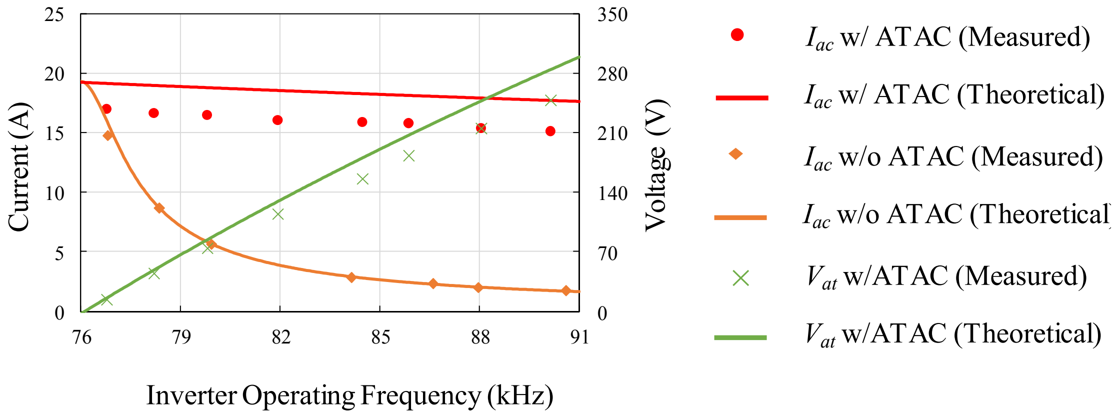


Fig.6: Dependence of I_{ac} and V_{at} on the operating frequency.

induction heating system, the variation of this impedance is supposed to be mainly caused in the inductance of the heating coil (L_1) and the capacitance of the resonating capacitor (C_1). However, in this experiment, we varied the operating frequency to make variation in this impedance. Therefore, we investigated the dependence of I_{ac} on the operating frequency. The phase angle α was set at −95˚.

Figure 6 shows the result. The system with the ATAC showed almost constant I_{ac} regardless to the operating frequency and therefore to $\omega L_1 - 1/\omega C_1$. On the other hand, I_{ac} decreased rapidly in the system without the ATAC, as the operating frequency deviates from the resonant frequency. Therefore, the ATAC offered stable I_{ac} regardless to $\omega L_1 - 1/\omega C_1$, as is expected from the theory. Certainly, V_{at} increased as the operating frequency deviates from the resonant frequency. This is also consistent with the theory, because (5) indicates that V_{at} is approximately proportional to the absolute value of $\omega L_1 - 1/\omega C_1$. Consequently, the experiment successfully proved the stability improvement by the ATAC against the variation of the impedance $\omega L_1 - 1/\omega C_1$, i.e. against the variation of the resonant frequency.

Conclusions

The induction heating often suffers from unstable heating performance due to susceptibility of the resonant frequency to the disposition of the material to be heated or the production error of the heating coil and the resonating capacitor. This issue is addressed in this paper by proposing application of a simple automatic resonant frequency tuning circuit known as the ATAC. This paper further investigated and derived a design and control instruction of the induction heating system with the ATAC to satisfy the soft-switching condition. As a result, the following two instructions were elucidated: 1. the ATAC should be operated with the phase difference slightly smaller than –π/2 from the inverter that drives the heating coil; and 2. the resonance frequency of the series resonator of the heating coil and the resonating capacitor should be designed to be smaller than the operating frequency of the inverter. Experiment successfully verified effectiveness of the ATAC in the induction heating application as well as appropriateness of the instructions to satisfy the soft-switching condition.

References

[1] Fabbri M., Forzan M., Lupi S., Morandi A., Ribani P. L.: Experimental and numerical analysis of DC induction heating of aluminum billets, IEEE Trans. Magn. Vol. 45 no 1, pp. 192-200

[2] Lubin T., Netter D., Leveque J., Rezzoug A.: Induction heating of aluminum billets subjected to a strong rotating magnetic field produced by superconducting windings, IEEE Trans. Magn. Vol. 45 no 5, pp. 2118-2127

[3] Choi S., Lee C., Kim I., Jung J., Seo D. H.: Comparison on current source rectifier and inverter topologies of induction heating power supply for forging applications, Proc. IEEE Intl. Conf. Elect. Mach. Syst. (ICEMS2017)

[4] Shijo T., Kurachi S., Uchino Y., Noda Y., Yamada H., Tanaka T.: High-frequency induction heating for small-foreign-metal particle detection using 400 kHz SiC-MOSFETs inverter, Proc. IEEE Energy Conversion Congr. Expo. (ECCE2017), pp. 5133-5138

[5] Paesa D., Franco C., Llorente S., López-Nicolás G., Sagüés C.: Adaptive simmering control for domestic induction cookers, IEEE Trans. Ind. Appl. Vol. 47 no 5, pp. 2257-2262

[6] Meng L. C., Cheng K. W. E., Ho S. L.: Multicoils design for induction cookers with applying switched exciting method, IEEE Trans. Magn. Vol. 48 no 11, pp. 4503-4506

[7] Han W., Chau K. T., Zhang Z.: Flexible induction heating using magnetic resonant coupling, IEEE Trans. Ind. Electron. Vol. 64 no 3, pp. 1982-1992

[8] O. Lucia, J. M. Burdio, I. Millan, J. Acero, and S. Llorente, "Efficiency optimization of half-bridge series resonant inverter with asymmetrical duty cycle control for domestic induction heating," In Proc. European Conf. Power Electron. Appl., pp. 1–6, Sept. 2009.

[9] H. Sarnago, O. Lucia, A. Mediano, and J. M. Burdio "Modulation scheme for improved operation of an RB-IGBT-based resonant inverter applied to domestic induction heating," IEEE Trans. Ind. Electron., vol. 60, no. 5, pp. 2066–2073, May 2013.

[10] Park H., Jung J.: Load-adaptive modulation of a series-resonant inverter for all-metal induction heating applications, IEEE Trans. Ind. Electron. Vol. 65 no 9, pp. 6983-6993

[11] Jain P. K., Espinoza J. R., Dewan S. B.: Self-started voltage-source series-resonant converter for high-power induction heating and melting applications, IEEE Trans. Ind. Appl. Vol. 34 no 3, pp. 518-525

[12] Okuno A., Kawano H., Sun J., Kurokawa M., Kojina A., Nakaoka M.: Feasible development of soft-switched SIT inverter with load-adaptive frequency-tracking control scheme for induction heating, IEEE Trans. Ind. Appl. Vol. 34 no 4, pp. 713-718

[13] Kwon Y., Yoo S., Hyun D.: Half-bridge series resonant inverter for induction heating applications with load-adaptive PFM control strategy, Proc. IEEE Appl. Power Electron. Conf. (APEC1999), pp. 575-581

[14] Tian J., Berger G., Reimann T., Scherf M., Petzoldt J.: A half-bridge series resonant inverter for induction cookers using a novel FPGA-based control strategy, Proc. European Conf. Power Electron. Appl. (EPE2005), pp. 1-9

[15] Kifune H., Hatanaka Y.: Resonant frequency tracking control by using one CT for high frequency inverter, Proc. European Conf. Power Electron. Appl. (EPE2009), pp. 1-7

[16] Nguyen K. L., Pateau O., Caux S., Maussion P., Egalon J.: Robustness of a resonant controller for a multiphase induction heating system, IEEE Trans. Ind. Appl. Vol. 51 no 1, pp. 73-81

[17] Esteve V., Jordán J., Sanchis-Kilders E., Dede E. J., Maset E., Ejea J. B., Ferreres A.: Enhanced pulse-density-modulated power control for high-frequency induction heating inverters, IEEE Trans. Ind. Electron., Vol. 62 no 11, pp. 6905-6914

[18] Namadmalan A.: Universal tuning system for series-resonant induction heating applications, IEEE Trans. Ind. Electron., Vol. 64 no 4, pp. 2801-2808

[19] Endo Y., Furukawa Y.: Proposal for a new resonance adjustment method in magnetically coupled resonance type wireless power transmission, Proc. IEEE MIT-S Intl. Microwave Workshop Series Innovative Wireless Power Transmission (IMWS-IWPT2012), pp. 263–266

[20] Nakanishi K., Sasaki M.: Data transmission system using magnetic resonance wireless power transfer, Proc. IEEE Wireless Power Transfer Conference (WPTC2017)