Online Parameter Estimation for Induction Heating Systems with Quasi-Resonant Inverter

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***Abstract*—Induction heating has become one of the most dominant heating technology in many industrial and domestic applications. Accurate modeling and control of such heating systems require an estimation of the load and the coil parameters. For the cases without a current sensor, the parameter estimation is usually done at so-called *load-detection* stage before starting the heating. This process needs, however, a certain execution time, and it is usually implemented by applying computationally-complex algorithms. This paper proposes an online estimation technique to estimate the load and the coil parameters of a quasi-resonant-inverter-topology-based induction heating system. The estimation is performed during the normal operation of the inverter without any pre-operation steps. The proposed method is implemented by fitting the sampled voltage to an exponentially-damped sinusoidal signal. This curve-fitting process is based on an iterative numerical algorithm which does not require any non-linear optimization or complex signal processing steps, thus making the method implementable in the existing digital control platform. An experimental prototype emulating the quasi-resonant-based induction heating system is used to verify the efficiency of the proposed estimation technique.**

***Index Terms*—Induction heating, Quasi-resonant inverter, Parameter estimation, Newton-Raphson technique.**

I. Introduction

Induction heating is a process of heating electrically conductive materials by using electromagnetic induction. A significant feature of the heating process is that the heat is produced inside the object instead of using an external heat source. Such a technology provides efficient, fast, and contact-free heating, and has become increasingly popular in many medical [1], industrial [2] and domestic applications [3]. The induction-heating systems can provide an efficiency of approximately 84 % which is much higher rate compared to non-induction systems [4]. In addition, the induction-heating technology provides safe heating, and also have a pollution-free nature which is of rising interest for environmental reasons [5].

The induction-heating systems are based on passing a very high frequency current through a coil of wire, thus generating an eddy electromagnetic field (EMF) in the coil shown in Fig. 1 [6], [7]. This eddy EMF in turn leads to heat production. The frequency of the alternating current is determined by the power semiconductor switches that are usually based on insulated gate-bipolar-junction transistor (IGBT) [8].

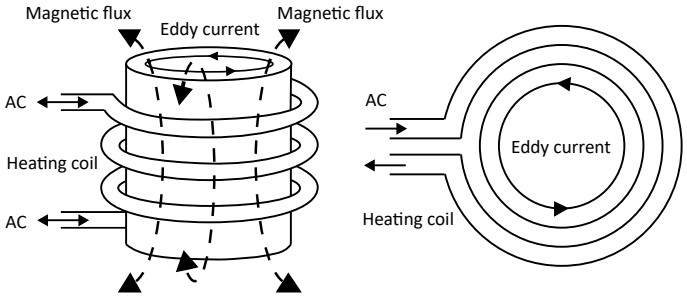

Fig. 1: Principle of induction heating.

A basic representation of an induction-heating system including the control subsystem and the power-electronics stage is shown in Fig. 2. The control subsystem is not only responsible for generating the pulse signals for the IGBT drivers but also for performing several other tasks such as thermal management and protection. Several topologies have been proposed for the IGBT-based inverters used in induction-heating technology [9]–[11]. Among these topologies, the quasi-resonant (QR) inverter is gaining a lot of interest due to the small size (as it applies only one switch and one resonance capacitor) and low price [11].

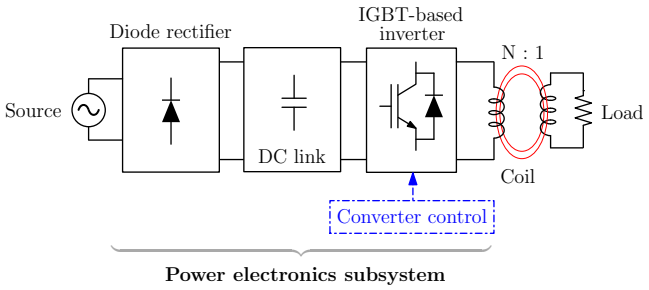

Fig. 2: Conceptual diagram of basic induction-heating system.

The control of QR inverters within an induction-heating system requires to properly determine the duty cycle (and the switching frequency). To determine the switching frequency, the information of the load resistance and the coil inductance are required [6], [12]. For the cases without a current sensor,

the load resistance and coil inductance are usually estimated at the *load-detection* stage which is performed before starting the actual system operation. This process can be implemented in several ways, for example, by considering a certain set of duty cycles in a look-up table of loads, and changing the duty cycle (or even the modulation scheme) iteratively until finding the corresponding resonant frequency [13]. Another example is to directly perform a duty cycle sweep, measuring the power, and comparing the power with the user-requested power [14]–[16]. These parameter-estimation processes need, however, a certain execution time. In addition, the processes require a computation algorithm which is often relatively complex. As a consequence, the conventional methods effectively limit the operation and efficiency of several induction-heating applications which typically apply simple commercial microprocessors in their digital control platform.

This paper proposes a novel technique to estimate the load resistance and the coil inductance for induction-heating systems applying QR inverter. In the method, the resistance and inductance values are estimated during the normal operation of the system (online). The proposed method is based on fitting the sampled voltage to an exponentially-damped sinusoid signal by using an iterative algorithm. The curve-fitting does not need any non-linear optimization or complex signal processing steps, and therefore, it is well implementable in the existing microcontroller of the practical QR inverters. In addition, the method is relatively robust to external noise. Applying the proposed method, the pre-operation process can be fully avoided, and therefore, implementing the estimation of the load resistance and coil inductance is significantly simplified. As the method is simple (from signal processing viewpoint) and generic, it can also be extended to the induction-heating systems with other types of inverters.

The remainder of the paper is organized as follows. Section II reviews the theory behind the quasi-resonant-inverter-based heating system. Section III presents the proposed online approach to obtain the load resistance and the coil inductance. Section IV demonstrates the efficiency and accuracy of the proposed method by applying an experimental prototype emulating the quasi-resonant-based induction heating system. Finally, Section V draws conclusions.

II. Concept Description

Detailed knowledge about all the common topologies used in induction-heating systems can be found in past studies [9]–[11]. In this work, for brevity, the discussion is limited to a simple QR-based induction-heating system. Fig. 3 shows a simplified model of the QR inverter (the parasitic components and saturation effects are neglected). In the figure, R stands for sum of the equivalent load resistance and the coil resistance, L is the equivalent coil inductance, and C is the resonance capacitance. The bus voltage v_{bus} is the half-wave at the fundamental frequency, and v_{tank} is the capacitance voltage. Considering the transient model of the circuit shown in Fig. 3, three operation modes are expected as follows.

i) The switch is on, so $v_{\text{tank}} = v_{\text{bus}}$,
ii) the switch is off, so there is an oscillating RLC circuit, and
iii) the diode is in conduction, and therefore, due to the effect of the bus capacitance, there is a new oscillating RLC circuit with an oscillation frequency different from previous case.

Detailed small-signal analysis of these three modes can be found in [17]. In this work, the second operation mode is particularly interesting as this part of the cycle is eventually used for the parameter estimation. When the switch is off, the time-domain behavior of v_{tank} is expected to follow an under-damped sinusoid given by

$$v_{\text{tank}}(t) = Ae^{-\alpha t}\sin(\omega t + \theta) \tag{1}$$

where:

$$\alpha = R/2L \text{ and } \omega = \sqrt{LC - \alpha^2} \tag{2}$$

and A and θ can be found based on the initial conditions for the capacitance voltage.

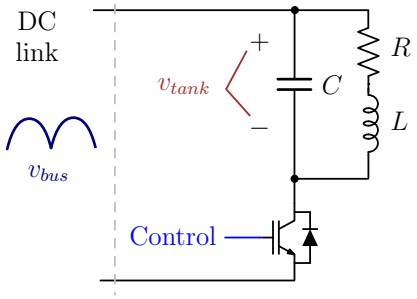

Fig. 3: Simplified model of QR inverter in induction-heating systems.

III. Proposed Approach

The control of a QR inverter is usually implemented through a duty-cycle control (rather than the switching-frequency control) [17]. The implementation requires an estimation of R and L (the value of C is already known). The parameter estimation is usually performed at the *load-detection* stage before starting the heating. This process needs, however, a certain execution time, and it is usually implemented through a computationally-complex algorithm. To tackle this issue, this paper proposes to estimate R and L online (i.e., during the normal operation of the inverter). The estimation process only requires the sampled voltage v_{tank} which has an under-damped sinusoid form, as given in (1).

According to [18], the parameters of an under-damped sinusoid can be estimated in different ways, such as, by solving a nonlinear optimization problem, least mean squared approximation, and performing Fourier or Hilbert Transform. However, a method which is simple and compatible with an existing microcontroller in the QR inverter would be most desired. Thus, in this paper, it is proposed to apply the Newton Raphson (NR) method as the technique is simple and provides fast convergence [19].

Let us assume that v_{tank} is the measured capacitance voltage with M samples. The proposed method to estimate the parameters of v_{tank} based on NR approximation can be performed by the following steps:

1) Assume an initial value for v_{tank}, as $v_{\text{est}}^{(0)}(t) = K_1^{(0)} e^{K_2^{(0)} t} \sin(K_3^{(0)} t + K_4^{(0)}) + K_5^{(0)}$. Thus, the initial vector of coefficients can be given by $\mathbf{K}^{(0)} = [K_1^{(0)}, ..., K_5^{(0)}]$
2) Define the error vector as $\epsilon^{(0)} = v_{\text{tank}} - v_{\text{est}}^{(0)}$ with a length of M
3) Define the Jacobian matrix as

$$J^{(0)} = \begin{bmatrix} \left.\frac{\partial v_{\text{est}}^{(0)}(t)}{\partial K_1^{(0)}}\right|_{t=1} & \cdots & \left.\frac{\partial v_{\text{est}}^{(0)}(t)}{\partial K_1^{(0)}}\right|_{t=M} \\ \vdots & \ddots & \vdots \\ \left.\frac{\partial v_{\text{est}}^{(0)}(t)}{\partial K_5^{(0)}}\right|_{t=1} & \cdots & \left.\frac{\partial v_{\text{est}}^{(0)}(t)}{\partial K_5^{(0)}}\right|_{t=M} \end{bmatrix} \quad (3)$$

4) Find new coefficients as $\mathbf{K}^{(i)} = \mathbf{K}^{(i-1)} - (H^{(i-1)} J^{(i-1)})^{-1} H^{(i-1)} \epsilon^{(i-1)}$, where i is the iteration number and $H^{(i)}$ is the transpose value of the Jacobian matrix at i^{th} iteration.
5) Repeat the above process until norm (or rms value) of the error vector becomes less than a specified threshold δ.
6) By noticing that K_2 is the estimated α, and K_3 is the estimated value of ω based on (2), there will be two unknown variables and two equations from which R and L can be obtained.

Notice that the choice of δ is a trade-off between the convergence speed and the accuracy. It is also emphasized that a distorted v_{tank} (with noise, harmonics, etc.) will lead to a less accurate estimation, as the error vector at each step will be a distorted signal.

IV. Case Study and Experimental Results

The accuracy of the proposed online estimation technique is experimentally validated in this section. In order to emulate an induction-heating system, a simple quasi-resonant circuit shown in Fig. 4 was constructed with an inductance of $L = 80$ μH which is consistent with the typical value for equivalent coil inductance of industrial low-power cooktop systems [14]. The capacitance value is chosen as 300 nF in order to have a resonance frequency around 32 kHz which is equal to the applied switching frequency. The load resistance is selected as $R = 1$ Ω which represents a relatively light load. It is emphasized that the implemented circuit is not a real induction heater but just emulating a simplified induction-heating circuit. However, the parameter values are consistent with a typical low-power cooktop system.

The proposed estimation algorithm is implemented inside a microcontroller to demonstrate the simplicity and the practical applicability of the method. In common induction-heating systems the duty cycle control and other signal processing algorithms are implemented similarly inside a microcontroller [14]–[16]. The implemented circuit is controlled by a digital platform (Texas Instrument microcontroller TMS320F2810

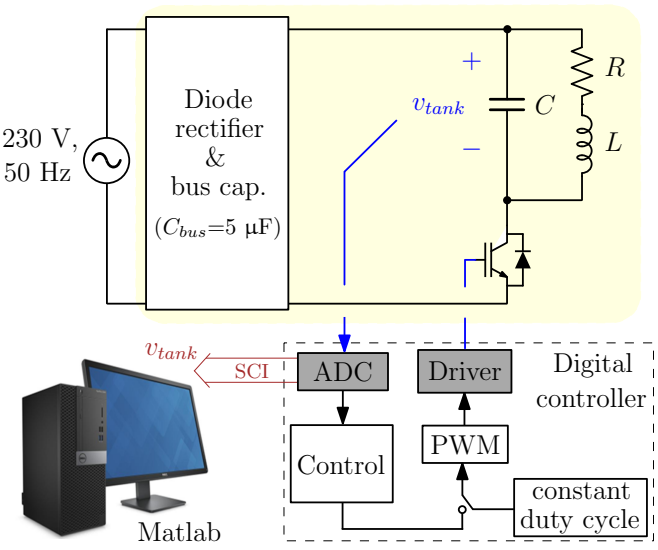

Fig. 4: Experimental setup emulating an induction-heating system by including a QR inverter and a resistive load.

with the core frequency of 150 MHz) that receives the sampled voltage across the capacitance (v_{tank}) and sends the pulse information to the IGBT via built-in driver. In this example, the inverter is kept running at a fixed duty cycle (open loop condition), so the controller is bypassed as shown in Fig. 4. The estimated parameter values (R and L) will be directly accessible for the QR controller, which then can apply the information to improve and optimize the operation the induction-heating system.

To simplify the process, the sampled data is transferred to a computer by using a serial communication interface (SCI). The sampled voltage v_{tank} is used to establish the Jacobian matrix at each iteration as described in the proposed approach in Section III. Then, the error vector is computed and the threshold error is achieved within a few iterations. In the example, δ is assumed to be approximately 0.01, but for other setups having less noise, even a smaller threshold could be considered in order to achieve more accurate results. Once obtained the value for v_{est}, the damped sinusoid equation in (1) is used as a basis to find the values for R and L. As (2) shows, having α and ω will produce two equations with two unknowns (R and L).

After implementing the proposed estimation technique on the experimental setup shown in Fig. 4 (with $L = 80$ μH, $R = 1$ Ω), the values of 79.84 μH and 1.06 Ω were obtained for L and R, respectively. The total execution time of the process was around 10 μs. Very accurate estimation of the parameters is achieved despite the high noise in the setup. The experiment is was repeated with different inductance and resistance values and the results are shown in Table I. In all experiments, the capacitance value was selected as $C = 300$ nF. As these experimental results show, the parameters are accurately obtained in each experiment (always in presence of a high noise).

TABLE I: Accuracy of the proposed online parameter estimation.

	Estimated L	Estimated R
Experiment #1: $L = 60\ \mu$H, $R = 0.5\ \Omega$	60.09 μH	0.48 Ω
Experiment #2: $L = 80\ \mu$H, $R = 1\ \Omega$	79.84 μH	1.06 Ω
Experiment #3: $L = 100\ \mu$H, $R = 2\ \Omega$	99.13 μH	2.19 Ω

In order to further justify the accuracy of the proposed method, the measured capacitance voltage is shown in Fig. 5. In the zoomed version, the measured voltage is compared to the estimated voltage v_{est}. In order to plot v_{est}, a damped sinusoid shown in (1) is assumed (in which the estimated R and L are used). Fig. 5 shows a good matching between the estimated and the measured voltages, thus proving the high accuracy of the proposed estimation technique.

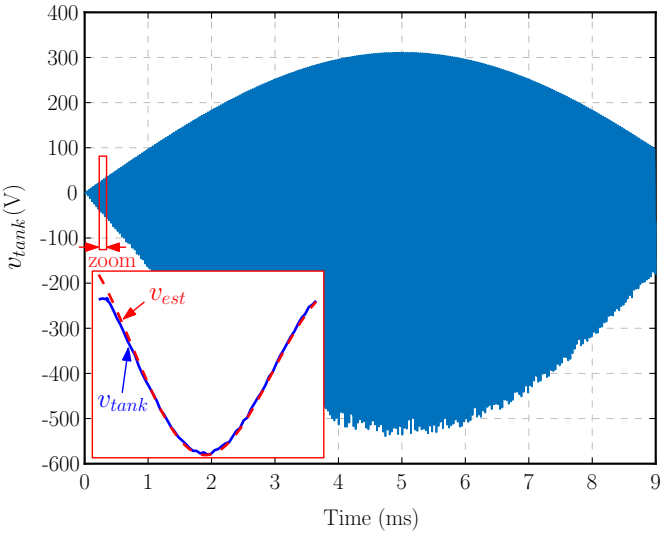

Fig. 5: Experimental results of the capacitance voltage in a QR-based induction-heating system. The measured voltage is compared to the NR-estimated value.

V. Conclusion

Accurate estimation of load and coil parameters play important role in the modeling and control of induction heating systems. The existing methods to estimate the parameters are typically based on computationally complex and time-consuming techniques thus effectively limiting the operation and efficiency of many induction-heating applications. This paper has presented an online estimation technique with which the load and coil parameters can be accurately obtained without time-consuming and complex pre-operation methods. The proposed method is based on fitting the sampled voltage to an exponentially-damped sinusoidal signal and applying an iterative numerical algorithm. The method does not require any non-linear optimization or complex signal processing, and therefore, the method is well implementable in the existing digital control platform in the system. Experimental results based on an emulated quasi-resonant-based induction heating system was used to verify the accuracy of the proposed estimation technique.

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