

Multi Half Bridge LLC Resonant Inverter for Induction Hardening

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ABSTRACT

A multi-half-bridge LLC resonant inverter with three induction coils is used to harden metal workpieces in this research. The system operates at 80 kHz–100 kHz and outputs 3 kW of power, based on load variations. Power is controlled through changing the duty cycle of each inverter module's output voltage waveform and a phase-locked loop for frequency tracking. This method allows soft-switching and improves system efficiency. Stable operation and improved performance demonstrate that the proposed system is suitable for induction hardening. The multi-inverter design improves power distribution, system dependability, flexibility, and scalability for many industrial applications.

Keywords: Induction hardening, LLC resonant inverter, Multi-inverter system, Phase-locked loop, Soft-switching, High-frequency operation

1. INTRODUCTION

Induction hardening is a surface hardening technique that employs electromagnetic induction to heat solely the outside layer of a metal, subsequently followed by quick cooling to create a hard martensitic structure while preserving a resilient core. This method is extensively employed in the automotive and machinery sectors owing to its exceptional precision and dependable quality assurance. In the last ten years, technology has progressed towards digital and automated systems, utilising simulation and data analysis to enhance efficiency and decrease energy use. Consequently, it is ideally suited for contemporary manufacturing and sustainable production methodologies [1–5].

Resonant inverters used in induction hardening can be classified into several main topologies, including series resonant, parallel resonant, series-parallel, and LLC resonant inverters [2, 6]. Each topology offers different characteristics in terms of power control, load adaptability, and operating frequency. The series resonant inverter is suitable for high-power applications with deep heating, while the parallel resonant inverter provides better voltage stability and is commonly used for surface hardening. Hybrid configurations combine the advantages of both types, enabling more flexible operation under varying load conditions. Recently, LLC resonant inverters have gained significant attention due to their high efficiency and soft-switching capability, making them well suited for modern induction hardening systems [7, 8].

The full-bridge resonant inverter is widely used in induction hardening applications due to its capability to handle high power levels; however, it presents several limitations. The circuit configuration is relatively complex, requiring four power switches and sophisticated gate drive and control strategies, which increases system cost and design difficulty. In addition, achieving soft-switching conditions such as zero-voltage or zero-current switching becomes challenging under varying load conditions, leading to increased switching losses and reduced efficiency when operating away from resonance. The inverter also experiences higher voltage and current stress on power devices, particularly during transient conditions, which may affect system reliability [9, 10].

Several studies [7, 11, 12] have applied a phase-locked loop (PLL) for frequency tracking in induction heating applications. This technique plays a crucial role in enabling the inverter system to continuously operate in alignment with the resonant frequency of the load. Since the resonant frequency of the workpiece and induction coil varies with temperature and coupling conditions, the PLL adjusts the inverter switching frequency in real time to match the resonance point. As a result, soft-switching conditions such as zero-voltage switching (ZVS) or zero-current switching (ZCS) can be effectively maintained. In addition, this approach helps reduce power losses, improve overall system efficiency, and minimize stress on power devices.

In addition, several studies [13, 14] have reported that the use of multi-inverter systems for grid-connected applications offers significant advantages in terms of efficiency, reliability, and flexibility. By operating multiple

Manuscript received on March 25, 2026; revised on June 7, 2026; accepted on June 19, 2026. This paper was recommended by Associate Editor Chainarin Ekkaravarodom.

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Digital Object Identifier: 10.37936/ecti-ec.2026243.264545

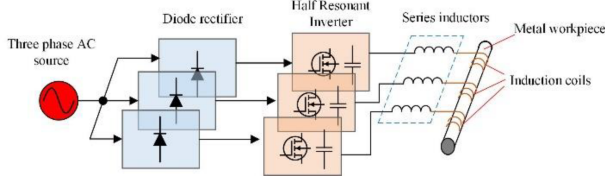


Fig. 1: Multi half-bridge resonant inverter system for induction hardening of metal forming applications.

inverters in parallel, the system can achieve higher power capacity and can be easily expanded. Moreover, system reliability is improved, as the failure of a single inverter does not result in a complete system shutdown, allowing the remaining units to continue operating.

The use of multiple inverters in a multi-half-bridge resonant inverter system provides several significant advantages. It enables effective power sharing among units, reducing stress on individual components and extending their operational lifetime. Each inverter can independently control its corresponding load, allowing precise regulation of voltage, current, and power, which is particularly beneficial for induction heating applications with varying load characteristics. The modular structure also enhances system flexibility, as individual inverters can be selectively operated to match load demand, improving overall energy efficiency. In addition, system reliability is increased since a failure in one inverter does not necessarily interrupt the entire operation. The modular design further simplifies system expansion, maintenance, and scalability. Moreover, operating multiple inverters near optimal conditions, such as zero-voltage switching, improves overall efficiency by minimizing switching losses. Finally, thermal performance is enhanced due to distributed heat generation, reducing localized overheating and facilitating more effective cooling.

The content of this paper is organized as follows. Section 2 presents the operating principle of the multi-half-bridge resonant inverter circuit for three induction coils in induction hardening metal forming applications. Section 3 provides the analysis of the LLC resonant inverter. The design and implementation of the control system and prototype are described in Section 4. Experimental results of the proposed system are presented in Section 5. Finally, conclusions are given in Section 6.

2. HALF BRIDGE RESONANT LLC INVERTER

For the purpose of induction hardening in metal forming applications, the overall architecture of a multi-half-bridge resonant inverter system is depicted in Fig. 1. A three-phase alternating current (AC) power supply, three full-bridge diode rectifiers for converting AC to direct current (DC), three half-bridge resonant inverter circuits, three series inductors, and three induction coils connected with the metal workpieces are the components that make up the system.

Fig. 2 presents the circuit configuration of a multi-half-bridge resonant inverter for three induction coils

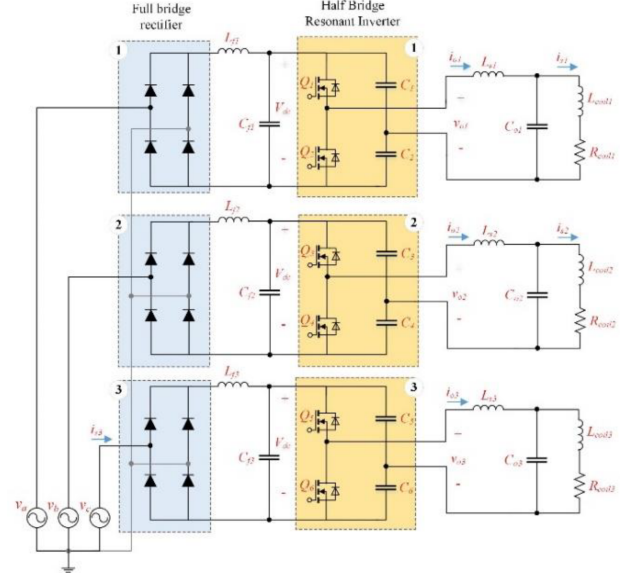


Fig. 2: Multi half-bridge resonant inverter circuit for three induction coils in induction hardening metal forming applications.

in induction hardening and metal forming applications. The system consists of three full-bridge diode rectifiers, each followed by an LC filter, namely L_{f1} and C_{f1} for the first half-bridge inverter, L_{f2} and C_{f2} for the second, and L_{f3} and C_{f3} for the third, respectively. Each filtered DC output supplies a dedicated half-bridge inverter stage. The first half-bridge inverter, composed of power switches Q_1 and Q_2 , delivers high-frequency power to the first LLC resonant tank load. Similarly, the second half-bridge inverter, consisting of switches Q_3 and Q_4 , feeds the second LLC resonant tank, while the third half-bridge inverter, formed by switches Q_5 and Q_6 , supplies the third LLC resonant tank. This configuration enables independent excitation of each induction coil, facilitating flexible and efficient multi-load operation in induction hardening processes.

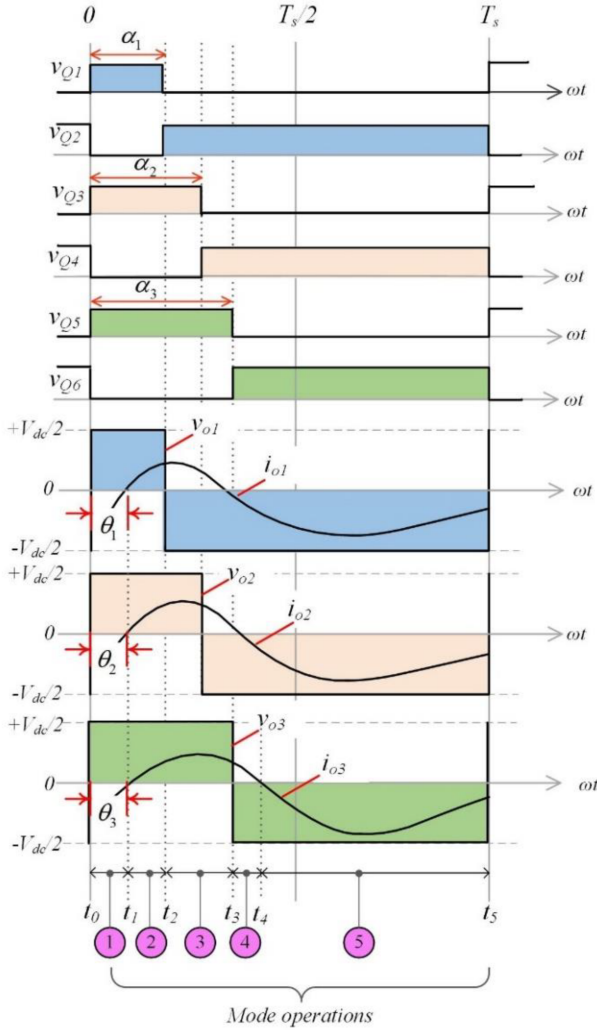
The working waveforms of a multi-half-bridge resonant inverter, which is made up of six power switches powered by control signals, are shown in Fig. 3. The duty cycle of the driving signals can be used to control the output power of each coil: duty cycle α_1 of switch Q_1 controls coil set 1, producing output voltage v_{o1} ; duty cycle α_2 of switch Q_3 controls coil set 2, producing output voltage v_{o2} ; and duty cycle α_3 of switch Q_5 controls coil set 3, producing output voltage v_{o3} . The inverter can function under ZVS conditions because the current lags behind the voltage during operation. Six operating periods can be identified by analyzing the system's operation over a single switching period once it has reached steady state.

3. CIRCUIT ANALYSIS

The analysis of the multi-half-bridge LLC resonant inverter for induction hardening can be represented by

Table 1: Mode operations of multi half bridge resonant inverter.

Mode operations	Half bridge inverter 1				Half bridge inverter 2				Half bridge inverter 3			
	Switches		Diodes		Switches		Diodes		Switches		Diodes	
	Q_1	Q_2	D_1	D_2	Q_3	Q_4	D_3	D_4	Q_5	Q_6	D_5	D_6
1 ($t_0 - t_1$)	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF
2 ($t_1 - t_2$)	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
3 ($t_2 - t_3$)	OFF	OFF	OFF	ON	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
4 ($t_3 - t_4$)	OFF	ON	OFF	OFF	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON
5 ($t_4 - t_5$)	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF

**Fig. 3:** Main waveforms of a multi half-bridge resonant inverter.

the equivalent circuits of the three induction heating loads, as shown in Fig. 4. Each circuit consists of a DC bus supply V_{dc} , a series inductor, and a capacitor connected in parallel with the induction coil load. Based on the circuit in Fig. 4, the total impedance of each load can be expressed as given in (1). When considering the phase angle between the current flowing through each

induction coil and the voltage across the LLC resonant tanks, the current must always lag the voltage due to the inductive nature of the load. To ensure that the resonant inverter operates under ZVS conditions, the phase angle for each branch can be expressed as given in (2).

$$Z_1(j\omega_o) = \frac{\omega_o R_{coil1} L_{coil1}^2}{\omega_o L_{coil1}^2 - j R_{coil1} (L_{s1} + L_{coil1})}$$

$$Z_2(j\omega_o) = \frac{\omega_o R_{coil2} L_{coil2}^2}{\omega_o L_{coil2}^2 - j R_{coil2} (L_{s2} + L_{coil2})} \quad (1)$$

$$Z_3(j\omega_o) = \frac{\omega_o R_{coil3} L_{coil3}^2}{\omega_o L_{coil3}^2 - j R_{coil3} (L_{s3} + L_{coil3})}$$

$$\theta_1 = \tan^{-1} \left(\frac{R_{coil1} (L_{s1} + L_{coil1})}{\omega_o L_{coil1}^2} \right) > 0$$

$$\theta_2 = \tan^{-1} \left(\frac{R_{coil2} (L_{s2} + L_{coil2})}{\omega_o L_{coil2}^2} \right) > 0 \quad (2)$$

$$\theta_3 = \tan^{-1} \left(\frac{R_{coil3} (L_{s3} + L_{coil3})}{\omega_o L_{coil3}^2} \right) > 0$$

The resonant frequency equations for the three LLC resonant tanks are given in (3).

$$\omega_{o1} = \left(\frac{L_{s1} + L_{coil1}}{L_{s1} \cdot L_{coil1} \cdot C_{o1}} \right)^{1/2}$$

$$\omega_{o2} = \left(\frac{L_{s2} + L_{coil2}}{L_{s2} \cdot L_{coil2} \cdot C_{o2}} \right)^{1/2} \quad (3)$$

$$\omega_{o3} = \left(\frac{L_{s3} + L_{coil3}}{L_{s3} \cdot L_{coil3} \cdot C_{o3}} \right)^{1/2}$$

The currents flowing through the resonant tanks for all three loads are expressed as given in (4), and the currents flowing through the induction heating coils are

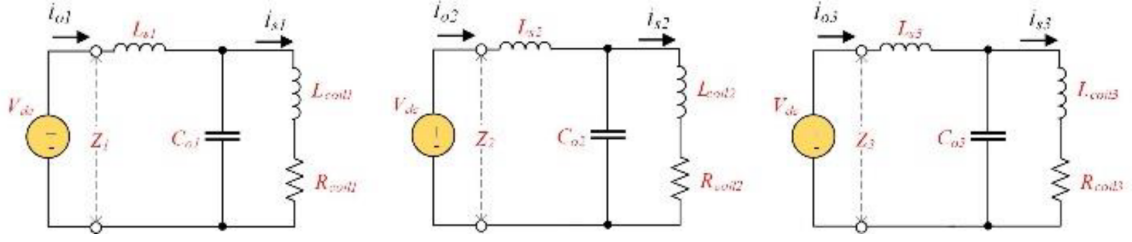


Fig. 4: The equivalent circuit of three multi half-bridge resonant inverters supplying inductive loads 1, 2, and 3.

expressed as given in (5).

$$\begin{aligned}
 i_{o1} &= \left(\frac{L_{s1}^2 L_{coil1}}{L_{s1}^2} - j \frac{L_{s1} + L_{coil1}}{\omega_o L_{s1}^2} \right) V_{o1} \\
 i_{o2} &= \left(\frac{L_{s2}^2 L_{coil2}}{L_{s2}^2} - j \frac{L_{s2} + L_{coil2}}{\omega_o L_{s2}^2} \right) V_{o2} \\
 i_{o3} &= \left(\frac{L_{s3}^2 L_{coil3}}{L_{s3}^2} - j \frac{L_{s3} + L_{coil3}}{\omega_o L_{s3}^2} \right) V_{o3} \\
 i_{s1} &= \frac{L_{s1}}{L_{coil1}} \cos \varphi_1 \cdot i_{o1} \\
 i_{s2} &= \frac{L_{s2}}{L_{coil2}} \cos \varphi_2 \cdot i_{o2} \\
 i_{s3} &= \frac{L_{s3}}{L_{coil3}} \cos \varphi_3 \cdot i_{o3}
 \end{aligned} \quad (4)$$

The average power at the load is determined by

$$\begin{aligned}
 P_{o1} &= \text{Re}\{Z_1(j\omega_o)\} I_{o1,\text{rms}}^2 \\
 P_{o2} &= \text{Re}\{Z_2(j\omega_o)\} I_{o2,\text{rms}}^2 \\
 P_{o3} &= \text{Re}\{Z_3(j\omega_o)\} I_{o3,\text{rms}}^2
 \end{aligned} \quad (5)$$

where $I_{o1,\text{rms}}$, $I_{o2,\text{rms}}$, and $I_{o3,\text{rms}}$ are the root-mean-square (RMS) current values of coil 1, coil 2, and coil 3, respectively. The total power equation of a multi-half-bridge resonant inverter can be expressed as follows:

$$P_{\text{total}} = \sum_{k=1}^{\infty} \frac{\omega_o^2 L_{sk}^2 R_{coilk}}{\omega_o^2 L_{sk}^2 - L_{coilk}^2 \left(1 + \frac{L_{sk}}{L_{coilk}} \right)} \quad (6)$$

The analysis of the LLC resonant tank and the conditions required for soft-switching can be evaluated according to the following criteria:

Mathematical analysis of the LLC resonant tank impedance: The input impedance $Z_{in}(j\omega)$ of the proposed LLC resonant tank seen by each half-bridge module can be expressed using the first harmonic approximation as follows:

$$Z_{in}(j\omega) = j\omega L_s + \frac{1}{j\omega C_o} + (j\omega L_{coil} \parallel R_{eq}) \quad (7)$$

where R_{eq} is the equivalent load resistance representing the workpiece.

Table 2: Measured and experimental setup parameters.

Experiment parameters	Values	Unit
V_{dc}	300	V
$C_1 = C_2 = C_3 = C_4 = C_5 = C_6$	10	μF
$C_{f1} = C_{f2} = C_{f3}$	27	μF
$L_{f1} = L_{f2} = L_{f3}$	100	μH
$L_{s1} = L_{s2} = L_{s3}$	2.85	μH
$C_{o1} = C_{o2} = C_{o3}$	1.5	μF
$L_{coil1} = L_{coil2} = L_{coil3}$	25	μH
$R_{coil1} = R_{coil2} = R_{coil3}$	0.867	Ω
FDL100N50F MOSFETs (Q_1 - Q_6)		
$V_{DS} = 500 \text{ V}$, $I_D = 100 \text{ A}$, and $R_{on} = 55 \text{ m}\Omega$		

Conditions required for soft-switching ZVS: To achieve ZVS for the power MOSFETs (Q_1 to Q_6) and eliminate capacitive turn-on losses, the resonant tank must operate in the inductive region. This requires the following conditions to be strictly satisfied:

Phase angle condition ($\theta > 0^\circ$): The phase angle of the input impedance must be positive, meaning the resonant current (i_{ok}) must lag behind the fundamental output voltage (v_{ok}). **Frequency condition ($f_s > f_o$):** The operating switching frequency managed by the PLL tracking system must be maintained slightly higher than the load resonant frequency, which is defined by:

$$f_o = \frac{1}{2\pi \sqrt{L_s C_o}} \quad (8)$$

Dead-time and inductive energy condition: The energy stored in the inductive components during the dead-time (t_d) must be sufficient to discharge the output capacitance (C_{oss}) of the incoming MOSFET and charge the outgoing MOSFET. This condition is governed by:

$$\frac{1}{2} L_{eq} I_{a,\text{peak}}^2 > \frac{1}{2} (2C_{oss}) V_{dc}^2 \quad (9)$$

4. SYSTEM IMPLEMENTATION

The practical implementation of the control system for a multi-half-bridge resonant inverter used in induction hardening is illustrated in Fig. 5. The system focuses on regulating both the output current and the phase angle of each load, which are controlled by a microcontroller, specifically the STM32F3 Discovery board. In this configuration, the output current of each resonant inverter

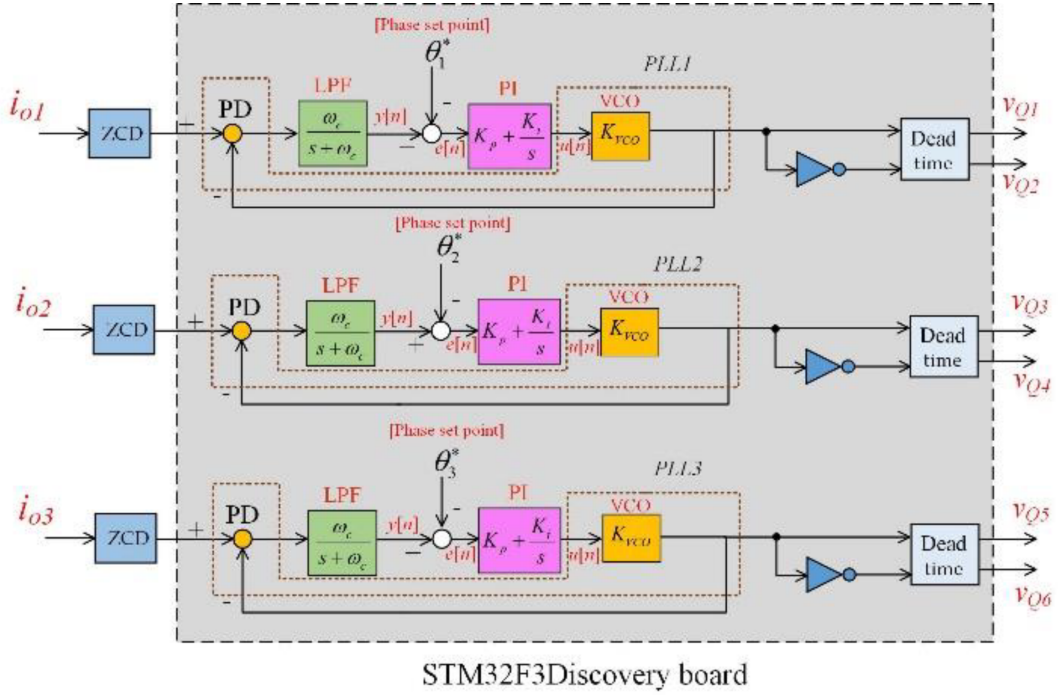


Fig. 5: Control system of a multi half-bridge resonant inverter using the STM32F3Discovery board.

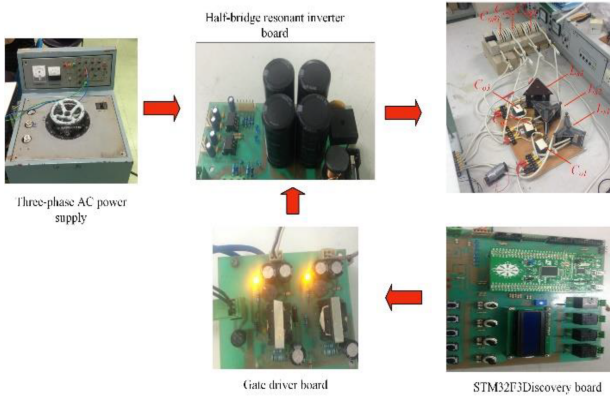


Fig. 6: Prototype of a multi half-bridge resonant inverter for induction hardening.

branch is first processed through a zero-crossing detector (ZCD). The primary function of the ZCD is to detect the zero-crossing points of the alternating current and convert the sinusoidal waveform into a digital signal within the range of 0–5 V, making it suitable as an input for the microcontroller. The resulting signal is then compared with the voltage oscillation signal generated by the voltage-controlled oscillator (VCO). This comparison produces an error signal, which is subsequently passed through a low-pass filter (LPF) to remove high-frequency components and noise. The filtered signal is then compared with a reference phase angle, generating a refined error signal. This error signal is processed through a proportional–integral (PI) controller for compensation, ensuring accurate tracking of the desired phase angle

and stable system performance. The compensated output is then fed back into the VCO, which generates the switching control signals. Finally, these control signals are used to drive the power stage of each half-bridge resonant inverter. Before being applied to the switching devices, the signals must pass through a dead-time circuit to prevent shoot-through and ensure safe operation of the inverter.

In the control architecture of the multi-half-bridge resonant inverter using the STM32F3Discovery board, the analog load currents i_{o1} , i_{o2} , and i_{o3} are acquired through the ADC to execute the feedback control loop. To attenuate the high-frequency switching noise inherent to the inverter, a discrete-time digital low-pass filter (LPF) is introduced to process the sampled signals, thereby significantly improving signal integrity. The first-order IIR filter, commonly referred to as the exponential moving average (EMA), offers rapid execution and minimal computational resource consumption on the STM32 microcontroller. In the continuous-time domain, its transfer function is expressed as:

$$H(s) = \frac{\omega_c}{s + \omega_c} \quad (11)$$

When converted to discrete-time, (11) yields the following difference equation:

$$y[n] = \alpha \cdot x[n] + (1 - \alpha) \cdot y[n - 1] \quad (12)$$

where $x[n]$ is the ADC reading at the current time step, $y[n]$ is the current filtered output, $y[n - 1]$ is the previous filtered output, and α is the filter coefficient ranging between 0 and 1. The filter coefficient is defined as

follows:

$$\alpha = \frac{2\pi f_c T_s}{1 + 2\pi f_c T_s} \approx 2\pi f_c T_s \quad (13)$$

where f_c is the desired cut-off frequency selected at 1 kHz, f_s is set to 95 kHz, and the sampling period (T_s) is $1/f_s = 10.526 \mu\text{s}$. Substituting f_c and T_s into (13) yields $\alpha = 0.062035$ and $1 - \alpha = 0.937965$. Therefore, the new discrete-time difference equation derived from (12) for implementation on the STM32F3 microcontroller becomes

$$y[n] = 0.062035x[n] + 0.937965y[n - 1] \quad (14)$$

The design of a PI controller for the PLL in a multi-coil multi-LLC resonant inverter system is crucial for resonant frequency tracking to ensure ZVS operation and stable power control. In the design and tuning of the PI controller for this system, the target phase angle is specified at 30° . This specific angle safely guarantees ZVS operation, even in the presence of cross-coupling interference among the three sets of coils. To provide a clear overview, the calculation of the PLL gains (K_p and K_i) is detailed, spanning from continuous-time s-domain modelling to digital implementation on a microcontroller. The PLL closed-loop structure has three main blocks in a feedback loop, and each block has its own gain. First, the Phase Detector (K_{PD}) changes the phase difference from degrees or radians into a control number; if 1 rad equals 1 control signal, then $K_{PD} = 1$. Second, the loop filter acts as the controller. Third, the VCO (K_{VCO}) or digital frequency generator, changes the controller output into an angular frequency (ω) in rad/s, where $K_{VCO} = 2\pi = 6.28318 \text{ rad/s}$.

Defined as the slope of the phase-versus-frequency characteristic around the inductor's 30-degree operating point, evaluated when the magnitude equals $K_{load} = 1 \times 10^{-5} \text{ rad/(rad/s)}$ where the system gain (K_T) is $K_{PD} \cdot K_{load} \cdot K_{VCO} = 6.28318 \times 10^{-5}$.

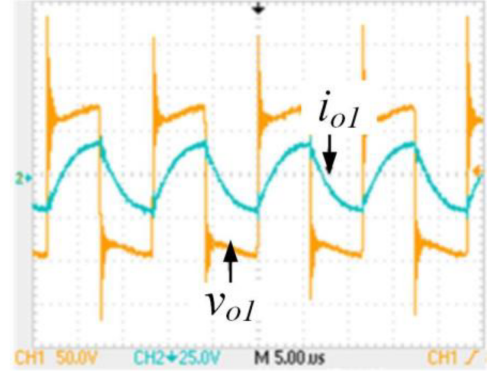
Set the damping ratio (ξ) to 1.0 for a critically damped system. This design ensures the PLL loop is stable, does not oscillate, and locks the phase smoothly. It keeps the frequency smooth and steady with no overshoot. To achieve an optimal settling time for loop response and phase locking, the natural frequency (f_n) is selected at 1000 Hz to filter out noise, where $\omega_n = 2\pi \cdot f_n = 6283.18 \text{ rad/s}$.

The calculation of K_p and K_i from the standard equation of a second-order control system defines the relationship between the desired parameters ξ and ω_n and the controller gains as follows:

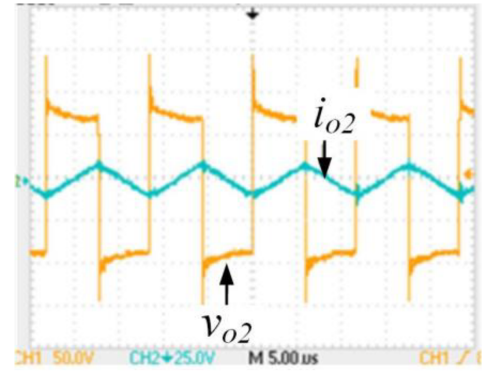
$$K_i = \frac{\omega_n^2}{K_T} \approx 6.283 \times 10^{11}$$

$$K_p = \frac{2\xi\omega_n}{K_T} \approx 2.0 \times 10^8$$

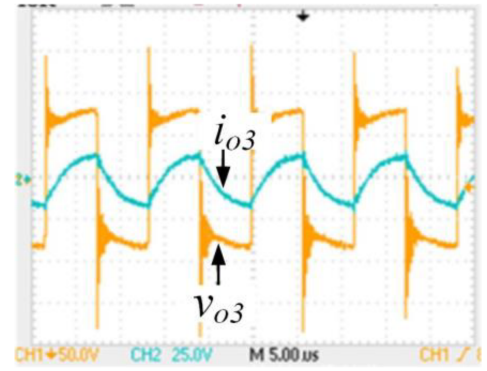
Therefore, the discrete-time equation of the PI controller implemented on the STM32F3 microcontroller



(a)



(b)



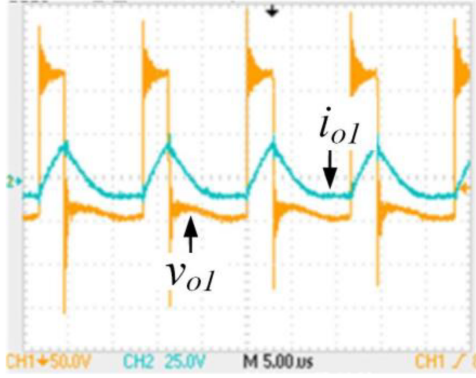
(c)

Fig. 7: Output voltage and current waveforms with a 50% duty cycle (v : 50 V/div, i : 25 A/div, Time: 5 μs /div).

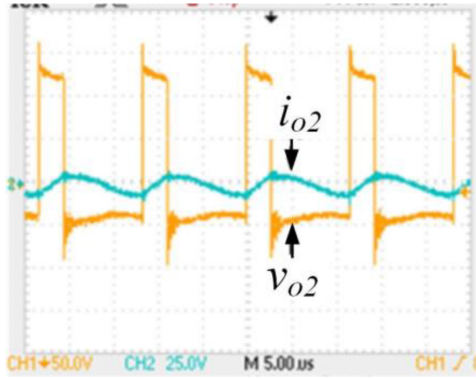
board is expressed as

$$u[n] = u[n - 1] + K_p \cdot e[n] + (K_i \cdot T_s - K_p) \cdot e[n - 1] \quad (15)$$

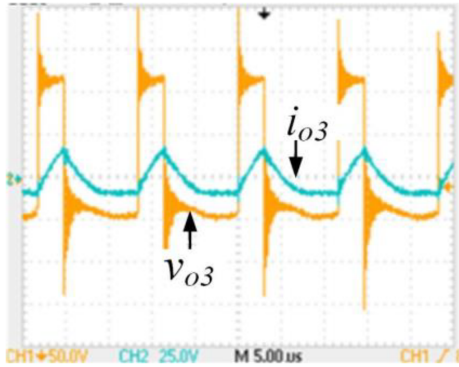
The parameters used for the practical implementation of the proposed system are summarized in Table 2. These parameters include key electrical and control variables required for the operation of the multi-half-bridge resonant inverter, such as component values in the resonant tank, switching conditions, and controller settings. The prototype of the multi-half-bridge resonant



(a)



(b)



(c)

Fig. 8: Output voltage and current waveforms with a 25% duty cycle (v : 50 V/div, i : 25 A/div, Time: 5 μ s/div).

inverter for induction hardening is shown in Fig. 6.

By substituting these electrical component values ($L_{s1} - L_{s3}$, $L_{coil1} - L_{coil3}$, and $C_{o1} - C_{o3}$) into the analytical mathematical model defined in (3), the theoretical resonant frequency of the system is calculated as $f_o = 94.34$ kHz. This computed frequency serves as the baseline for the microcontroller-based control loop to achieve stable phase tracking and maintain soft-switching operations.

The high-frequency inductor with an inductance of

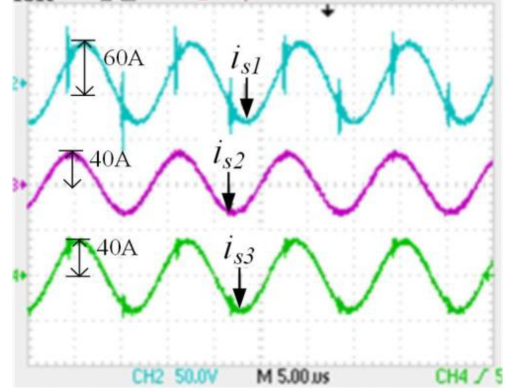


Fig. 9: Current waveforms flowing through the induction coil 1, coil 2, and coil 3 with a 50% duty cycle (Scale: 50 A/div, 5 μ s/div).

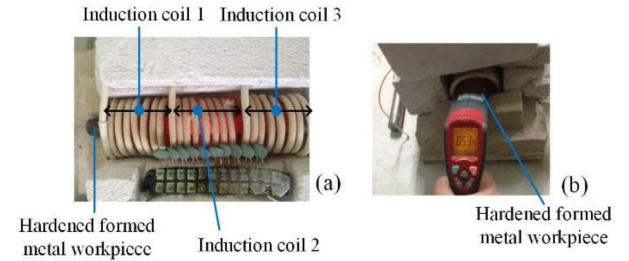


Fig. 10: Induction hardening of a metal workpiece: (a) the workpiece during induction heating, (b) temperature during the hardening process.

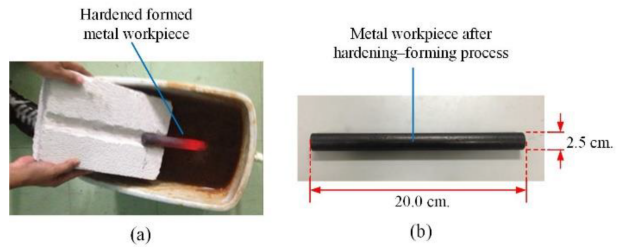


Fig. 11: Hardened workpiece: (a) the workpiece after removal from the crucible, (b) the workpiece at steady state at room temperature.

2.85 μ H is designed using a ferrite core structure with an appropriate air gap to prevent saturation and achieve the desired inductance. The winding is implemented using thick or multi-strand conductors to handle a high current of 30 A while minimizing skin and proximity effects at 90 kHz. The design also considers thermal management and core loss reduction to ensure stable operation at the resonant frequency, making it suitable for high-frequency resonant inverter applications.

5. RESULTS

The proposed prototype of a multi-half-bridge resonant inverter circuit for three induction coils in induction hardening metal forming applications is rated at 3 kW.

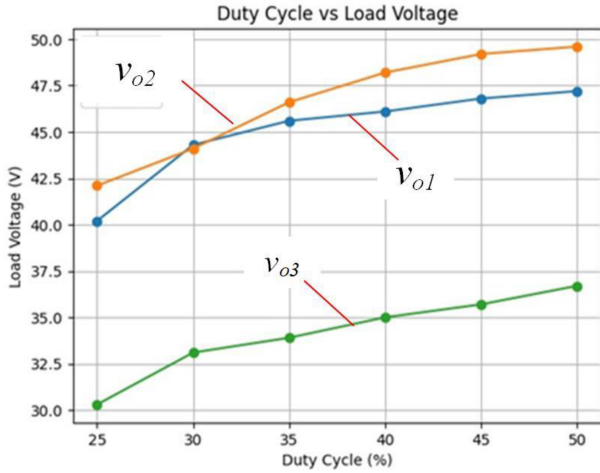


Fig. 12: Relationship between duty cycle and voltage of a multi half-bridge resonant inverter.

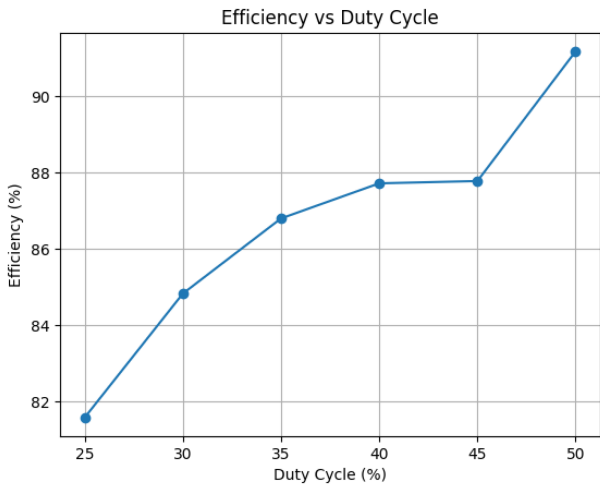


Fig. 13: System efficiency during power adjustment.

It operates within a switching frequency range of 80–100 kHz, which varies depending on changes in load parameters. The experimental results of the proposed system are illustrated in Figs. 7–8. Fig. 7 depicts the voltage and current waveforms shown at a 50% duty cycle during power regulation. In this figure, subfigures (a), (b), and (c) show responses of induction coil loads 1, 2, and 3, respectively. In comparison, Fig. 8 shows the comparable voltage and current waveforms at a 25% duty cycle. Similarly, subfigures (a), (b), and (c) demonstrate the behavior of induction coil loads 1, 2, and 3, respectively. Based on the examination results, the control system successfully ensures that the inverter operates in ZVS mode throughout the power regulation range. Fig. 9 shows the currents flowing through all three loads during power regulation with a 50% duty cycle and an operating frequency of 96.15 kHz. Fig. 10 illustrates the induction hardening process of a metal workpiece. In Fig. 10(a), the workpiece is subjected to induction heating, where a high-frequency alternating current flows through the

induction coil, generating a rapidly varying magnetic field. This induces eddy currents within the workpiece, resulting in localized heating due to resistive losses. The heating is concentrated on the surface layer, which is essential for achieving surface hardening while maintaining the core properties of the material. Furthermore, because the workpiece moves sequentially through the multi-coil arrangement, a progressive thermal propagation occurs from left to right. This motion creates a cumulative thermal gradient along the workpiece, where the material entering the subsequent coil stages carries residual heat accumulated from the preceding stage. This localized temperature rise directly influences the material's physical property, modifying both its magnetic permeability and electrical resistivity. Consequently, this cumulative thermal gradient alters the equivalent load impedance of each progressive stage, particularly causing a parameter mismatch in the coil 2 and leading to the non-identical current waveform characteristics observed in the experimental results.

The temperature profile during the hardening process is illustrated in Fig. 10(b). Driven by high power density and localized electromagnetic induction, the system successfully elevates the surface temperature of the medium-carbon steel workpiece to its required austenitizing range (850°C to 950°C) within just 8 to 10 seconds. This precise thermal control ensures uniform hardening and prevents thermal damage. Immediately after attaining the target temperature, the workpiece undergoes quenching to achieve the desired hardness and mechanical characteristics. Fig. 11 presents the hardened workpiece at different stages after the induction hardening process. In Fig. 11(a), the workpiece is shown immediately after being removed from the crucible, where it still retains a high temperature following the heating and quenching processes. At this stage, the surface layer has undergone rapid cooling, resulting in increased hardness, while the core maintains its original mechanical properties. Fig. 11(b) illustrates the workpiece after it has cooled down and reached thermal equilibrium at room temperature. In this condition, the material properties become stable, and the effectiveness of the hardening process can be observed. This stage is important for evaluating the final surface quality, hardness distribution, and overall structural integrity of the workpiece.

Fig. 12 illustrates the relationship between the duty cycle and the load voltage of a multi-half-bridge resonant inverter for three load branches v_{o1} , v_{o2} , and v_{o3} . As observed from the graph, the load voltage of all three branches increases as the duty cycle rises from 25% to 50%, indicating that the output voltage can be effectively regulated by adjusting the duty cycle. Specifically, v_{o2} exhibits the highest voltage across the entire operating range, followed by v_{o1} , while v_{o3} shows the lowest voltage levels. The rate of voltage increase is relatively linear for v_{o1} and v_{o2} , suggesting stable and predictable control characteristics. In contrast, v_{o3} shows a more

gradual increase, which may be attributed to differences in load conditions or impedance characteristics of the third branch.

Fig. 13 illustrates the measured system efficiency as a function of the duty cycle. The experimental measurements were conducted under a constant DC bus voltage of 140 V, while the duty cycle was varied from 25% to 50% of the rated power. As observed from the curve, the overall system efficiency exhibits an upward trend as the output power increases, rising from 81% at a 25% duty cycle to 91% at a 50% duty cycle. This improvement is primarily attributed to the system's capability to maintain ZVS operation for the inverter across the entire operating range, thereby significantly reducing switching losses under heavy load conditions. This trend indicates that the inverter operates more efficiently at higher power levels. In the mid-range (around 35–45%), the efficiency shows a gradual improvement and begins to stabilise, suggesting that the system reaches a relatively optimal operating region. At the highest duty cycle of 50%, the efficiency reaches its peak value, demonstrating improved power conversion performance and reduced relative losses. Overall, the results confirm that the proposed multi-half-bridge resonant inverter maintains high efficiency across the entire power adjustment range, with particularly strong performance at higher duty cycles.

6. CONCLUSION

This paper discusses the design and implementation of a multi-half-bridge LLC resonant inverter for induction hardening applications employing three induction coils. The proposed approach functions efficiently within a switching frequency range of 70 kHz to 100 kHz and can provide up to 3 kW of power for the hardening process while supporting variations in load characteristics. The application of numerous inverters facilitates efficient power control, increased flexibility, and enhanced system reliability in contrast to traditional single-inverter systems.

In addition, the application of PLL control ensures accurate frequency tracking, allowing the system to continuously operate at or near the resonant frequency under varying conditions. This enables the maintenance of soft-switching conditions, reduces switching losses, and improves overall system efficiency. Furthermore, the LLC resonant topology helps reduce stress on power devices and supports high-frequency operation.

The key contributions and advantages of the proposed system include:

- 1) **Simplified topology and low complexity:** Unlike conventional multi-inverter LLC architectures that rely on intricate decoupling networks, the proposed system employs a streamlined design, which effectively minimizes the overall component count, system volume, and fabrication costs.
- 2) **Independent power distribution:** By utilizing an innovative system, the system guarantees precise and

independent power sharing among multiple induction heating coils simultaneously, completely eliminating cross-regulation issues.

- 3) **Extended soft-switching capabilities:** The proposed design secures the exceptionally wide ZVS operating range for all inverter switches, preventing the loss of soft-switching even during light load operations.
- 4) **High overall efficiency:** The suppressed switching losses across the entire power adjustment range, the system yields enhanced performance under heavy loads, achieving an impressive peak efficiency of up to 91%.

Experimental results validate the effectiveness of the system, demonstrating stable operation, improved thermal performance, and high efficiency. Therefore, the developed multi-inverter LLC resonant system is a promising solution for modern induction hardening applications, offering high performance, scalability, and suitability for industrial implementation.

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