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High Frequency Inverter with Fuzzy Logic Controller for Portable Induction Heater

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Abstract – *The development of technology today makes humans strive to save natural resources and switch to alternative energy. For reasons of saving energy, saving costs, easy to use, and having a high level of safety, induction heaters can be used as an alternative to overcome these problems. Induction heaters can generate heat through the process of electromagnetic induction when cookware made of metal is brought closer. In this process, the coil is supplied with alternating electric current from a high-frequency inverter, which then induces the cookware with metal material to cause heat. The heat in the induction heater will be regulated through the switching frequency of the high-frequency inverter, which gets its voltage source from a 24V battery and increases the voltage to 48V. This induction heater is designed to maintain the setpoint temperature of 70°C and 100°C using fuzzy logic control. From the test results, it can be seen that the fuzzy logic control can reach a setpoint temperature of 70°C within 20 minutes, and after being disturbed, the fuzzy logic control can maintain the setpoint temperature with an error percentage of around 0.14% - 0.29%. Meanwhile, the setpoint temperature of 100°C can be achieved within 35 minutes, and after being disturbed, the fuzzy logic control can maintain the setpoint temperature with an error percentage of around 0.14% - 0.9%.*

Keywords – *High Frequency Inverter; Electromagnetic Induction; Eddy Current; Induction Heater; Fuzzy Logic Controller.*

I. INTRODUCTION

CURRENT technological developments make humans strive to save natural resources and switch to alternative energy [1]. One of them is a heating device for cooking or a stove. The transition from fossil fuel-based cooking to electric stoves has been driven by the need for cleaner, more efficient, and sustainable energy use [2,3]. Electric stoves, particularly induction cookers, have shown higher energy efficiency and lower carbon emissions compared to traditional gas stoves [4,5]. However, the adoption of improved cookstoves in developing countries faces challenges such as high costs, cultural preferences, and lack of awareness [6,7]. To address these issues, researchers have proposed innovative solutions like hybrid stoves combining gas and induction technology [8] and smart electric stoves with automatic control systems [9]. The success of electric cooking programs depends on factors such as targeted implementation, field testing, and consumer involvement [7]. Overall, electric cooking presents a promising option for clean and efficient cooking, particularly in countries with abundant renewable energy resources [2]. However, this will have an impact on increasing the use of electrical energy.

Recent research highlights induction stoves as a promising alternative for efficient and clean cooking. Induction stoves offer higher energy efficiency (up to 90%) compared to gas (40%) and traditional electric stoves (74%) [10]. They provide economic benefits, with potential savings of 44% compared to LPG in Peru [11] and better cost-efficiency in Indonesia [12]. Induction stoves are also safer and more environmentally friendly, with lower carbon emissions than LPG stoves [4]. Factors influencing adoption include speed, maintenance, cost, and safety [13]. Implementation challenges include high initial costs, required magnetic cookware, and perceived reliability issues [10]. However, successful implementation, as seen in Ecuador's "Plan Fronteras," can lead to significant energy savings and reduced greenhouse gas emissions [14]. Technological readiness and social context play crucial roles in acceptance and continued use of induction stoves [15]. The heating system of an induction stove does not origi-

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nate from fire, so the possibility of a fire accident is low and the level of safety is higher. Induction stoves do not require oil or gas fuel but instead use electrical energy, the same as electric stoves. The difference is that an electric stove uses a filament to produce heat, while an induction stove uses electromagnetic induction from the stove to metal cooking utensils to produce heat.

Induction stoves use electromagnetic induction to heat metal cookware directly, offering superior thermal response, convenience, and safety compared to conventional ranges [16]. These stoves operate at frequencies of 20-100 kHz [17] and can produce conducted emissions that may interfere with other electronic devices [18]. While traditional induction stoves were limited to ferromagnetic cookware, recent developments have enabled heating of non-magnetic metals like aluminum [19, 20]. Multi-resonant inverters have been applied to reduce power losses and device size for all-metal compatibility [20]. Research has also explored utilizing leakage flux for wireless power transfer applications [21]. Studies have measured electromagnetic field strengths around induction stoves to assess user exposure levels [22]. Ongoing research focuses on improving multiphysical simulations and addressing design challenges for these increasingly popular cooking appliances [17]. In this process, the coil is fed by a high frequency alternating electric current, which will produce electrical energy that can induce cooking utensils made of metal. In cooking utensils, eddy currents and hysteresis losses will form, which will cause heat [23]. This heat is used to heat food ingredients. Therefore, a high-frequency inverter is needed as a heating supply that can be applied easily and the heat produced by the induction stove can be adjusted according to user needs.

Based on these problems, in this paper, the author will design a high-frequency inverter connected in series with a resonant circuit to produce high-frequency alternating electricity. The inverter will get a source from the battery, and heat regulation on the induction heater or induction stove is done by adjusting the switching frequency on the inverter. The heat produced by the induction stove will be detected by a temperature sensor and fed back to the microcontroller. From this data, the microcontroller will adjust the switching frequency on the inverter so that the heat produced by the induction stove can be kept close to the required value.

II. RESEARCH METHODS

In this paper, a high-frequency inverter with a full-bridge series resonant inverter topology is implemented, which is applied to induction heaters (induction stoves).

In the induction heating process, a coil that is powered by a high-frequency alternating electric current will produce electrical energy that can induce the cooking utensil. Cooking utensils made of stainless steel have ferromagnetic properties, so eddy currents will form, which will generate heat. This heat will be used for cooking. The heat in this induction heater will be regulated by the switching frequency on a single-phase inverter, which gets a voltage source from a 24V battery whose voltage has been increased to 48V. The PWM setting on this inverter uses STM32F407VGTx with a fuzzy logic controller to regulate the switching frequency on the induction heater. The push button here functions as a menu for selecting the temperature setpoint that will be used on the induction stove. The voltage sensor is used to measure the input voltage value on the inverter, while the temperature sensor is used to measure the temperature value on the induction heater. The sensor is connected to the ADC on the microcontroller, and the results are then displayed on the LCD. The system planning in this paper can be shown in the system block diagram in Figure 1 and the system design in Figure 2.

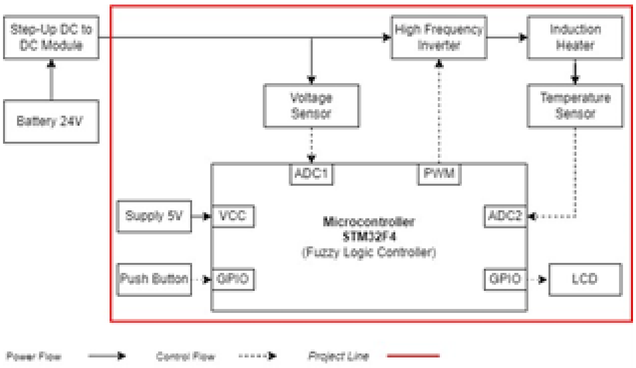

Figure 1: System Block Diagram

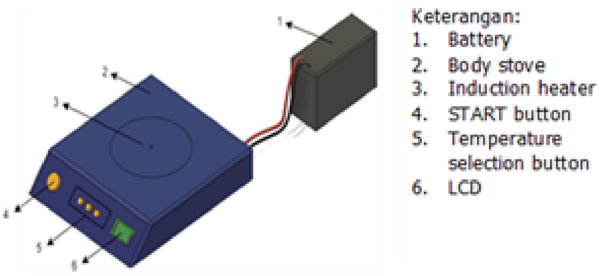

Figure 2: System Design

i. *High-Frequency Inverter*

An inverter is a circuit that can convert DC electricity into AC electricity. One type of inverter that is often used is a full-wave inverter. This inverter circuit consists of four semiconductor switches, a DC current source, and a driver to run the four switches.

The source of the inverter is DC voltage obtained from the battery. Based on the principle and conversion process, inverters are divided into three types: series, parallel, and bridge models. The bridge model itself consists of a half-bridge model and a full-bridge model. In principle, this full-bridge inverter has three voltage levels, namely $+V_{\mathrm{DC}}$, $-V_{\mathrm{DC}}$, and 0 (zero), depending on which switch is closed [24]. The switching combinations of S1, S2, S3, and S4 can be shown in Figure 3.

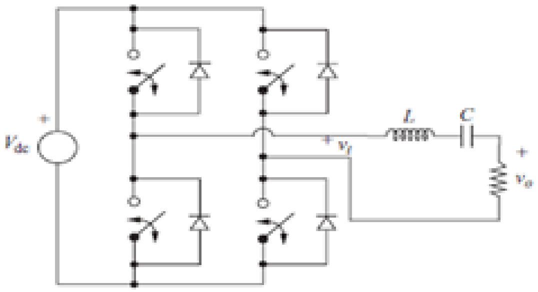

Figure 3: Full-Bridge Series Resonant Inverter

The specifications of the high-frequency inverter and other supporting components can be shown in Table 1.

Table 1: High-Frequency Inverter Specifications and Supporting Components

Hardware	**Specifications**
High-Frequency Inverter	
Switching Frequency (F)	55 kHz–95 kHz
Resonant Frequency (f_0)	40 kHz
Input Voltage (V_{in})	48 V
Output Voltage (V_{o})	37.26 V
MOSFET	35N60C6
Induction Heater	
Inductor (L)	163 μH
Capacitor (C)	97.13 nF
Microcontroller	STM32F407VGTx
Display	LCD 20x4
Communication	USB TTL
Temperature Sensor	NTC 10 kΩ

ii. Induction Heater

Induction heating is the principle of a magnetic field being induced in a coil, causing eddy currents in the load and generating heat. This heat is generated by the material, depending on the magnitude of the eddy current induced by the inducing coil. The conducting wire will become surrounded by a magnetic field when an alternating electric current passes through the coil. The magnitude of the magnetic field changes according to the current flowing in the winding. If there is a conductive material around the changing magnetic field, a current will flow, which is called an eddy current [1]. If alternating current is passed through a conductor, the current is not distributed evenly. A conductor carrying an alternating current will be surrounded by a concentric magnetic field $H(t)$. This field will re-induce the conductor so that eddy currents arise. This eddy current will be against the direction of the main current at the center of the conductor and in the direction of the conductor surface. This causes the distribution of the main current to be uneven, namely that the current is reduced in the middle and is greatest at the surface; this is called the skin effect. The skin effect will be greater when a high-frequency current is used. The skin effect will cause the current to tend to flow on the surface of the conductor so that the concentration of current flowing on the system conductor is on the surface of the conductor, which means that the effective surface area of the conductor through which the current passes will be smaller, which will result in an increase in the system resistance value so that the value of the current flowing in the system will increase small and the temperature increase in the system is also smaller [25], this is in accordance with Equation (1).

$$R_{\mathrm{ac}} = R_{\mathrm{dc}} + R_{\mathrm{se}} = R_{\mathrm{dc}}\left(1 + F_{\mathrm{se}}\right) \tag{1}$$

The magnitude of the skin effect factor is obtained from Equation (2).

$$F_{\mathrm{se}} = \frac{d}{\delta} \tag{2}$$

And the amount of skin depth is obtained from Equation (3).

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \tag{3}$$

Based on the equations above, it can be seen that the greater the frequency, the greater the system resistance value, which causes the current in the system to become smaller. The smaller the current flowing in the system, the lower the power in the system, which will result in the temperature increase in the system being smaller.

iii. Fuzzy Logic Controller

In this paper, fuzzy logic is used which functions to achieve and maintain the temperature according to the setpoint. This fuzzy logic uses the Mamdani method because it is considered more specific, meaning that in the process, the Mamdani fuzzy method pays more attention to the conditions that will occur for each fuzzy area, thus producing more accurate decision results [26]. The flow diagram for setting the switching frequency of a high-frequency inverter using a fuzzy logic controller can be shown in Figure 4.

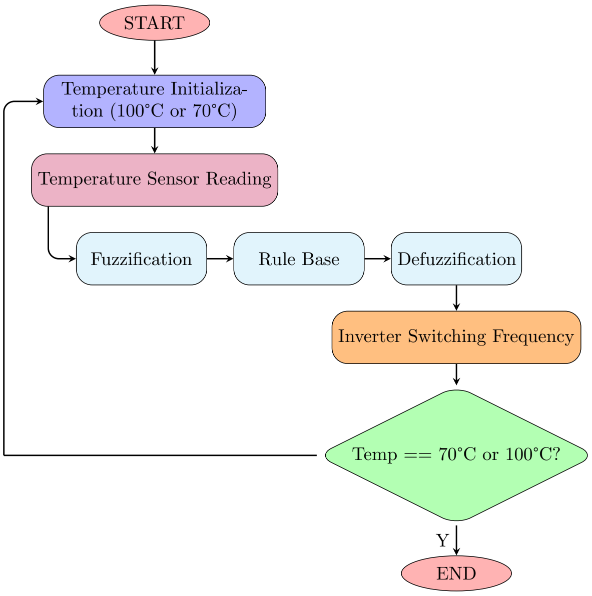

Figure 4: Flow Diagram of Fuzzy Logic Controller

As shown in Figure 4, the input for the fuzzy logic controller comes from the conversion of temperature sensor readings, with the planned temperature setpoints being 70°C and 100°C. This portable induction stove is designed as a cooking tool for camping or outdoor recreation, which is usually only for cooking simple meals. The temperature of 70°C was chosen based on a good temperature standard for brewing tea, milk, and instant noodles. And the temperature of 100°C is chosen based on the boiling point of water. The fuzzy design using the Mamdani method consists of two inputs, namely error and delta error obtained from the conversion of temperature sensor readings. Meanwhile, the output is in the form of switching frequency settings on the inverter. The fuzzy logic controller input is defined in Equations (4) and (5).

$$\text{Error}(t) = \text{reference} - \text{actual temperature} \tag{4}$$

$$\Delta\,\text{Error} = \text{Error}(t) - \text{Error}(t-1) \tag{5}$$

Based on this planning, plans for membership function error (e), membership function delta error (Δe), and membership function output from the switching frequency are made, as shown in Figure 5.

After determining the membership function of the fuzzy logic controller, the next step is to determine the rule base. The fuzzy logic controller rule base planning for this system is shown in Table 2.

(a) (b) (c)

Figure 5: (a) Membership Function Error, (b) Membership Function Delta Error, (c) Membership Function Output

Table 2: Fuzzy Logic Controller Rule Base

Error Δ Error	eNB	eNM	eNS	eZ	ePS	ePM	ePB
deNB	NB	NB	NM	NM	NM	NS	Z
deNM	NB	NM	NM	NM	NS	Z	PS
deNS	NM	NM	NS	NS	Z	PS	PS
deZ	NM	NM	NS	Z	PS	PM	PM
dePS	NM	NS	Z	PS	PS	PM	PM
dePM	NS	Z	PS	PM	PM	PM	PB
dePB	Z	PS	PM	PM	PM	PB	PB

III. RESULTS AND DISCUSSION

This paper is conducted to determine the performance of the system made and whether it has run according to plan. This test is divided into two parts, namely open loop system integration testing (without control or feedback) and closed loop system testing (with fuzzy logic control).

Figure 6: System Testing Process

Figure 6 is the system testing process. This test requires several supporting components including a DC source, Boost Converter Module, STM32F4, inverter driver, high-frequency inverter, LCD, temperature sensor, and induction heater.

i. Open Loop Test Results

This open loop test is performed with several switching frequencies. The frequency used is a frequency above the resonant frequency; this aims to make the load operate in inductive load mode. The resonant frequency is not used as a switching frequency because it is the peak current in the circuit that will cause a short circuit. So, in this system, the switching frequencies used are 30 kHz, 35 kHz, 40 kHz, 45 kHz, 50 kHz, 55 kHz, 60 kHz, 65 kHz, 70 kHz, 75 kHz, 80 kHz, 85 kHz, 90 kHz, and 95 kHz. The results of the open loop test system can be shown in Table 3.

Table 3: Open Loop Test Results

Freq (kHz)	V_{in} (V)	I_{in} (A)	Power (W)	Temperature (°C)	Time (min)
30	24	5.49	131.76	106.8	35
35	24	4.38	105.12	90.1	35
40	24	3.32	79.68	83.2	35
45	24	2.66	63.84	74.1	35
50	24	2.20	52.80	66.8	35
55	24	1.90	45.60	59.3	35
60	24	1.67	40.08	56.1	35
65	24	1.50	36.00	50.8	35
70	24	1.38	33.12	48.5	35
75	24	1.26	30.24	46.7	35
80	24	1.18	28.32	44.1	35
85	24	1.10	26.40	40.9	35
90	24	1.03	24.72	39.1	35
95	24	0.92	22.08	37.6	35

Table 3 is the result of open loop testing of the system, which shows that the switching frequency used is between 30 kHz to 95 kHz. From these results, it can be seen that if the switching frequency is increased or away from the resonant frequency, the power generated becomes smaller. This is in accordance with the existing theory, where the power in the full-bridge series resonant inverter will increase and reach a peak when the switching frequency is equal to the resonant frequency, and after passing the resonant frequency, the power will decrease again.

ii. Closed Loop Test Results with Setpoint 70°C

In this test, 300 ml of water is heated according to the desired setpoint of 70°C. Then the disturbance for fuzzy logic control is created by adding 100 ml of water when it reaches the first setpoint, after which, when it reaches the setpoint temperature again, vegetables are added. The results of closed loop testing of the system with a setpoint of 70°C are shown in Table 4.

Table 4 is the result of closed loop testing of the system with a setpoint of 70°C. This test was carried out using 300 ml of water; the test results show that it takes about 20 minutes to heat 300 ml of water to a setpoint temperature of 70°C. After reaching the setpoint, 100 ml of water is added; when more water is added, the temperature drops to 57.8°C and can rise to a temperature of 70.2°C within 10 minutes. After reaching the second setpoint, another disturbance is added in the form of vegetables; when vegetables are added, the temperature drops to 59.2°C and can rise to a temperature of 70.1°C within 10 minutes. The results of closed loop testing of the system with a setpoint temperature of 70°C obtained a percentage error value of about 0.14%–0.29%. The graph of the system closed loop test results with a setpoint of 70°C can be shown in Figure 7.

Table 4: Closed Loop Test Results with Setpoint 70°C

Time (min)	V_{in} (V)	I_{in} (A)	Power (W)	Temp (°C)	Frequency (kHz)
300 mL Water					
0	24	5.49	131.76	27.0	30.0
5	24	5.49	131.76	43.2	30.0
10	24	5.49	131.76	59.8	30.0
15	24	1.57	37.68	69.4	61.4
20	24	1.52	36.48	70.0	63.0
25	24	1.57	37.68	69.4	61.4
100 mL Water Added					
0	24	5.49	131.76	57.8	30.0
5	24	1.75	42.00	67.5	59.5
10	24	1.51	36.24	70.2	64.2
Added Vegetables					
0	24	5.49	131.76	59.2	30.0
5	24	1.72	41.28	67.9	59.9
10	24	1.51	36.24	70.1	64.1

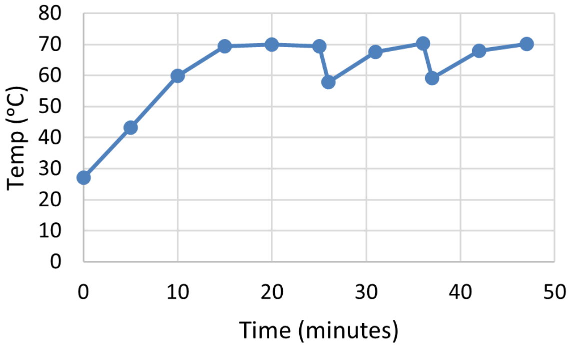

Figure 7: Graph of the results of closed loop testing of the system with a setpoint of 70°C

iii. Closed Loop Test Results with Setpoint 100°C

In this test, 300 ml of water is heated according to the desired setpoint of 100°C. Then the disturbance for fuzzy logic control is created by adding 100 ml of water when it reaches the first setpoint, after which, when it reaches the setpoint temperature again, vegetables are added. The results of closed loop testing of the system with a setpoint of 100°C are shown in Table 5.

Table 5 shows the results of the closed loop test

Table 5: Closed Loop Test Results with Setpoint 100°C

Time (min)	V_{in} (V)	I_{in} (A)	Power (W)	Temp (°C)	Frequency (kHz)
300 mL Water					
0	24	5.49	131.76	29.7	30.0
5	24	5.49	131.76	48.9	30.0
10	24	5.49	131.76	63.7	30.0
15	24	5.49	131.76	75.4	30.0
20	24	5.49	131.76	85.0	30.0
25	24	4.10	98.43	93.1	35.2
30	24	2.40	57.60	98.5	58.5
35	24	1.60	38.40	100.0	60.0
40	24	1.58	37.92	100.2	60.2
100 mL Water Added					
0	24	5.49	131.76	74.1	30.0
5	24	5.49	131.76	89.3	30.0
10	24	2.50	60.00	97.5	57.5
15	24	1.60	38.40	100.1	60.1
20	24	2.40	57.60	98.3	58.3
Added Vegetables					
0	24	5.49	131.76	91.3	30.0
5	24	2.70	64.80	95.8	55.8
10	24	2.30	55.20	98.7	58.7
15	24	2.00	48.00	99.1	59.1
20	24	2.30	55.20	98.7	58.7

of the system with a setpoint of 100°C. Similar to the previous test conducted using 300 ml of water, the test results show that to heat 300 ml of water to a setpoint temperature of 100°C takes about 35 minutes. After reaching the setpoint, 100 ml of water is added; when more water is added, the temperature drops to 74.1°C and can rise to a temperature of 100.1°C within 15 minutes. But after being left for 20 minutes, the temperature dropped back to 98.3°C. After reaching the second setpoint, another disturbance is added in the form of vegetables; when vegetables are added, the temperature drops to 91.3°C and can rise to the highest temperature of 99.1°C within 15 minutes. When vegetables are added, this induction heater has not been able to reach the setpoint. The results of closed loop testing of the system with a setpoint temperature of 100°C obtained a percentage error value of about 0.14%–0.9%. The graph of the system closed loop test results with a setpoint of 100°C can be shown in Figure 8.

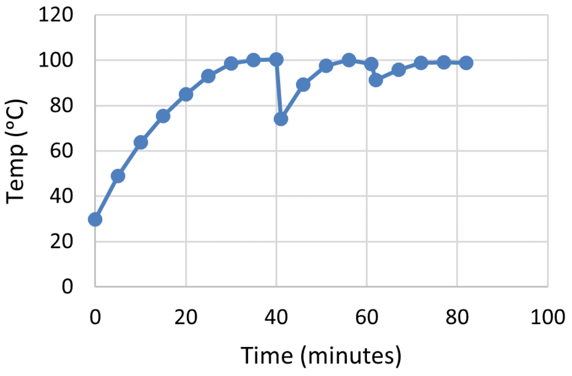

Figure 8: Graph of the results of closed loop testing of the system with a setpoint of 100°C

IV. CONCLUSION

This research discusses the high-frequency inverter with fuzzy logic control method implemented for portable induction heaters. The induction heater that has been made uses a 24 V battery source, so it can be used without the need for a source from the PLN electricity network. The results of open loop testing of the system show that if the switching frequency is increased or moves away from the resonant frequency, the power generated becomes smaller. Meanwhile, the results of closed loop testing of the system show that fuzzy logic control can reach the setpoint temperature 70°C within 20 minutes and, after being given a disturbance, fuzzy logic control can maintain the setpoint temperature with a percentage error of about 0.14%–0.29%. For the setpoint temperature of 100°C, it can be reached within 35 minutes, and after being given a disturbance, fuzzy logic control can maintain the setpoint temperature with a percentage error of around 0.14%–0.9%.

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