Potential Induction Heating using MOSFET H-Bridge Circuit for Material Synthesis

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Abstract. Here we report our effort to integrate microcontroller to control AC current-generating MOSFET H-bridge circuit-based device. We have carried out the tests of the potential application of the induction heating generated by the device for material synthesis by controlling the variation of AC current at constant frequency value. The results showed that at the constant frequency value, the heating process depended on the amount of AC current. The different responses of different kind of materials to the different frequencies at constant AC current value have also been observed. The results provide the fundamental base for further development of induction heating furnace using microcontroller based AC current generation device.

Keywords: Induction Heating, MOSFET H-bridge, material analysis, current generation device.

1. Introduction
In material science, synthesis is the backbone of any efforts to develop advanced materials for both fundamental research and technological applications. Among many effective synthesis routes, solid state reaction is still the first option for many material scientists to look at every time they need to prepare a compound or further heating treatment to study. However, solid-state reaction and annealing routes require a heating process that sometimes consumes electrical energy in a huge amount. We are considering induction heating as an alternative method to be applied in the laboratory to carry out the solid-state reaction process.

To get into the principle of induction heating, we start from a stationary electric current (DC). According to the Biot-Savart law, the magnitude of the magnetic field generated by the electric current is steady at any points around the path (conductor) of DC current. In other words, the magnetic flux does not change. On the other hand, the AC electric current will produce magnetic flux changing around the conductor. If we place a conducting material (material with intrinsic electric resistant) around the pathway of this AC current, it will experience the magnetic flux fluctuation. As the magnetic flux generated by AC current is also changing in direction, the so-called eddy current is then generated inside the material [1-3]. This phenomenon has a wide potential technological application.
such as in medical physics treatment of cancer [4]. The schematic diagram to give a picturesque explanation of the principle of induction heating by AC electric current is given in Figure 1. In such configuration, if one places a metal such as iron in the inductor, it will be heated rapidly by generating Eddy current within the metal due to the changing of AC magnetic flux [5-7].

The challenge is how to control the AC current phase for induction heating. The AC current fluctuations can be controlled by electronic circuit, both its frequency and the current strength. Therefore, we are applying MOSFET with H-bridge circuit configuration to control the current strength flowing into the load copper coil. In this way, the period of the current flow and the direction of the current flow are fully controlled by the microcontroller. Some parameters came up during the induction heating performance testing are frequency variation, the control of current strength by the duty cycle of the MOSFET modification, load coil geometry which has also been reported [6].

This contribution deals only with controlling the frequencies and the amount of AC current as the first step of many of our research sequences to design and construct AC current generating H-Bridge configuration based induction heating furnace for Universitas Negeri Malang (UM), Indonesia, with the effective use of electrical current. Further design and optimizations of the device as well as its evaluation related to the maximum value of applied current are still ongoing.

2. Experimental Methods

2.1. MOSFET H-bridge

Four N-channels MOSFETs were employed to control the current flow in the coil. To prevent short currently in the MOSFET, the microcontroller was programmed to manipulate its delay time. When the delay is in progress, all MOSFETs are not transmitting the current. The schematic diagram of how current flows in the H-bridge MOSFETs circuit can be seen in Figure 1. The MOSFETs driver is constructed using the optocoupler and power supply with a different ground. The bipolar transistors are used for driving 4 gates MOSFET. It is used to get the low-frequency work, DC to several hundred hertz AC electric current. The driver modification was done to provide a high-frequency working range. This is different from commercial MOSFET driver which is only capable of working below one hundred Hz.

![Figure 1. Schematic diagram of the current flow (red line) in H-bridge MOSFET circuit: (a) off, (b) the current flows to the right, and (c) the current flows to the left](image)

We employed an ATMega8 microcontroller to generate controlled square-signals. The period of these signals can be controlled by a microcontroller with a variation value starting from 4.6 μs. The duration of this ‘OFF’ signal can also be controlled by a microcontroller with variations ranging from 4.96 μs. The signal ‘ON’ allows the current to flow into the load, the ‘OFF’ signal makes the current does not flow on the load.

Acting as the load here is a 50 mm diameter copper enameled wire coil, the coil diameter is 18 mm, 50 μH inductance value. By using microcontroller, the ‘UP’ signal will allow the current moving from one end to another and the ‘DOWN’ signal will reverse the direction. These ‘UP’ and ‘DOWN’ signals control the MOSFET accordingly, so the MOSFET has the lowest possible RDS value. This low RDS value is variable and can be used to suppress the heat dissipation in the MOSFET and maximize the current flow on the coil. Previous research says that using the coil as an inductor can generate the heating rate up to 8.0 °C/s. From an initial temperature of 40 °C to the surface temperature of 159.9 °C took 15 seconds of the heating process [7].
Figure 2. Schematic diagram electronic circuit for DC-AC conversion
2.2. Heating Performance
To attest to the performance of H-bridge based device shown in Figure 2, we applied the generated AC current into the coiled copper-enamed wire. The diameter of the wire is 1.5 mm and the diameter of the coil was 18 mm. The explanation of possible heating effect is given by schematic diagram in Figure 3.

We used 3.13 grams iron ball for the material. Two strategies were carried out to study the effect of AC current value (duty-cycle) and frequencies. We measured the heating temperature of the iron ball by using thermocouple thermometer. The 337 Hz frequency was chosen to keep the MOSFET in the safe working range to anticipate any unexpected heating process. At constant frequency number, duty-cycle was varied between 149-248 μs. We varied the frequencies between 773-864 Hz at constant duty cycle value 244 μs to study the effect of frequency on induction heating effect.

![Figure 3](image1.png)

Figure 3. Schematic diagram of Eddy current heating effect, (a) AC current is flowing in coil results in electromagnetic with directions represented by blue lines. Any material placed in the coil will be experiencing Eddy current represented by red lines and accordingly will be heated up by this phenomenon, (b) visual effect of heating process induced by electromagnetic effect from (a).

![Figure 4](image2.png)

Figure 4. Overall microcontrolled induction heating device: 1) DC-AC conversion, 2) power adaptor, 3) electric current safety control, 4) thermocouple thermometer, 5) generated AC current amperemeter, 6) windows operating system to control the microcontroller, 7) copper enameled coil system, can be considered as a very small laboratory scale, for safety reason.
3. Results and Discussion

From the experimental results given in figure 5 and 6, we can see that the longer duty cycle the bigger the effect of the increase in heating temperature. This is possible as a result of the current that causes the vortex of the heated material to be longer. The smaller duty cycle also causes the current vortex to be shorter anyway. In the 337Hz frequency range, for 149μs current flow, causing the iron ball possesses Eddy current approximately 5% of the cycle and was able to heat the iron ballup to 37.5°C. Under these conditions, the effective current consumption of 2.3A, the voltage applied to the system is 12 V. Therefore, the effective power is $2.3A \times 12V = 27.6\text{Watt}$.

For AC current frequency 864Hz and duty cycle 244 μs, current flow is causing the material to experience Eddy current about 21% of the cycle. It can raise the temperature up to 112.3°C for 30 minutes heating time. At that condition, effective current consumption equal to 6.3A, the voltage used in system of 12V. So, the effective power is $6.3A \times 12V = 75.6\text{Watt}$.

During the device performance tests, we maintained the duty cycle under 300 μs for safety reason. The duty cycle value is proportionally affecting the heating temperature at a constant frequency, 149μs provides a maximum temperature of 37.5 °C (60 minutes heating), 174 μs duty cycle providing maximum temperature of 42.7 °C (60 minutes heating), 198 μs provides a maximum temperature of 43.1 °C (60 minutes heating), 223 μs provides a maximum temperature of 47.1 °C (60 minutes heating), 248 μs provides a maximum temperature of 58.7 °C (60 minutes heating). At this stage, it is important to elaborate the results with details calculation as reported by Aung [10] for further optimization and power output analysis.

Interestingly, the variation of AC current frequency at the constant duty cycle value 244μs (frequency range 773Hz-864Hz) give maximum temperature as high as 112.3 °C in only 30 minutes heating period, for AC current frequency 864Hz. This heating temperature achievement is enough to be applied for micro-furnace for annealing process of small material samples as reported by Lu [11]. From these results, we have conceived that for the device scale up, we need to optimize the MOSFETs configuration first to obtain optimum highest duty cycle and then to optimize the frequency generation.

![Figure 5. Heating temperature as the function of heating period (t) of induction heater at constant AC current frequency 343 Hz.](image-url)
Figure 6. Heating temperature as the function of heating period (t) of induction heater at the constant duty cycle. Note that the AC current is degrading from 6.3 to 5.8 A despite the duty cycle is constant, another question for further development.

4. Conclusion
We have developed a MOSFET H-bridge configuration based induction heating micro-furnace as a fundamental step for further development of induction heating furnace in Universitas Negeri Malang (UM), Indonesia. The microcontroller has been integrated into the device system to manipulate the AC current frequency and duty cycle. There is saturation heating temperature for every duty cycle and frequency values. Up to this report, we have reached a maximum heating temperature of 112.3 °C at the duty cycle of 244μs and AC current frequency 864Hz provides for a heating period only in 30 minutes. These small-scale induction heating tests clearly showed the potential of induction heating to be applied for clean solid-state reaction process as well as providing important basis for its further scale up development.

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References
[1] Griffiths, David J. (1998), Introduction to Electrodynamics (3rd ed.), Prentice Hall. pp. 222–224, 435–440. ISBN 0-13-805326-X
[2] Jackson, John David (1999), Classical Electrodynamics (3rd ed.), New York: Wiley, Chapter 5. ISBN 0-471-30932-X
[3] I.S. Grant, W.R. Phillips, Electromagnetism (2nd Edition), Manchester Physics, John Wiley & Sons, 2008, ISBN 978-0-471-92712-9
[4] Robert P. Stigliano, Fridon Shubitidze, James D. Petryk, Levan Shoshiaisvili, Alicia A. Petryk & P. Jack Hoopes, (2016), Mitigation of eddy current heating during magnetic nanoparticle hyperthermia therapy, International Journal of Hyperthermia, Volume 32, Issue 7, DOI:10.1080/02656736.2016.1195018
[5] Bae, J., Hwang, J., Park, J., & Kwag, D, (2009), Modeling And Experiments On Eddy Current Damping Caused By A Permanent Magnet In A Conductive Tube, 23, 3024–3035. DOI:10.1007/s12206-009-0819-0
[6] Du, H., Li, J., & Qu, Y, (2014), Mathematical Modeling of Eddy-Current Loss for a New Induction Heating Device,
[7] Lin, H., Chen, S., Jeng, M., Son, P., Chang, J., & Hwang, J. (2012), Induction Heating With The Ring Effect For Injection Molding Plates, International Communications In Heat And Mass Transfer, DOI:10.1016/j.icheatmasstransfer.2012.02.009

[8] Bowmaker, G., A., Effendy, Fariati, Rahajoe, S., I., Skelton, B., W., & White, A., H., 2011, Structural and Infrared Spectroscopic Studies of Some Adducts of Divalent Metal Dihalides (MX2, M = Zn, Cd; X = Cl, Br, I) with Variously Hindered Monodentate Nitrogen (Pyridine) Base Ligands (L = Pyridine, 2-Methylpyridine, and Quinoline) of 1:2 Stoichiometry, Z. Anorg. Allg. Chem, 637 : 1361–1370.

[9] Qing, W., A., Kun, Z., F., Zhen, C., L., Cong, G., G., & Shun, H., J., 2004, Synthesis and Crystal Structures of Two Novel 1-D Metal Complexes with Dicyanamide: [Zn(pheen)(dca)2]n and [Cu(quin)2(dca)2]n, Chinese Journal Structure Chemistry, 23(10) : 1148

[10] Soe Sandar Aung, Han Phyo Wai, and Nyein Nyein Soe, Design Calculation and Performance Testing of Heating Coil in Induction Surface Hardening Machine, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol:2, No:6, 2008

[11] Zhiqiu Lu, Kirill Poletkin, Ulrike Wallrabe and Vlad Badilita, Performance Characterization of Micromachined Inductive Suspensions Based on 3D Wire-Bonded Microcoils, Micromachines 2014, 5, 1469-1484; doi:10.3390/mi5041469