Demagnetization Method for Reducing Inrush Current of Single Phase 1 kVA Transformer

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***Abstract*— This study deals with an effort to reduce inrush current of single phase transformer during its energizing. Inrush current affected by residual flux was minimized using demagnetization method in order to reduce residual flux trapped in the core of transformer. Two methods of demagnetization namely variable frequency-constant voltage (VFCV) and variable voltage–constant frequency (VVCF) were applied and the effectiveness of both methods were then compared. Both methods were supplied with alternated direct current (DC), however the one was changed its frequency and the other one was changed its voltage. The results obtained after transformer was demagnetized using these methods show that VFCV method reduced inrush current up to 76%, on the other hand VVCF method reduced inrush current only up to 37%. Moreover, demagnetization time process of VFCV method was about 1.46 s, which is 1 s faster than VVCF method.**

***Keywords*—demagnetization; inrush current; variable voltage-constant frequency; variable frequency-constant voltage**

I. INTRODUCTION

Transformer is one of the most widely used electromagnetic machine in power system. One of the unwanted phenomenon but cannot be avoided of transformer is inrush current during its energizing. The inrush current on primary windings is characterized by a much greater amplitude than its full load current. This amplitude is affected by residual flux and circuit impedance.

The present of inrush current leads to: 1) Possibility of fault operation of overload protection and internal fault which lead to transformer out of system. 2) Mechanical failure of transformer. 3) Problems of power quality, such as overvoltage and voltage sags [1]. Consequently, these effects will provide disadvantages for industry as a transformer user.

The effects of inrush current can be mitigated by reducing the amplitude of current itself. This effort can also extend lifetime of transformer.

In this paper, reducing of residual flux by mean reducing of inrush current using demagnetization method is analyzed based on experiment. The experiments were conducted on single phase low voltage 1 kVA transformer. The methods of demagnetization consist of variable frequency – constant voltage (VFCV) and variable voltage – constant frequency (VVCF). Both methods are supplied with alternated direct current (DC), however the one is changed its frequency and another one is changed its voltage. In the end of research, the proposed method can be evaluated as an inrush current mitigation method using DC source [2-7].

II. INRUSH CURRENT AND DEMAGNETIZATION METHOD

A. Inrush Current of Transformator

The inrush current, also known as magnetizing current, is one of the transient phenomenon of transformer. The magnetizing current will flow on primary windings of transformer during its energizing to produce flux in ferromagnetic iron core. This current amplitude is usually 8 times until 12 times greater than its full load current. The source voltage magnitude, residual flux in iron core and circuit impedance will affect on the amplitude of inrush current [8].

Demagnetization of residual flux as a mitigation method of inrush current refers to Faraday Law. When an inductor is connected with a voltage source, current of the inductor will rise linearly with time according to the voltage source magnitude, as follows:

$$i(t) = \int v(t).dt = \frac{v}{L}t \qquad (1)$$

The flux has waveform equal with magnetizing current, whereas the value of inductor, L, is constant because inductance corresponds with the number of windings and its wire type [1]. Therefore, the increasing and decreasing of magnetizing current will be linear with its input voltage, as shown in (2). The relation of voltage, current and flux can be seen in Fig. 1.

$$\phi = Li \qquad (2)$$

B. Variable Frequency – Constant Voltage (VFCV)

Based on Faraday Law, VFCV can be used for demagnetization of residual flux. In this method, DC voltage source is converted to square alternating current (AC) voltage.

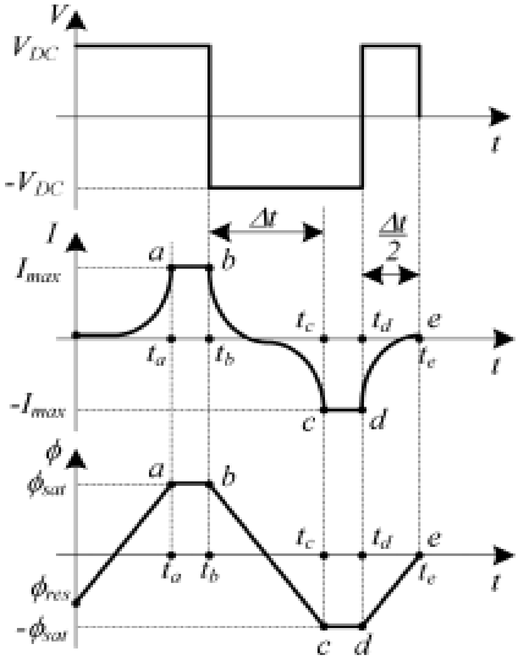


Figure 1. Relation of voltage, current and flux [1].

Its frequency is changed for each a half of period with very low initial frequency, as depicted on Fig. 2. Later, the frequency will rise with time, as follows:

$$\Delta t_x = \frac{\Delta t_{x-1}}{2} \tag{3}$$

with x = 3, 4, 5 and so on.

C. *Variable Voltage – Constant Frequency (VVCF)*

Another method based on Faraday Law is VVCF. This method also involves DC voltage source that will be converted to square AC voltage. The voltage is changed for each a half of period with constant frequency, as depicted on Fig. 3. In this case, the lower voltage is given, the lower flux value is obtained according to certain period. The initial voltage is not so high. The voltage is then lower gradually until zero.

III. EXPERIMENTAL SETUP

The demagnetization devices were designed to reduce the amplitude of inrush current during transformer energizing. Two methods were given, namely VFCV and VVCF.

A. *Demagnetization Using VFCV*

Basic principle of this device was based on full bridge inverter with 4 units of MOSFET as semi-conductor switch [2]. The device was supplied by DC source that was then converted to square AC wave. Fig. 4 shows the circuit of VFCV consisting of 3 main components, such as MOSFET with gate driver, current sensor and microcontroller.

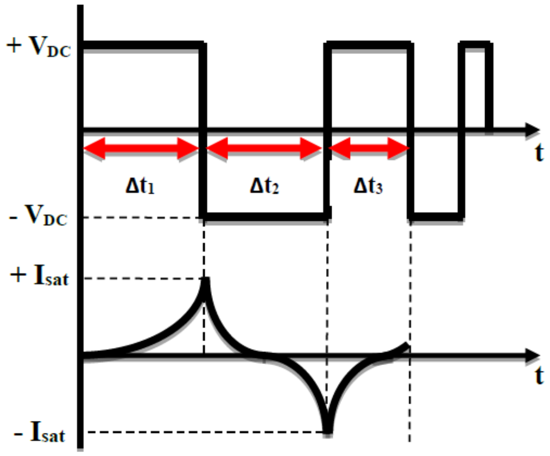


Figure 2. VFCV method [1]

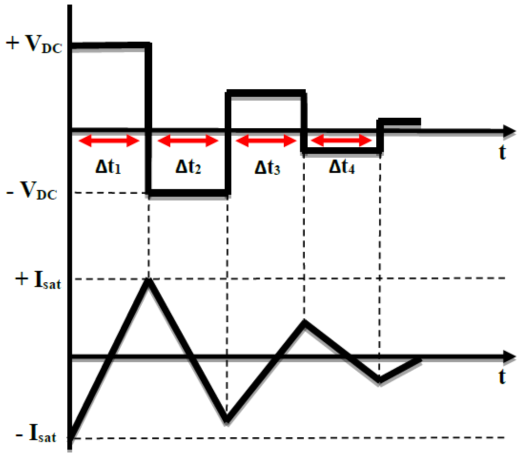


Figure 3. VVCF method [1].

Determining of maximum inrush current (saturation current) was based on open circuit test of the transformer, that was 1.16 A. At this value, DC excitation current reached 1.2 A. The current sensor could only measure the excitation current on primary windings, so that the saturation current was set at 1.2 A in order to be forwarded to microcontroller module as switching signal.

There were 3 units of DC source. The first unit, 12 V, was to supply the gate driver and buck converter. The output voltage of buck converter would be 5 V that was then connected to microcontroller. The second unit had 2 panels, in which the right one as a main supply for demagnetization circuit, that was 3 V, the left one was 15 V to supply the pin VB of gate driver. The direct current supply for the DC source corresponded with nominal voltage of system. Based on the measurement, resistance of the transformer was 2 Ω. If 3 V was used to supply the transformer, the injected current reached 1.2 A. The 15 V was the result of V_S + 12, in which this formula was based on parameter of components. The main supply, 3 V, was obtained as equation in (4).

$$V_{dc} = (I.R) + (2.r_d.I) \qquad (4)$$

Based on the measurement, resistance of the transformer was 1.95 Ω, rd of MOSFET was 17.5 mΩ and saturation current was 1.2 A. Then, the maximum of supply voltage was calculated as:

$$V_{dc} = (1.2\,\text{x}\,1.95) + (2\,\text{x}\,0.0175\,\text{x}\,1.2) = 2.4\,\text{V} \qquad (5)$$

However, in testing, the voltage experienced reduction, so that the supply current could not reach 1.2 A. The main supply voltage was then increased until 3 V.

The basic principle of this demagnetization device could be explained in more detail as follows. DC voltage source was connected with switching part consisting of 4 units of MOSFET, 2 units of half bridge driver and some supporting components, such as LED, resistor and capacitor. Part of controller consisted of a buck converter module, a microcontroller module and some supporting components, such as LED, resistor, capacitor, push button and LCD.

The microcontroller was set in order to produce Pulse Wide Modulation (PWM) pulse that was injected to gate driver of switching part to switch on the MOSFET alternately. When DC voltage with its positive polarity was connected with the transformer, switch 1 and 3 were on, while switch 2 and 4 were off. Later, DC excitation current would rise linearly until its positive saturation point was measured by current sensor. When the magnetizing current had experienced negative saturation condition, current sensor sent signal back to microcontroller in order to change the polarity of the DC voltage. After that, the demagnetization process of residual flux took a place. Period of switching from negative polarity to positive polarity, and vice versa, would continue to be reduced by a half of period from the previous a half of period.

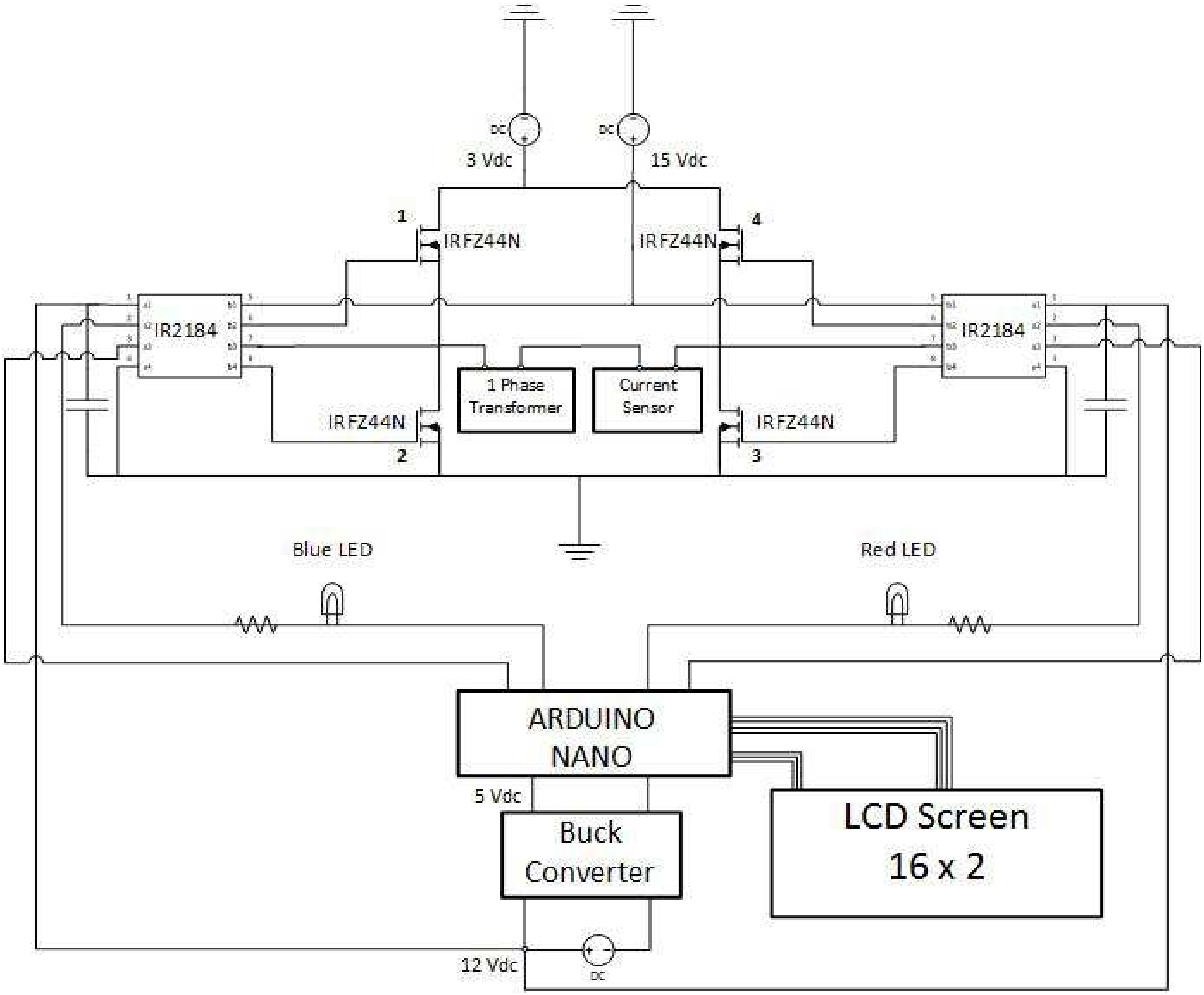


Figure 4. Picture of demagnetization device with VFCV method.

B. Demagnetization Using VVCF

Faraday Law states that inductor current will rise linearly when the inductor is supplied by DC voltage. In this test, when the inductor current reached its positive saturation value, polarity of DC voltage was changed until the current reached its negative saturation value. If this scheme was performed continuously with variation of voltage value, the magnitude of residual flux would be affected, as shown in (1) and (2).

By giving the variation of DC voltage reduction consecutively for a half of period, flux of inductor would be lower gradually. In the beginning of demagnetization, DC voltage supplied the transformer until the saturation condition of current transformer was reached. The period to reach this condition was then used as a reference time for switching of the DC voltage next period. The initial DC voltage of transformer during demagnetization would be determined after comparison of output voltage and current of demagnetization device had been obtained. After the initial DC current supplied to transformer is known, the voltage polarity was changed and its amplitude was reduced. This reduction was conducted for each a half of period with particular combination. The result of comparison between simulation and device output with its voltage level combination can be seen in Table 1.

Basic principle of demagnetization device using VVCF method can be explained in more detail, as seen in Fig 5. Combination of DC voltage variation was set by microcontroller to determine the binary combination of digital to analog converter (DAC). It was conducted in order to obtain positive and negative output voltage as predetermined. Current sensor was a main component to determine switching period. This sensor would sense the current flowing when the certain initial voltage (V+) was given to the transformer. The voltage was then in saturation condition at certain value with particular period time. The saturation time of initial voltage would be recorded by current sensor and forwarded to microcontroller. The microcontroller set saturation period time of initial voltage as period of voltage polarity switching for next a half of period.

IV. RESULT AND ANALYSIS

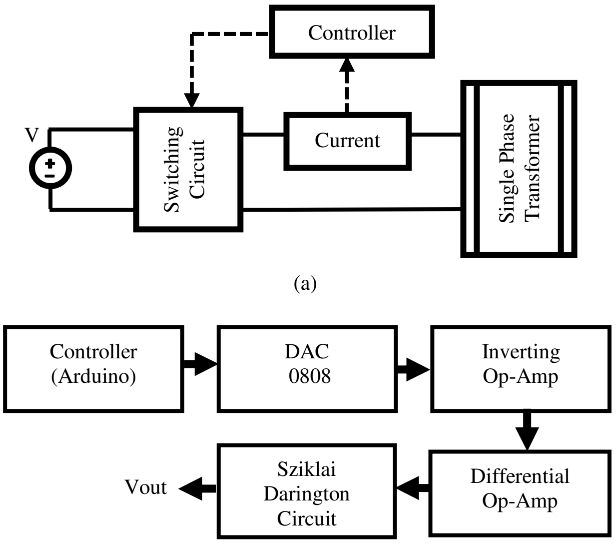
A. VFCV Based Demagnetization Device

Demagnetization process of VFCV took a place about 1.46 s as depicted on Fig. 6. In the end of process, the DC excitation current flowing to iron core reached almost zero. At a half of period with positive polarity, the input DC signal was 3 V. However, the recorded signal in oscilloscope was only 2.4 V. The present of voltage polarity changing with its low frequency until high frequency was also obtained.

The voltage had experienced reduction during demagnetization. The switching process given repeatedly with higher frequency could explain this reduction. Therefore, to solve this problem, the operation of demagnetization device wolud be off when a half of period was 0.1 ms.

TABLE 1. COMPARISON BETWEEN SIMULATION VOLTAGE AND DEVICE OUTPUT

DAC Binary	**Simulation Voltage (DC Volt)**	**Device Output**	
		Voltage (DC Volt)	*Current (A)*
10000001	1.03	1.7	1.72
01111111	0.93	0.95	0.98
10000000	0.98	1.65	1.67
10000011	1.12	1.77	1.79
01111110	0.89	0.91	0.94
01111101	0.84	0.87	0.9
01111100	0.79	0.83	0.86
01111001	0.65	0.7	0.73
01110111	0.56	0.62	0.65
01110101	0.47	0.53	0.57
01110011	0.37	0.45	0.48
01101110	0.14	0.9	0.93
01100000	-0.5	0.3	0.36
01001111	-1.3	-0.4	-0.41
01000001	-1.96	-1.05	-1,06
01000010	-1.82	-0.92	-0.94
01000111	-1.6	-0.83	-0.8
01001011	-1.4	-0.6	-0.62
01001010	-1.54	-0.67	-0.67
01001111	-1.35	-0.45	-0.49
01010000	-0.6	-0.47	-0.49
01011110	0.002	0.77	0.8



(a)

(b)

Figure 5. Block diagram of demagnetization device using VVCF method: (a) Scheme. (b) Switching components.

B. VFCV Based Demagnetization Device

The demagnetization time of VVCF was less than 2.6 s as shown in Fig. 7. In the end of process, The DC excitation current was almost zero.

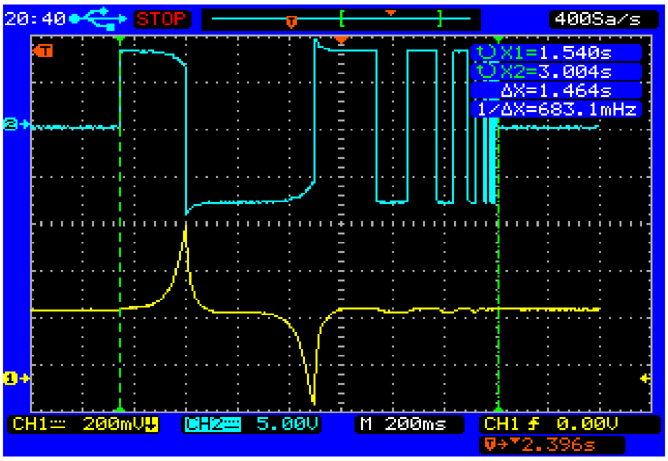


Figure 6. Input voltage and output current of demagnetization device using VFCV method.

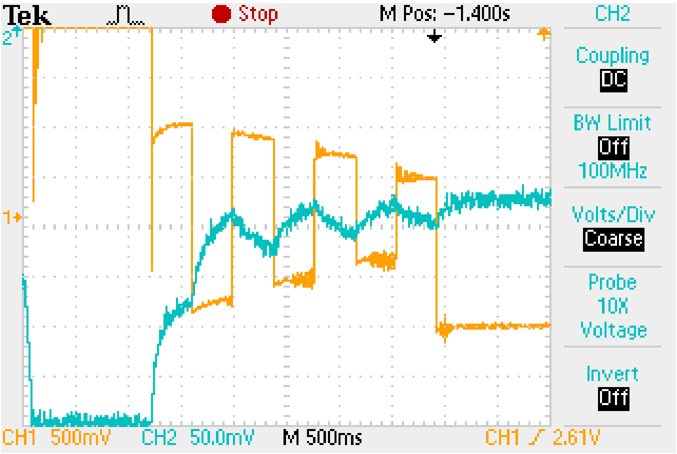


Figure 7. Input voltage (yellow) and output current (blue) of demagnetization device using VVCF method.

When DC excitation current was almost zero, it could be stated that residual flux in iron core was reduced. Moreover, the demagnetization device corresponded with theory as seen in Fig. 3. The magnetizing current reached its positive saturation when positive voltage was given. The voltage polarity was then changed until its negative saturation was reached. Furthermore, the demagnetization with DC voltage reduction was given consecutively for each a half of period. The period was equal with the first period when magnetizing current reached its positive and negative saturation.

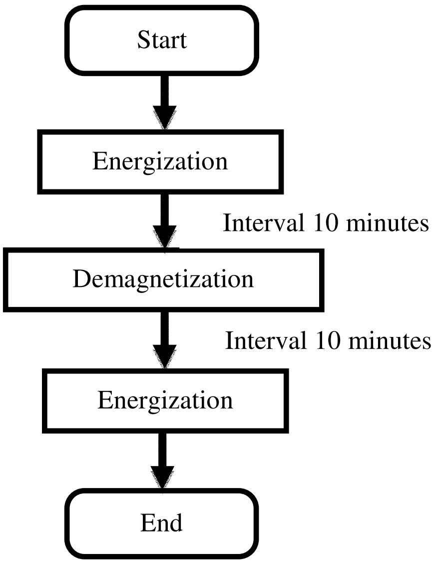


Figure 8. Procedure of inrush current measurement.

C. *Comparison of Inrush Current*

The inrush current before and after demagnetization for each method was compared based on demagnetization duration and inrush current amplitude. The measurement method of inrush current conducted is shown in Fig. 8. The firing angle of power supply for energization process was same with all test. It was controlled by a switching module as depicted on Fig. 9.

The amplitude of inrush current was affected by firing angle. In this test, 0° and 90° were choosen as variation of firing angle. Refer to [1], the inrush current amplitude with firing angle of 0° will be greater than 90°. The result of comparison between inrush current after demagnetization of both methods can be seen in Fig. 10.

The test result of inrush current reduction using VFCV method can be seen in Table 2. The demagnetization time for all tests was 1.46 s. This value was reasonable since the demagnetization device had been set to be off when a half of period of the last wave signal was 0.1 ms. The inrush current reduction was different for all test. It was caused by the number of residual flux trapped in iron core of transformer. If the transformer was more often energized, the number of the residual flux would rise. Consequently, the demagnetization with very low frequency power supply was unable to reduce the residual flux until zero. However, the amplitude of inrush current could be reduced, as shown in Table 2.

TABLE 3. RESULT OF INRUSH CURRENT REDUCTION WITH VVCF METHOD

Firing Angles (°)	**Demagnetization Time (s)**	**Inrush Current (A)**		***Inrush reduction*** **(%)**
		Before Demagnetization	*After Demagnetization*	
0	1.46	27.4	7.6	72.3
	1.46	32	12.5	61
90	1.46	5.2	1.26	75.8
	1.46	6.2	4	35.5

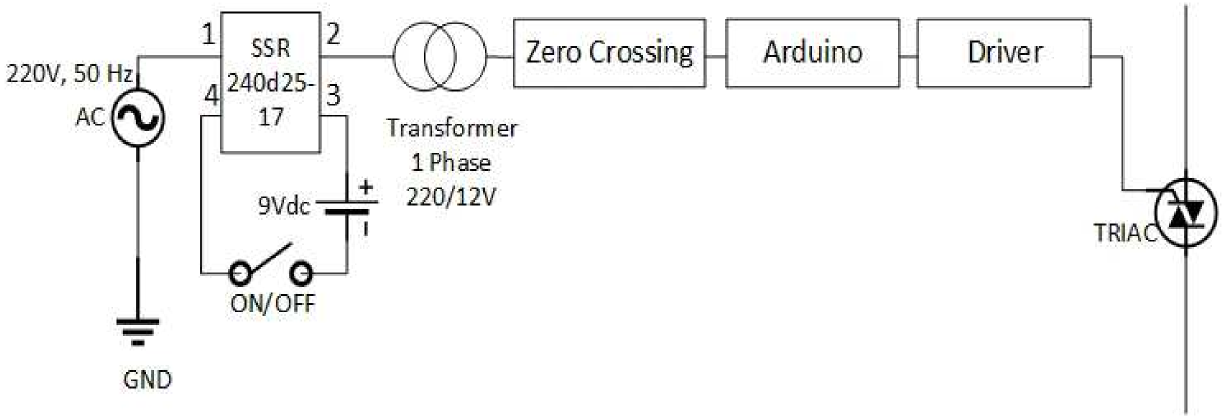
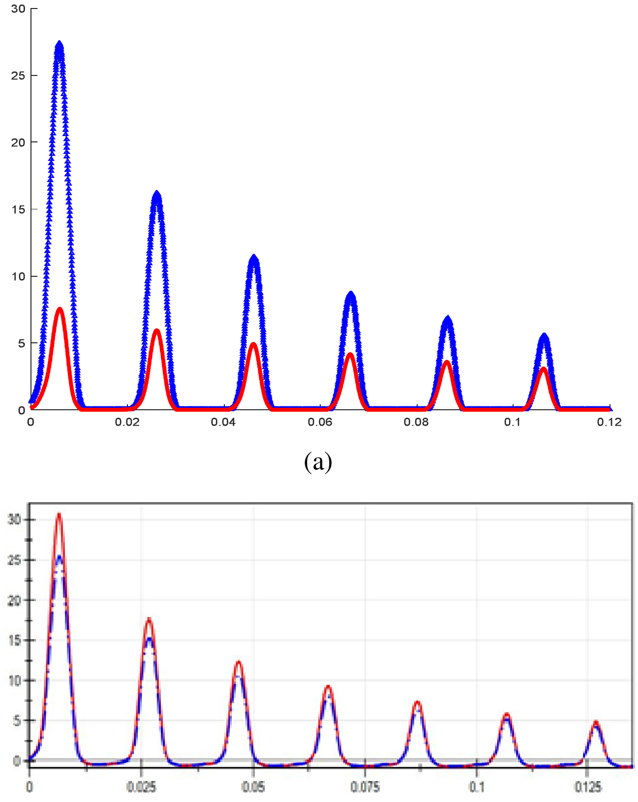


Figure 9. Switching module.



(a)

(b)

Figure 10. Result of inrush current reduction with firing angle 0°: (a) VFCV. (b) VVCF.

Another test result using VVCF method can be seen in Table 3. The inrush current was also reduced. However, the demagnetization time in tabel 3 is longer than in Tabel 2. In the other word, the demagnetization using VFCV was faster than VVCF. This result was proper with theory [1]. The VFCV method focused on period of inrush current reduction, while VVCF method focused on voltage variation of demagnetization.

V. CONCLUSION

The inrush current during energizing is affected by phase angle of voltage and residual flux in iron core of transformer. Both of demagnetization device (VVCF and VFCV) were succesful implemented and able to decrease the amplitude of inrush current. The results show that VFCV method is more efective reducing resiudal flux compare to VVCF method. The demagnetization using VFCV reduced inrush current more than 76%, while using VVCF only reaches 37%. Moreover, demagnetization time process of VFCV method was about 1.46 s, which is 1 s faster than VVCF method

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