MICROCONTROLLER-BASED COOLING OF A SINGLE-PHASE TRANSFORMER WITH THERMOELECTRIC MODULE

Adem DALCALI
Electrical-Electronics Engineering, Karabük University
ademdalcali@karabuk.edu.tr

Hüseyin DEMIREL
Electrical-Electronics Engineering, Karabük University
hdemirel@karabuk.edu.tr

Emre CELIK
Electrical-Electronics Engineering, Gazi University
emrecelik@gazi.edu.tr

ABSTRACT: Copper and core losses produced in the windings and core of a transformer cause the transformer to heat up, thereby deteriorating the transformer performance. The resulting heat needs to be thrown away out of the machine as it is more likely to damage either machine itself or its equipment, or both. For this aim, a new cooling technique for transformer core and windings, which is a unique one in its field related to transformer cooling systems, is presented in this paper using the peltier effect of thermoelectric module. In the several tests carried out, an industrial type single-phase transformer is heated by a certain amount under various operating conditions. Thanks to the presented technique, the transformer heat has been successfully kept within a predefined temperature band. Other than single-phase transformers, the presented technique can be easily applied for cooling of three-phase transformers as well. Due to its ease of application, simple structure and low cost, the presented technique is a powerful alternative to other existing techniques in the literature.

Key words: transformer cooling, temperature control, thermoelectric module, peltier effect

INTRODUCTION

During the design phase of a transformer, optimal design for each stage in solutions of electromagnetic, thermal and mechanical problems is required to achieve. As soft magnetic materials forming the transformer core constitute the magnetic circuitry of the machine, these materials are expected to have the following characteristic features; high permeability to reduce the magnetic circuit reluctance, high saturation property to reduce the volume and weight of the iron in addition to lower iron losses which give rise to increase in machine temperature (Gürdal, 2015). Copper losses produced in the windings and iron losses in ferromagnetic core under the effect of time-varying magnetic field release heat in the windings and magnetic core of the machine, respectively. By transferring the released heat into the external environment, winding temperature needs being reduced as much as possible. In this way, more current of the desired magnitude can pass through the same conductor cross-section and it is also possible to avoid the saturation flux density that decreases with temperature.

Büyükbıçakcı developed an alternative approach to the transformer cooling methods using a phase shifter material. As a result of the experiments carried out, it is shown that the utilized material cooled the heated points of the transformer at the same time and succeeded in keeping them in a certain temperature value (Büyükbıçakçı, 2006). In the literature, there are many applications that have been performed using both effects of thermoelectric material (Aly & Al-Lail, 2006; Yu et al., 2012; Liu et al., 2007; Vinoth & Prema, 2014; Hsu et al., 2013). Çicek and et.al carried out the design and implementation of a blood transport container and expressed that it is possible to carry the medical samples without any distortion (Çicek et al., 2010). Demirel identified a close relationship between the temperatures of brain and other parts in the hypothermia system which was modeled with artificial neural networks and implemented based upon the microcontroller (Demirel,2010). Tan, in his thesis, carefully examined the system performance and temperature values upon the processor and motherboard belonging to a server using heat spreader, water cooling system and thermoelectric cooler (TEC), which is called as Peltier. After performing several tests by means of software for each cooling system, he identified that the most effective cooling method came out to be the TEC while the server was continuously under the workload (Tan, 2013). Chein and Chen analyzed the thermoelectric cooling system theoretically and experimentally to make the tank cooling, which was full of water. According to the test results, they found that the tank temperature decreased over time (Chein & Chen, 2005). Demirel and et.al conducted a test system that computed the characteristic parameters of the thermoelectric modules under dissimilar thermal loads (Demirel et al., 2007).

Although the cooling operation in rotating machines are performed by inherent air currents, in transformers which have no rotating parts, it can be done in various ways such as via air, oil and water. In this paper, a unique cooling system based on microcontroller has been developed by taking advantage of the peltier effect of thermoelectric module

Experiments have been carried out for different secondary currents using both single and dual thermoelectric modules. Cooling is performed by single module when Is is 3 A and 4 A, while two modules are used for a secondary current of 5 A because of the fact that single module could not be sufficient for cooling operation. In the successive experimental studies, good results are achieved. With this regard, the presented technique is a powerful alternative to other existing techniques in the literature due to its ease of application, simple structure and low cost.

THERMOELECTRIC MODULE

Thermoelectric materials are the elements whose terminals direct current (DC) electrical energy is obtained when forming a temperature difference between their two surfaces. On the other hand, they produce temperature difference when given DC energy to their connection terminals. We may mention about two effects upon the operation of thermoelectric modules. Firstly, it is the seebeck effect that generates electrical current with the principle of temperature difference between the surfaces. Secondly, it is the peltier effect that constitutes a temperature difference between the surfaces when a thermoelectric module is connected to a DC power supply (Ionescu et al., 2011; Wey, 2006; Shaojing & Qin, 2010).

Thermoelectric module is an element composed of P- and N-type semiconductors materials that are connected in series electrically and in parallel thermally. They have the upper and bottom surfaces covered by ceramic, and they also have a feature of working quite (Yalçınkaya, 2008; Kim et al., 2014; Carmo et al., 2011). If one ends of the two conductors having distinct self-resistance are combined with each other and a current is allowed to flow through these combined conductors, temperature of the one end is decreased while the other's is increased, in a manner that provides heat transfer from one to another. The resulting effect is called the peltier effect, and can be represented in Figure 1.

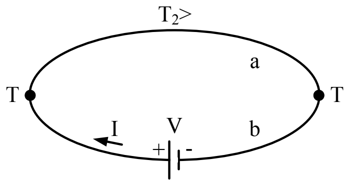


Figure 1. Peltier Effect

The amount of heat generated at the junction is proportional to the applied current and its definition per unit time can be expressed as in Eq. (1).

$$Q_p = \pi \cdot I \qquad (1)$$

where π is the peltier coefficient, Q_p is equal to the peltier heat stated in watts and I is the electrical current (Tan, 2013; Carmo et al., 2011; Dikmen, 2002; Lineykin et al., 2007; Martinez et al., 2012; Wang et al., 2012). The temperature difference between the two surfaces of a thermoelectric module can be given by Eq. 2

$$\Delta T = T_k - T_c \qquad (2)$$

In Eq. 2, T_k and T_c are the hot and cold surface temperatures of the thermoelectric module, respectively (Bulut, 2005). Heating and cooling effect coefficients (COP) of thermoelectric modules can be defined as in Eq. (3) and (4).

$$COP_k = Q_k / W_e \tag{3}$$

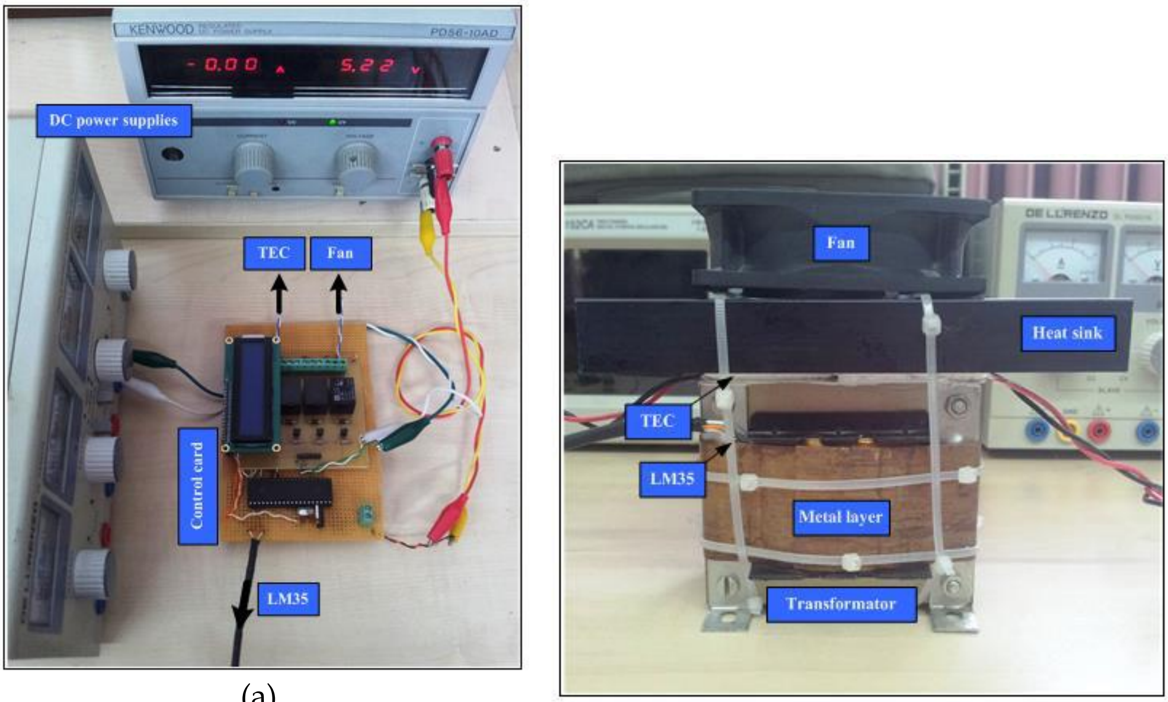
$$COP_c = Q_c / W_e \tag{4}$$

where COP_k is the heating and COP_c is the cooling effect coefficient.

THE DEVELOPED COOLING SYSTEM

The designed and implemented system is given in Figure 2. The developed control card, which consists of a PIC16F877A microprocessor, 12 V low-power relays and BC547 transistors for driving the TECs and fan, is seen in Figure 2(a). Figure 2(b) shows the cooling configuration where a typical single-phase transformer, TEC-12706 thermoelectric modules, LM35 temperature sensor, low-volume heat sink, and a small fan are used. The thermoelectric modules are located on the upper part of the transformer core underneath the heat sink. The cold side of the module is against the core, and the hot side is adjacent with the heat sink. Thermal paste is used in order to ensure thermal conductivity.

The transformer temperature is measured with LM35 placed between the transformer and the surrounding metal layer. This metal layer covers the surface of the transformer allowing the heat transmission from the windings to the core. Thus, when the cooling operation is enabled, the windings cooling from the core becomes faster. The exact temperature is compared to its reference within the microcontroller. As a result of this comparison, on/off state of the thermoelectric module and fan system are determined. If the temperature is higher than the reference, then the cooling system is activated and it is kept active until the temperature falls below the reference. Both fan and thermoelectric module are driven by the transistors and relays in the control card to isolate them from the microprocessor.



(a)

(b)

Figure 2. The Experimental Setup (a) Control Card, (b) Cooling Configuration

The flowchart of the presented technique is given in Figure 3 where the microcontroller input-output pin adjustments, variable definitions, analog-digital converter settings, etc. are set firstly. Then, the transformer temperature is read by LM35, which is displayed on the LCD screen for operator knowledge. If the measured temperature is above 35 °C, the thermoelectric module and fan become active forthwith. Once the temperature drops below 35 °C, the thermoelectric module is deactivated. For the purpose of removing the resulting heat in the hot side of the thermoelectric module, fan operation is maintained for a while. As understood from the above explanations, the system operates like a hysteresis control, which is known as the simplest technique in control theory.

As for the loaded operating conditions of the corresponding transformer, short-circuit tests are performed under different current values where the primary voltage is increased until the secondary short-circuit current reaches the value up to the 125% times its rated current 4 A.

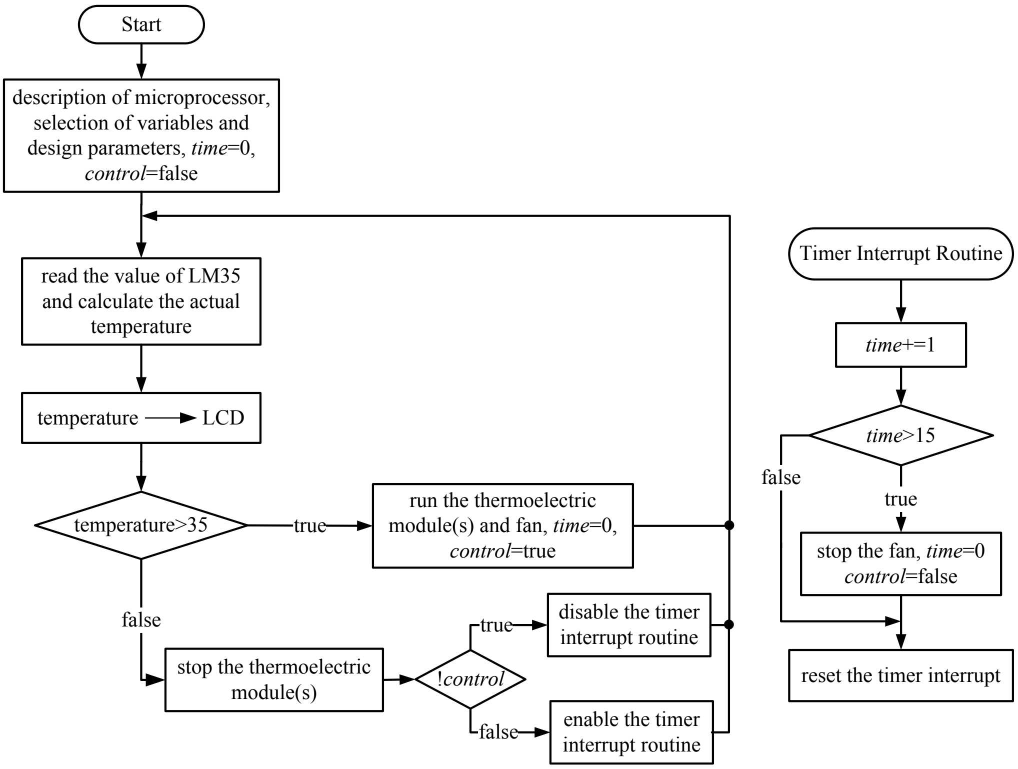


Figure 3. Flowchart of the Proposed System

Technical specifications of the thermoelectric module are reported in Table 1.

Table 1. Specifications of TEC-12706

Specifications	25 °C	50 °C
$Q_{\max}$ [W]	50	57
$I_{\max}$ [A]	6,4	6,4
$V_{\max}$ [V]	14,4	16,4
$\Delta t_{\max}$ [^{0}C]	66	75
Module Resistance [Ω]	1,98	2,3

In Table 1, $Q_{\max}$ is the maximum heat drawn from the cooling environment, and $\Delta t_{\max}$ is the highest temperature difference that can occur between the cooling surfaces.

EXPERIMENTAL RESULTS

In the experimental studies, supplying the transformer from variable AC power source, short-circuit tests are performed by taking the transformer secondary current I_s and primary voltage V_p into consideration. The secondary currents are set to 3 A, 4 A and 5 A, respectively. The obtained results using single TEC module is given in Figure 4 where I_s is 3 A. After a 39 minute period from the beginning of the experiment, the transformer temperature raised over its reference temperature 35.2 °C. In this case, the TEC module was activated and it could drop the temperature to 34.2 °C in 15 seconds. When the temperature is above the reference, the temperature was again lowered successfully by making the TEC become active. In Table 2, TEC and fan currents and voltage measurements are given.

Table 2. TEC and Fan Measurements

	Current[A]	Voltage[V]	Power[W]
TEC	2,81	8,6	24,16
Fan	0,07	12,1	0,85

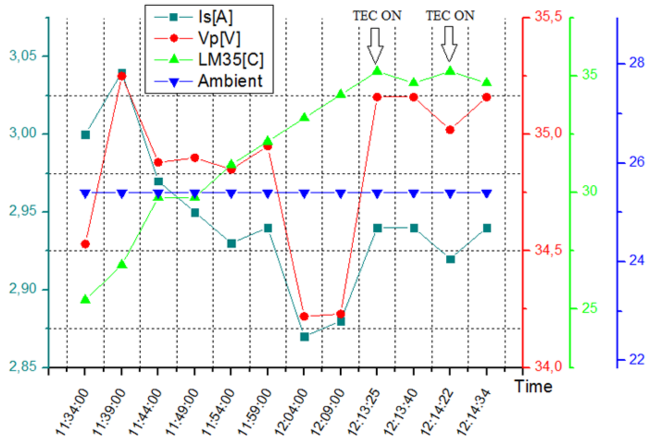


Figure 4. Experimantal Results When The Secondary Current Is 3A

In Figures 5-6, similar satisfactory experimental results are given when Is is 4 A and 5 A, respectively. In Figure 6, the experiment started at 14:03, and when the temperature reached to 35.2 °C at 14:16:53, the TEC module was activated and it again dropped the temperature to 34.2 °C in 22 seconds.

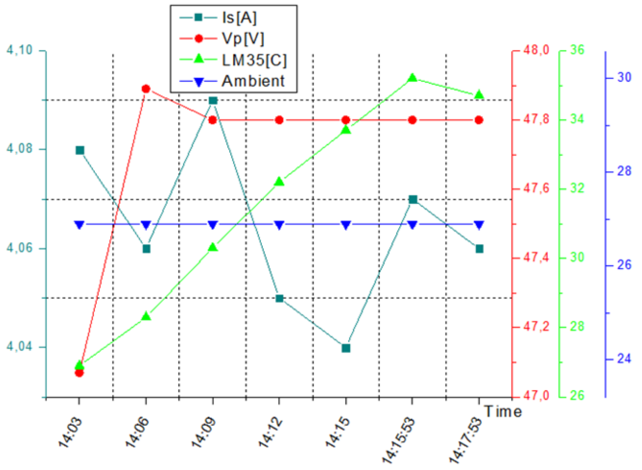


Figure 5. Experimantal Results When The Secondary Current Is 4A

In Figure 6, after 8 minutes from the beginning of the experiment, as the transformer temperature raised over the reference temperature 35.2 °C, the TEC module became active. However, in this operating condition, the temperature could not be reduced below the reference with single TEC module. In order to ensure adequate amount of cooling, one more TEC module was added to the experimental setup and the experiment was repeated under the same conditions. The obtained results with two TEC modules are promising and are given in Figure 7. In the new system with two TEC modules, the required cooling was provided and the temperature could be kept within the desirable range consistently. In Table 3, the current and voltage values of the fan, TEC1 and TEC2 modules are given when they are active.

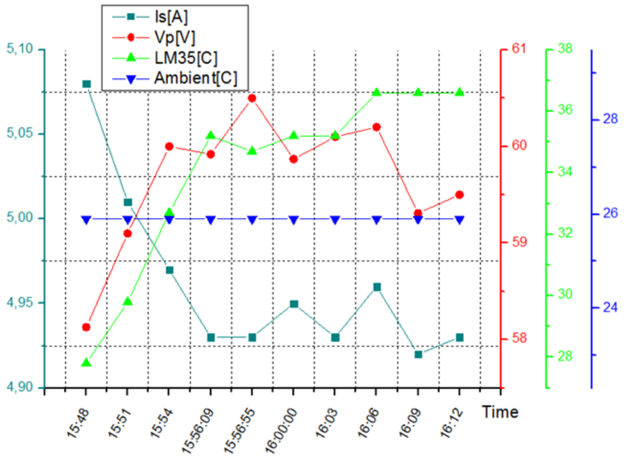


Figure 6. Experimantal Results When The Secondary Current Is 5A

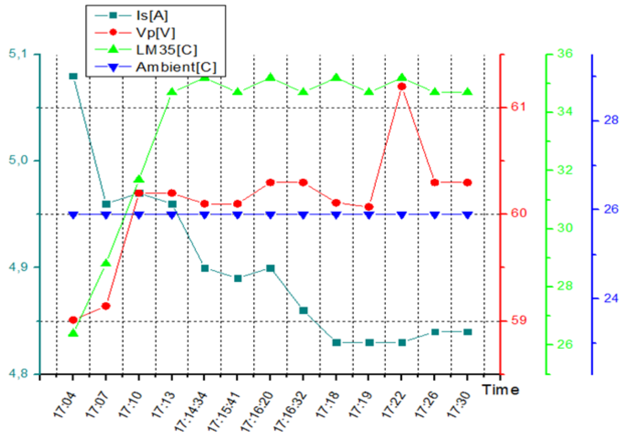


Figure 7. Experimantal Results When The Secondary Current Is 5A With Two TEC Modules

Table 3. Current and Voltage Values of the Fan, TEC1 and TEC2 Modules

	Current[A]	Voltage[V]	Power[W]
TEC1	2,92	9,1	26,57
TEC2	2,91	8,2	23,87
Fan	0,07	12,1	0,85

CONCLUSIONS

In this paper, a successful cooling scheme for transformer core and windings has been carried out using the peltier effect of thermoelectric module. According to the experimental results, the heat arisen due to the power losses could be ensured to efficiently remain within the certain range, protecting the machine and its equipment from probable excessive heat. This means that more currents can be drawn from the windings for longer time with the improved cooling system compared to uncooled transformer systems. The metal layer used to allow the heat transmission from the windings to the core and vice versa has a great importance as well since most of the heat is formed in the current-carrying coils.

In the performed successive experimental studies, good results are achieved. With this regard, the proposed study is a powerful alternative to other studies in the literature due to its simplicity and low cost. One should note that better cooling can be achieved with addition of more TEC modules provided that the hot side temperature of the modules can be removed carefully as it can be said that how much better the heat is removed from the hot side, so well done the cooling is.

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