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The Neural-Fuzzy Control of a Transformer Cooling System

Jong-Yong Lee[1] and Chul Lee[2*]

[1]Ingenium college of liberal arts, KwangWoon University, Seoul 01897, Korea
*[*2]Department of Mechatronics, Inhatechnical Collage, 100 Inha-Ro, Namgu, Incheon, 402-752*
*E-mail: [1]jyonglee@kw.ac.kr, [*2]clee@unhatc.ac.kr*

Abstract

In transformer cooling systems, oil temperature is controlled through the use of a blower and oil pump. For this paper, set-point algorithms, a reset algorithm and control algorithms of the cooling system were developed by neural networks and fuzzy logics. The oil inlet temperature was set by a 2× 2× 1 neural network, and the oil temperature difference was set by a 2× 3× 1 neural network. Inputs used for these neural networks were the transformer operating ratio and the air inlet temperature. The inlet set temperature was reset by a fuzzy logic based on the transformer operating ratio and the oil outlet temperature. A blower was used to control the inlet oil temperature while the oil pump was used to control the oil temperature difference by fuzzy logics. In order to analysis the performance of these algorithms, the initial start-up test and the step change test were performed by using the dynamic model of a transformer cooling system. Test results showed that algorithms developed for this study were effective in controlling the oil temperature of a transformer cooling system.

Keywords: *Transformer cooling system, Setpoint algorithm, Reset algorithm, Control algorithm, Neural network, Fuzzy logic*

1. Introduction

The railway is great in ecofriendly, safety and punctuality to be a good transportation for passenger and cargo. Tilting train which is excellent in connectivity with previous track and can upgrade travelling speed and comfortable to drive in curve track [1, 2]. The third-phase induction motor is used for propelling railway and main transformer is installed for changing high voltage supply electricity to low voltage. Generated loss, which is generated during transforming, is cooling and circulating as heating energy through oil that is flowing main transformer. Previous main transformer cooling system has relay and concervator etc. which are just safety equipment therefore lots of energy is used when oil pump and air blower is working at full capacity. The improvement is required [3]. Following report is about suggesting and identifying system which can improve energy efficiency to consider safety of railway transformer.

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Corresponding Author: clee@unhatc.ac.kr
Tel:+82-32-870-2470, Fax: +82-32-870-2504
Department of Mechatronics, Inhatechnical Collage

2. Mathematic model of cooling system

Generated energy in main transformer is absorbed to system oil which is flowing through main transformer. System oil is circulating main transformer as cooling through oil pump, oil cooler and air blower for managing main transformer's cooling system effectively. Mathematic model is used which can copy kinetic state of cooling system that composited by main transformer, oil pump, oil cooler and air blower. Static model and kinetic model, which is 1st system having delay, are used as oil pump and air blower. Main transformer model is formed as single current energy exchanger. Static model, which is using effectiveness number of transfer units as formed cross flow energy exchanger, and kinetic model, which is 1st system having delay, are used as oil cooler model [4, 5].

3. System algorithm

3.1 Setpoint algorithm

Transformer loss is increased as rate of operation and oil temperature of main transformer is increased. Power consumption is increased when oil pump and air blower's rate of operation is increased for decreasing oil temperature. Therefore the algorithm is required to operate cooling system considering oil pump and air blower's power consumption which is depending on operation rate for transformer profit and cooling oil. Equation (1) shows the total power consumption of cooling system,

$$P_{loss} = P_{mtr,loss} + P_{pump} + P_{blower} \tag{1}$$

$P_{mtr,loss}$ is transformer loss during transformation, P_{pump} is oil pump's power consumption for cooling oil, P_{blower} is power consumption of air blower for cooling oil. Main transformer oil pump and air blower operation rate is changed every 0.1 point for calculating the optimum inlet temperature and optimum outlet temperature of main transformer oil when P_{loss} is minimum. Multilayered neural network is used which is outputting $T_{i,neural}$ and input $T_{air.i}$ and S_{mtr} as shown Fig. 1 for showing $T_{i,set}$ gaining from simulation using S_{mtr} and $T_{air,i}$. 2×2×1 structure is chosen considering correlation coefficient of $T_{i,set}$ and $T_{i,neural}$ for $T_{i,neural}$. $T_{d,set}$is chown as Fig. 2 that multilayered neural network is used which is outputting $T_{d,neural}$. $T_{d,neural}$ choose 2×3×1 structure by considering correlation coefficient of $T_{d,set}$ and $T_{d,neural}$. Sigmoid and linear function are used as activation function of hidden and output layer. Back propagation algorithm is used as learning algorithm. Table 1~4 show the learned neural network's connection strength and bias [6].

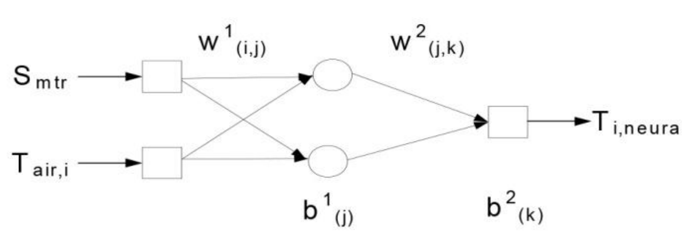

Figure 1. Neural network for the inlet oil temperature

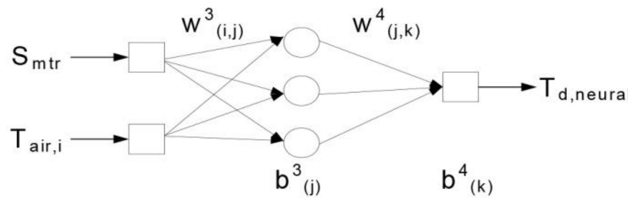

Figure 2. Neural network for the oil temperature difference set-point

Table 1. Weights and biases for the hidden layer(inlet oil temperature set-point)

j	$W^1_{(1,j)}$	$W^2_{(1,j)}$	$b^1_{(j)}$
1	0.021556	-1.0527	-1.4214
2	0.098403	0.13541	-0.36644

Table 2. Weights and bias for the output layer(inlet oil temperature set-point)

J	$W^2_{(j,1)}$	$b^2_{(j)}$
1	-7.2597	-10.8995
2	30.7216	

Table 3. Weights and biases for the hidden layer(oil temperature difference set-point)

j	$W^3_{(1,j)}$	$W^3_{(1,j)}$	$b^2_{(j)}$
1	-0.26164	0.2010	-0.06581
2	3.4831	1.4041	-0.98238
3	-0.02158	-3.2435	-3.3749

Table 4. Weights and bias for the output layer(oil temperature difference set-point)

J	$W^4_{(j,1)}$	$b^4_{(j)}$
1	-10.1358	5.2739
2	0.02939	
	-2.579	

3.2 Reset algorithm

Set oil temperature is considering rate of transformer cooling system through setpoint algorithm. When T_o is too high, the damage of main transformer system can be happened. Oil temperature reset algorithm is developed which can control $T_{i,set}$ depending on main transformer operating rate and output temperature. S_{mtr} and T_o are set as reset algorithm and fuzzy logic is used as $\Delta T_{i,set}$ which is set entrance oil temperature changes. Fig. 3 and Fig. 4 show the input variable's membership, Fig. 5 shows output variable's membership, Table 5 shows the rule used. Min-Max method is used as inference method and center of gravity method is used as turn-fuzzy method [7]. Reset entrance oil temperature value ($T_{i,rest}$) is calculated by equation (2).

$$T_{i,reset} = T_{i,set} + \Delta T_{i,set} \quad (2)$$

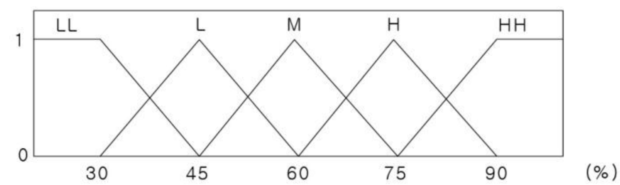

Figure 3. Membership for S_{mtr}

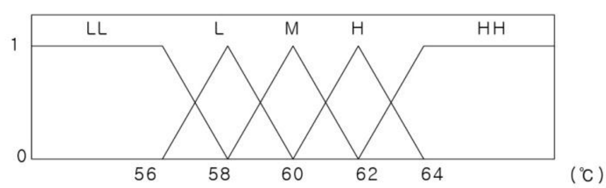

Figure 4. Membership for T_o

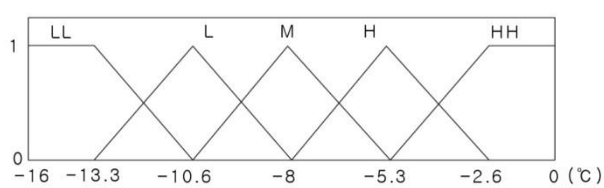

Figure 5. Membership for $\Delta T_{i,set}$

Table 5. Rule base for the resetpoint algorithm

	$\Delta T_{i,set}$	S_{mtr}				
		LL	L	M	H	HH
	LL	HH	HH	H	M	L
	L	HH	H	M	M	L
T_o	M	H	H	M	L	LL
	H	H	M	M	L	LL
	HH	H	M	L	LL	LL

3.3 Control algorithm

In-Put temperature rate is controlled every 20 seconds using oil pump and air blower is used as entrance temperature of main transformer oil for controlling set temperature from system setpoint algorithm. Fuzzy logic is used for controlling air blower. Main transformer input temperature rate $T_{i,d}$ is shown as equation (3) and change rate of $T_{i,d}$ ($\Delta T_{i,d}$) shown equation (4) is used as input variable of fuzzy algorithm. Air blower operation rate S_{blower} is used as output variable which is expressed as equation (3) and (4).

$$T_{1,d} = T_{i,set} - T_i \quad (3)$$

$$\Delta T_{i,d} = T_{i,d} - T_{i,d,old} \quad (4)$$

T_i is input temperature of main transformer oil and $T_{i,d,old}$ is the $T_{i,d}$'s previous value. Fig. 6 and Fig. 7 show the input variable's membership, Fig. 8 shows the output variable's membership, Table 6 shows the rule used. Air blower operation rate (S_{blower}) is calculated from output variable ΔS_{blower} using equation (5).

$$S_{blower} = S_{blower,old} + \Delta S_{blower} \quad (5)$$

$S_{blower,old}$ means S_{blower}'s previous value.

Fuzzy logic is used for controlling oil pump. The difference of main transformer's in-output temperature as shown in equation (6) and change rate of $T_{d,d}$ ($\Delta T_{d,d}$) as shown in equation (7) are used as input variable of fuzzy algorithm. ΔS_{pump} is used for output variable therefore equation (6) is induced.

$$T_{d,d} = T_{d,set} - T_d \quad (6)$$

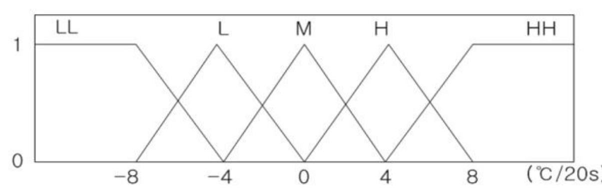

Figure 6. Membership for $T_{i,d}$

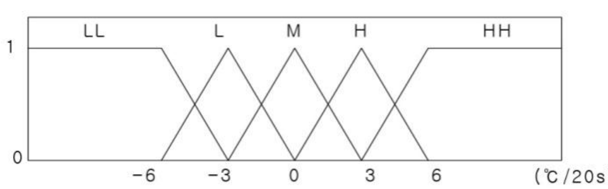

Figure 7. Membership for $\Delta T_{i,d}$

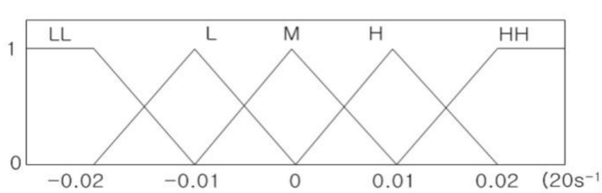

Figure 8. Membership for ΔS_{blower}

Table 6. Rule base for the blower control algorithm

ΔS_{blower}		$S_{i,d}$ LL	L	M	H	HH
$\Delta T_{i,d}$	LL	LL	LL	L	M	M
	L	LL	L	M	M	H
	M	L	L	M	H	H
	H	L	M	M	H	HH
	HH	M	M	H	HH	HH

$$\Delta T_d = \Delta T_{d,d} - \Delta T_{d,d,old} \tag{7}$$

T_i is the temperature rate of in and output of main transformer oil, $\Delta T_{d,d,old}$ is the previous value of $T_{d,d}$. Fig. 9 and 10 show membership of input variable, Fig. 11 shows membership of output and Table 7 shows the rule used. Oil pump operation rate (S_{pump}) is calculated using equation (8) from output variable ΔS_{pump} [9].

$$S_{pump} = S_{pump,old} + \Delta S_{pump} \tag{8}$$

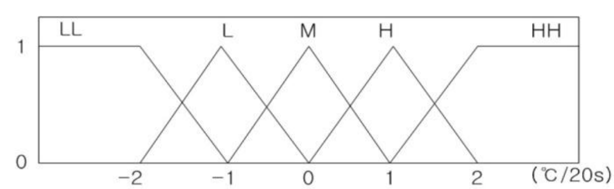

Figure 9. Membership for $T_{d,d}$

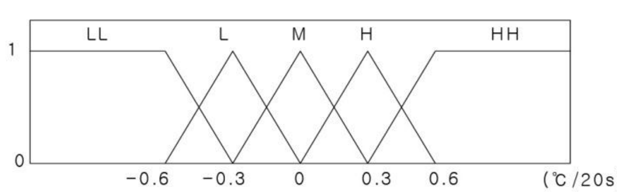

Figure 10. Membership for $\Delta T_{d,d}$

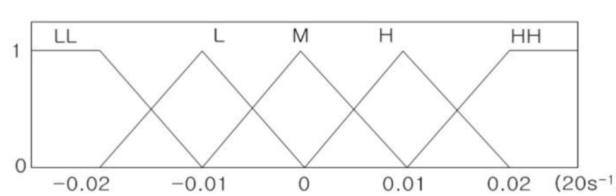

Figure 11. Membership for ΔS_{pump}

Table 7. Rule base for the oil pump control algorithm

ΔS_{pump}		$S_{d,d}$				
		LL	L	M	H	HH
$\Delta T_{d,d}$	LL	LL	L	M	M	M
	L	LL	L	M	M	H
	M	L	L	M	H	HH
	H	L	M	M	H	HH
	HH	M	M	H	HH	HH

Table 8. Power savings

$\Delta P_{loss}[W]$		S_{mtr}									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$T_{air,i}$[℃]	-15	2632	4358	5489	4807	4726	4065	3284	2507	2411	951
	-5	2669	4369	5496	4820	4733	4090	3301	2534	2426	1019
	5	2732	4421	5512	4849	4751	4121	3321	2558	2441	1037
	15	2761	4459	5546	4863	4772	4134	3368	2597	2484	1062
	25	2732	4472	5582	4873	4821	4146	3409	2621	2505	1023

4. Efficiency analysis of algorithm

P_{full} is the energy consumption of maximum operation of oil pump and air blower. $P_{optimal}$ is the energy consumption of controlled oil pump and air blower using setpoint algorithm. ΔP_{loss} can be calculated by equation (9).

$$\Delta P_{loss} = P_{full} - P_{optimal} \tag{9}$$

As Table 8 shows large amount of energy profit can be algorithm by changes of $T_{air,i}$ and S_{mtr}. Initial operating efficiency test and main transformer operation rate step variation efficiency test are tested for analyzing efficiency of system algorithm which is composed by setpoint algorithm, reset algorithm and control algorithm.

4.1 Initial operating efficiency test

Initial operating test is tested at outside temperature 25℃, oil initial temperature 30℃ with 0.6 of main transformer operating rate for identify initial control efficiency of cooling system.

Fig. 12 and 13 shows the result of initial operation applied by system algorithm. Oil temperature is set up by setpoint algorithm and reset algorithm. Oil temperature is controlled as set value by control algorithm of air blower and oil pump.

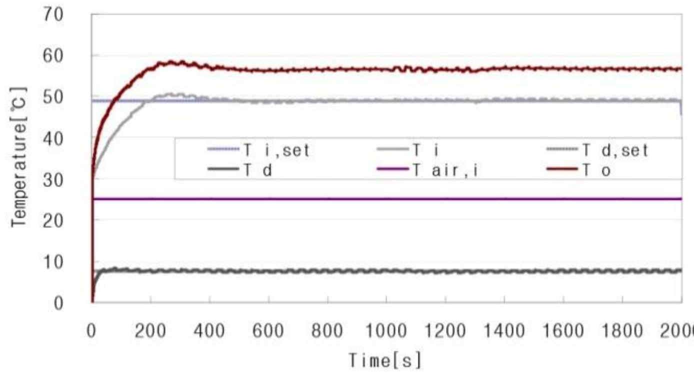

Figure 12. Oil temperature (initial start-up test).

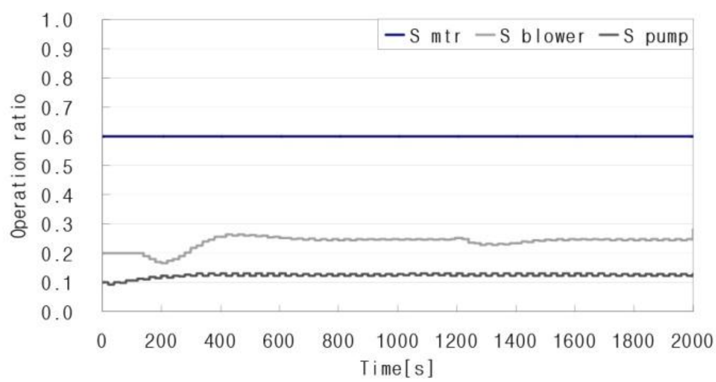

Figure 13. Control signals (initial start-up test).

4.2 Main transformer operation rate step variation efficiency test

Operation rate step variation efficiency test is operated every 1000seconds by 0.1 at 25℃ outside temperature, 25℃ initial temperature of oil with 0.5 main transformer operation rate for identify control efficiency depending on operation rate difference of train.

Fig. 14 and 15 shows the result of main transformer operation rate step variation applied by system algorithm. Oil temperature is set up as suitable temperature in every section through set and reset process. Oil temperature is controlled as set value by controlling air blower and oil pump.

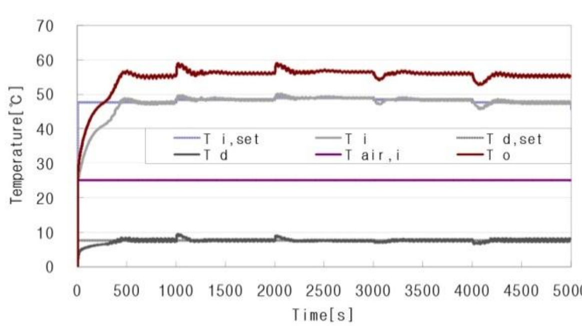

Figure 14. Oil temperature (step change test).

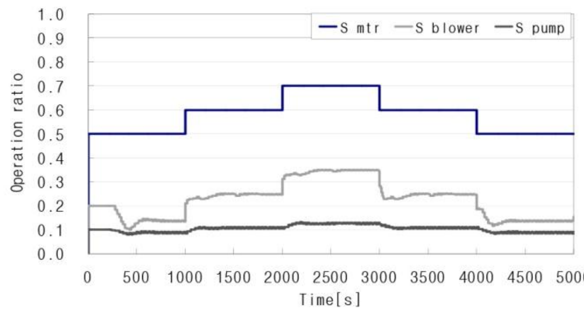

Figure 15. Control signals (step change test).

5. Conclusion

Kinetic model is used which can copy kinetic state of cooling system that composed by main transformer, oil pump, oil cooler and air blower for developing each algorithm of train main transformer cooling system effectively. Setpoint algorithm, which is the difference of optimum input temperature and optimum in-out temperature as system energy consumption is minimum for operating train main transformer cooling system safety and effectively, and reset algorithm which is reset transformer input oil temperature for safety of transformer, are developed. Air blower and oil pump’s control algorithm is developed for controlling oil temperature using reset operator. Neural algorithm is used as setpoint algorithm which is inputting outside temperature and main transformer operation rate. Fuzzy algorithm is used for output entrance oil temperature and main transformer operation rate and output oil temperature is input as reset algorithm. Fuzzy algorithm is used as air blower control algorithm for controlling set input temperature by input difference and change of main transformer input temperature. Fuzzy algorithm is developed as oil pump control algorithm by input difference and changes of main transformer in-out temperature. Energy saving is identified by calculation of energy profit for identifying utility of developed setpoint algorithm. Initial efficiency test and main transformer operation rate step variation efficiency test is examined for analyzing control efficiency depending on system algorithm. The result shows system algorithm that is developed using neural network and fuzzy logic can be used effectively for safe and effective management of main transformer cooling system.

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