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A Study on the Hot Spot Temperature in 154kV Power Transformers

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Abstract – The life of a power transformer is dependent on the life of the cellulose paper, which influenced by the hot spot temperature. Thus, the determination of the cellulose paper's life requires identifying the hot spot temperature of the transformer. Currently, however, the power transformer uses a heat run test is used in the factory test to measure top liquid temperature rise and average winding temperature rise, which is specified in its specification. The hot spot temperature is calculated by the winding resistance detected during the heat run test. This paper measures the hot spot temperature in the single-phase, 154kV, 15/20MVA power transformer by the optical fiber sensors and compares the value with the hot spot temperature calculated by the conventional heat run test in the factory test. To measure the hot spot temperature, ten optical fiber sensors were installed on both the high and low voltage winding; and the temperature distribution during the heat run test, three thermocouples were installed. The hot spot temperature shown in the heat run test was 92.6℃ on the low voltage winding. However, the hot spot temperature as measured by the optical fiber sensor appeared between turn 2 and turn 3 on the upper side of the low voltage winding, recording 105.9℃. The hot spot temperature of the low voltage winding as measured by the optical fiber sensor was 13.3℃ higher than the hot spot temperature calculated by the heat run test. Therefore, the hot spot factor (H) in IEC 60076-2 appeared to be 2.0.

Keywords: Power transformer, Life, Hot spot, Temperature, Optical fiber sensor

1. Introduction

Power transformers are unlikely to suffer from a breakdown, however if a breakdown occurs it may cause a huge damage to society and economy. The power transformers installed during the rapid growth of the economy, and came close to a 30 year operation. The life of the power transformer should be calculated with statistical data in order to establish the criteria. But its materials and manufacturing technologies change over the years and any normal distribution has not been formed. Therefore just plain statistical methodology is not enough to determine the life of the transformer [1]. The life of the power transformer depends on the life of the cellulose paper whose deterioration is affected by temperature, moisture and oxygen. However, since the effects of moisture and oxygen on cellulose paper's deterioration can be controlled for it to remain in minimum, it may be stated that the deterioration of the cellulose paper is largely affected by temperature [2]. In particular, as temperature distribution inside the power transformer is not uniform, the cellulose paper around the hot spot temperature will be deteriorated the most. Therefore, the standards define the transformer's life, depending on the life of the cellulose paper, which influenced on the hot spot temperature.

Generally, the deterioration function of the cellulose paper according to the hot spot temperature is based on the Arrhenius reaction rate theory in IEEE C57.91 [3].

$$\text{Per Unit Life} = 9.8\times10^{-18}\exp^{\left(\frac{15000}{\theta_H+273}\right)} \tag{1}$$

where, θ_H is the hot spot temperature.

The life of the power transformer is suggested to be 7.4 years of 50% retained tensile strength and 15.4 years of 25% retained tensile strength of the thermally upgraded kraft paper with the hot spot temperature of 110℃; which are under the ambient temperature of 30℃, the average winding temperature rise limit of 65℃ and the hot spot temperature rise of 15℃ [4-6].

IEC 60076-7 also recommends to evaluate the cellulose paper's life based on the hot spot temperature of 110℃ [7]. JEC-2200 suggests that the transformer's life to be 30 years if the power transformer is continuously operated at the hot spot temperature of 95℃ [8]. In this case, IEC and JEC calculate the hot spot temperature by multiplying the hot spot factor (H) by the difference between the average winding temperature rise and the average liquid temperature rise. The hot spot factor (H) is applied 1.1 for the distribution transformer and 1.3 for the power transformer, respectively.

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Likewise, the standards define that the power transformer's life is absolutely subject to the hot spot temperature; thus, the identification of the power transformer's life requires a clear and exact hot spot temperature. Currently, however, the power transformer uses a heat run test to measure top liquid temperature rise and average winding temperature rise by the factory test, which is specified in its specification. The hot spot temperature is calculated by the winding resistance for reference which is detected during the heat run test. If the hot spot temperature calculated by the winding resistance is different to the actual hot spot temperature, the life of transformer will be estimated a big error. In order to estimate the life of transformer accurately, this paper measures the hot spot temperature in the single-phase, 154kV, 15/20MVA power transformer by the optical fiber sensors and compares with the hot spot temperature calculated by the conventional heat run test in the factory test.

2. Manufacture of 154kV transformer to measure the hot spot temperature

2.1 Manufacture of 154kV transformer

To measure the hot spot temperature of the transformer, a single-phase, 154/22.9kV, 15/20MVA transformer was manufactured based on the ES-6120-0001 [9]. The transformer used in this paper had the same structure as the transformer used in a substation.

The total loss of the transformer was 90,236W based on 15MVA which no-load loss is 11,280W and load loss was 78,956W. The cooling method of the transformer is ONAN/ONAF. The top liquid temperature rise limit is 60℃ measured by the thermometer and the average winding temperature rise limit is 65℃ calculated by the resistance method on the rated power.

The major specifications of the transformer are shown in Table 1.

Table 1. Specification of the transformer

Classification		Specification
Loss	No-load	11,280W
	Load	78,956W
	Total	90,236W
Rated voltage		154/22.9kV
Rated capacity		Single-phase, 15/20MVA, 60Hz
Core type		Shell
Temperature rise limits		Top liquid 60℃
		Average winding 65℃
Cooling method		ONAN/ONAF
% impedance		20%
Liquid volume		11,000 liters

2.2 Optical fiber sensor

To measure the hot spot temperature, ten optical fiber sensors were installed on both the high and low voltage winding. The temperature measurement range of the optical fiber sensor is 20℃~275℃. The temperature sensitivity of the optical fiber sensor is ~10pm/℃ (±1.7pm/℃), and its response time is 0.2 seconds. The fiber type is SMF28-compatible, and the probe has diameter of 1.07mm and length of 27.1mm. In addition, fiber bend radius is over 17mm. The major specifications are shown in Table 2.

Table 2. Specification of the optical fiber sensor

Classification	Specification
Model	OS4200
Operating temperature range	20℃ ~ 275℃
Temperature sensitivity	~10pm/℃ (±1.7pm/℃)
Response time	0.2 seconds
Probe (Diameter x Length)	1.07 x 27.1mm
Fiber type	SMF28-compatible
Fiber bend radius	Over 17mm
Peak reflectivity (Rmax)	Over 70%
Isolation	Over 15dB

As the hot liquid inside the transformer ascends to the upper side, the upper side of the winding shows the hot spot temperature, in general. However, it is difficult to measure the location of hot spot temperature with only one optical fiber sensor so several optical fiber sensors should be installed on the upper side of the winding where the hot spot temperature is expected to occur.

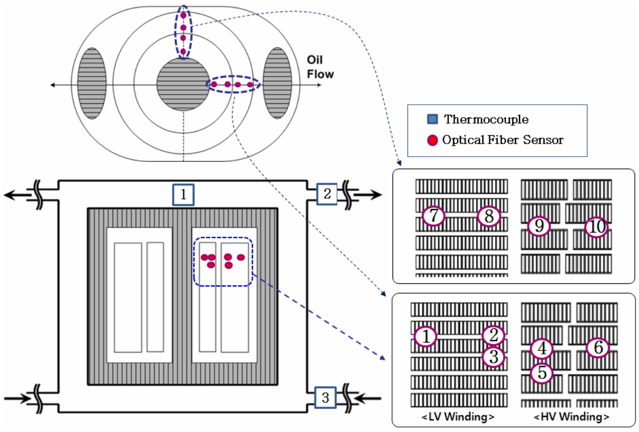

Fig. 1. Locations of the optical fiber sensor

Fig. 1 shows where the optical fiber sensors were installed in the 154kV transformer. Three optical fiber sensors each were installed on the upper side of the high voltage winding and the low voltage winding to measure the hot spot temperature (①~⑥). The temperature of the highest winding is lower than the hot spot temperature due to liquid flow, the optical fiber sensors were installed between turn 2 and turn 3, and between turn 3 and turn 4 of the winding (②~⑤). In addition, to measure the temperature distribution of the winding, the optical fiber sensors were installed inside of the low voltage winding (①) and outside of the high voltage winding (⑥). Two optical fiber sensors each were installed on the high voltage winding and low voltage winding to compare the temperature in the direction of liquid flow and that in the direction perpendicular to liquid flow (⑦~⑩). Moreover, thermocouples were installed on the top of liquid (11), on the outlet pipe (22) which liquid flows to the radiator, and inlet pipe (33) which liquid flows from the radiator for the heat run test.

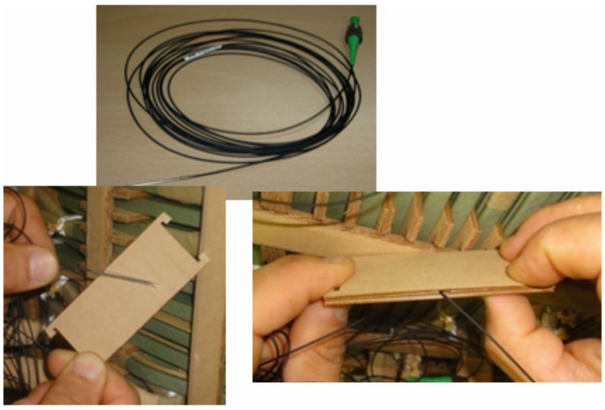

Fig. 2. Installation of the optical fiber sensor

Fig. 2 shows how to install the optical fiber sensor used in this paper: to mount an optical fiber sensor in the spacer, insert it between the windings; thus, only insulation paper of winding between the optical fiber sensor and the winding conductor.

3. Hot spot temperature measurement in 154kV transformer

The heat run test is conducted to determine whether the temperature rise limits of the top liquid and the average winding satisfy to the specification or not [10, 11]. The heat run test is mostly used for the routine test in the factory. Test methods of the heat run test are actual loading method, loading back method and short circuit method. In the factory test, however, the heat run test is measured by the short circuit method. The heat run test by the short circuit method makes the secondary winding short and applies voltage to the primary winding, supplying current equivalent to loss.

3.1 Hot spot temperature calculated by the heat run test

The top liquid temperature rise test was conducted when the transformer is subjected to a test current corresponding to the total losses (the sum of no-load loss and load loss) of the transformer. After the top liquid temperature rise test has been established, the average winding temperature rise test is continued without a break with the test current reduced to rated current equivalent to load loss (the sum of copper loss and stray loss). For the convenience of the test, however, the two steps of the test may be combined in one single application of power.

The primary rated voltage is a voltage to generate maximum loss; 77,798V was measured on the lowest tap (21 tap) equivalent to the lowest voltage under the rated phase voltage ($154\text{kV}/\sqrt{3} \ \pm\ 12.5\%$). No-load loss is indicated a loss when the rated voltage is applied to the primary winding and the secondary winding is open; it was measured to be 11,280W. Load loss is the sum when copper loss (62,769W) and stray loss (16,277W) are added; it was measured 78,956W. Therefore, the total loss was 90,236W by adding no-load loss and load loss.

The rated current (I_r), equivalent to load loss is;

$$\frac{\text{Rated capacity}}{\text{Primary rated voltage}} = \frac{15\text{MVA}}{77{,}798\text{V}} = 192.8\text{A}$$

The ratio of the current transformation is 400/5A;

$$I_r = \frac{192.8}{400/5} = 2.410 \ \text{A}$$

The total loss current (I_t) is;

$$\text{Rated current} \times \sqrt{\frac{\text{Total loss}}{\text{Load loss}}}$$

$$= 192.8 \times \sqrt{\frac{90{,}236}{78{,}953}} = 206.1 \ \text{A}$$

$$I_t = \frac{206.1}{400/5} = 2.576A$$

In this paper, the injection current (I_t) was supplied as 2.580A in the heat run test.

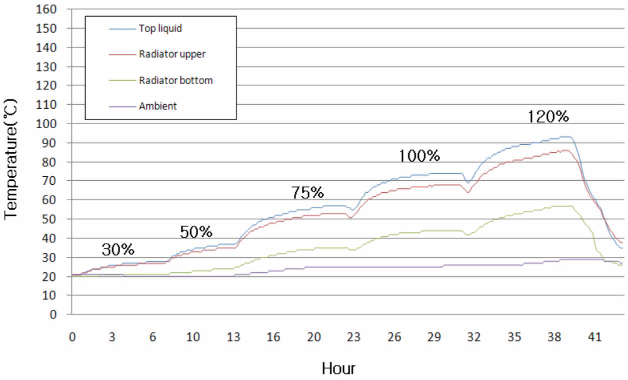

Fig. 3. Top liquid, radiator upper and bottom temperatures

Fig. 3 shows the top liquid temperature, radiator upper temperature, radiator bottom temperature and ambient temperature as measured by the thermocouples with 30%, 50%, 75%, 100%, and 120% of the rated power.

3.1.1 Top liquid temperature rise test

(1) Ambient temperature (θ_a)

The temperature of the cooling medium in the heat run test is based on the ambient temperature in the case of the ONAN transformer. The ambient temperature, averaged from the measurements of the three thermocouples, was 24.7℃. The thermocouples were distributed around the transformer, about 2m away from the tank, and placed at a level about halfway up the radiator.

(2) Top liquid temperature (θ_o)

The top liquid temperature is the temperature of the insulating liquid at the top of the tank, representative of top liquid in the cooling flow stream. The top liquid temperature is conventionally determined by thermocouple immersed in the insulating liquid at the top of the tank. The top liquid temperature was measured while the injection current (I_t) was applied at 2.580A. The test was terminated when the rate of change of top liquid temperature rise has fallen below 1 K/h and has remained there for a period of 3 hours. In this paper, continuous automatic recording was applied; the average value during the last hour was taken. The top liquid temperature (θ_o) was 73.7℃ on the rated power and the top liquid temperature rise ($\Delta\theta_o$) was 49.0℃ which is the temperature difference between the top liquid temperature and the ambient temperature. This satisfies the top liquid temperature rise limit of 60℃ as in the transformer specification in Table 1.

(3) Radiator upper temperature (θ_u) and radiator bottom temperature (θ_b)

The radiator upper temperature measured on the outlet pipe wherein oil flows to the radiator was 66.2℃. And the radiator bottom temperature measured on the inlet pipe was 42.3℃ when it flowed in through the bottom pipe after it had cooled down in the radiator. Bottom liquid temperature is the temperature of insulating liquid as measured at the height of the bottom of the windings. For practical reasons, it is identified with the temperature of the liquid returning from the radiator to the tank.

(4) Average liquid temperature (θ_{om})

The average liquid temperature, in principle, is intended to be the average temperature of the cooling liquid in the windings. The average liquid temperature is the average temperature of the top and bottom liquid temperatures.

The average liquid temperature was;

$$\theta_o - \frac{\theta_u - \theta_b}{2} = 73.7 - \frac{66.2 - 42.3}{2} = 61.7 \text{ ℃}$$

Therefore, the average liquid temperature rise ($\Delta\theta_{om}$) was 37.0℃ which is the temperature difference between the average liquid temperature and the ambient temperature.

3.1.2 Average winding temperature rise test

The winding temperature at the end of the temperature rise test is normally determined by the measurement of the winding resistance. The measurement of winding resistance is started after shutdown of the test power and connection to the windings of DC measuring current source according to the winding resistance detection method [10].

(1) Winding resistance after shutdown of the power supply (R_2)

The measured winding resistance after shutdown of the power supply was 0.92422Ω on the high voltage winding; and was 0.020085Ω on the low voltage winding.

The average winding temperature shall be determined using the value of resistance at the instant of shutdown. In this case, when making power shutdown, connecting the DC power supply and measuring the winding resistance, the winding temperature goes down, resulting in the lower measurement of the winding resistance compared to the instant of power shutdown.

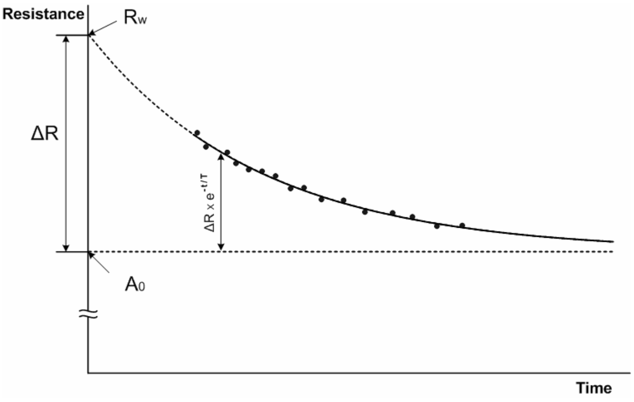

Fig. 4. Average winding temperature variation after shutdown

In Fig. 4, the decay of the winding resistance with time t after shutdown of the power supply can be expressed with the relation:

$$R(t) = A(t) + \Delta R \times e^{-t/T} \tag{2}$$

where T is an estimate for the time constant of the winding cooling down to the liquid with an exponential decay. Thus, the winding resistance at the instant of shutdown is as follows;

$$R_W = A_0 + \Delta R \;\; R_W = A_0 + \Delta R \tag{3}$$

(2) Fall of the resistance (ΔR)

The fall of the resistance from power shutdown to measuring winding resistance is calculated by the extrapolation method.

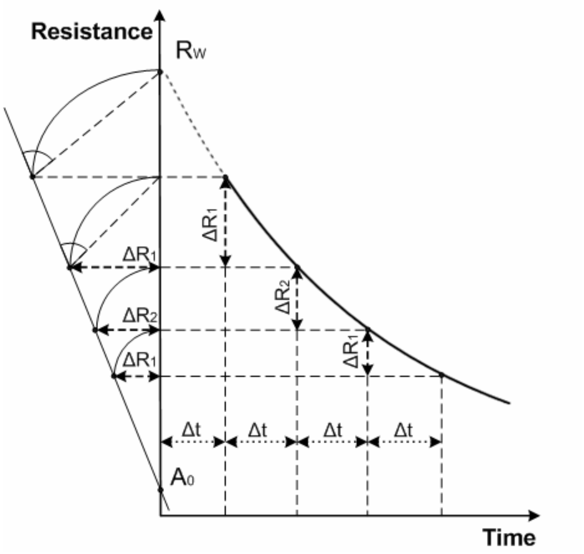

Fig. 5. Fall of the resistance at the instant of shutdown

The extrapolation method is to shutdown the power, measure the winding resistance at a certain interval and calculate the fall of the winding resistance which exponentially decreases, as seen in Fig. 5.

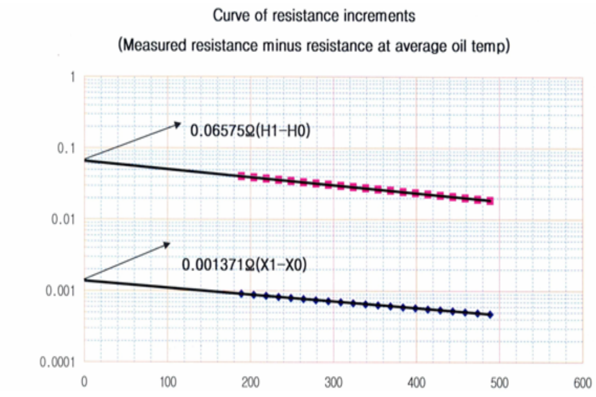

Fig. 6. Fall of the resistance by the extrapolation method

As shown in Fig. 6, the fall of the resistance (ΔR) measured by the extrapolation method was 0.06575Ω on the high voltage winding and 0.001371Ω on the low voltage winding. Thus, the winding resistance at the instant of shutdown (R_W) was 0.98997Ω on the high voltage winding and 0.021456Ω on the low voltage winding.

(3) Average winding temperature (θ_W)

The average winding temperature is the winding temperature determined at the end of temperature rise test from the measurement of winding resistance.

$$\theta_W = \frac{R_W}{R_1}(235+\theta_1)-235 \tag{4}$$

where, reference measurement R_1 and θ_1 are the winding resistance and the liquid temperature before the heat run test.

The cold temperature (θ_1) was;

$$\theta_{o_1} - \frac{\theta_{u_1}-\theta_{b_1}}{2} = 20 - \frac{20-19}{2} = 19.5\ ℃$$

The cold resistance (R_1) measured 0.79277Ω on the high voltage winding and 0.017228Ω on the low voltage winding. Accordingly, the average winding temperature (θ_W) was 82.8℃ on the high voltage winding and 82.0℃ on the low voltage winding. The average winding temperature rise ($\Delta\theta_W$) appeared to be 58.1℃ on the high voltage winding and 57.3℃ on the low voltage winding. This satisfies the average winding temperature rise limit of 65℃ as in the transformer specification in table 1.

(4) Average winding to liquid temperature gradient (g)

The average winding to liquid temperature gradient is the difference between the average winding temperature and the average liquid temperature which appeared to be 21.1℃ on the high voltage winding and 20.3℃ on the low voltage winding.

(5) Corrected average winding to liquid temperature gradient (g_c)

The top liquid temperature rise should be tested by flowing 2.576A, which is equivalent to the total loss (I_t); and the average winding temperature rise should be tested by using a current of 2.410A, which is equivalent to the rated current (I_r). In this paper, however, the above two steps of the test were combined in one single application of power under the injection current (I_l) of 2.580A. Thus, the temperature rise values for top liquid and average winding should then be corrected the correction rules [12].

$$g_c = g\left(\frac{I_r}{I_l}\right)^{1.6}$$

The corrected average winding to liquid temperature gradient (g_c) appeared to be 18.9℃ on the high voltage winding and 18.2℃ on the low voltage winding.

(6) Hot spot factor (H)

Hot spot factor is a dimensionless factor to estimate the local increase of the winding gradient due to the increase of additional loss and variation in the liquid flow stream. According to IEC 60076-2, the temperature distribution of liquid immersed transformer is as seen in Fig. 7.

The temperature rise of the liquid inside the windings of the transformer is assumed to increase linearly with the height of the windings. The heat, transferred from the winding to the liquid along the winding requires a temperature drop between winding and surrounding liquid which is assumed to be constant at all levels of height.

In Fig. 7, the winding temperature rise and the liquid temperature rise will therefore appear as two parallel lines with a certain gap (g). The maximum temperature on the winding is called the hot spot temperature wherein the value indicates the thermal limit of the transformer. The hot spot temperature is higher by the hot-spot factor (H) compare to the difference of temperature between the conductor and liquid. This hot spot factor is suggested to be 1.1 on the distribution transformer and 1.3 on the middle and large transformer according to JEC and 1.3 on the power transformer according to IEC. Thus, this paper applied 1.3 as the hot spot factor (H). The difference between the hot spot temperature and the top liquid temperature ($H \times g_c$) appeared to be 24.6℃ on the high voltage winding and 23.7℃ on the low voltage winding.

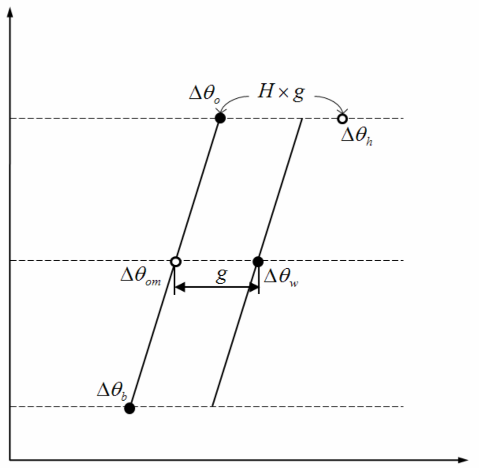

Fig. 7. Temperature rise distribution model

(7) Hot spot temperature (θ_h)

Hot spot temperature is the hottest temperature of winding conductors in contact with solid insulation or insulating liquid.

$$\theta_h = \theta_o + (H \times g_c)$$

The hot spot temperature appeared to be 98.3℃ on the high voltage winding and 97.3℃ on the low voltage winding.

(8) Hot spot temperature rise ($\Delta\theta_h$)

The hot spot temperature rise is the difference between the hot spot temperature and the ambient temperature. The hot spot temperature rise appeared to be 73.6℃ on the high voltage winding and 72.6℃ on the low voltage winding.

(9) Hot spot temperature at 20℃ ($\Delta\theta_{h(20)}$)

The hot spot temperature at ambient temperature 20℃ appeared to be 93.6℃ on the high voltage winding and 92.6℃ on the low voltage winding.

3.2 Hot spot temperature measured by optical fiber sensor

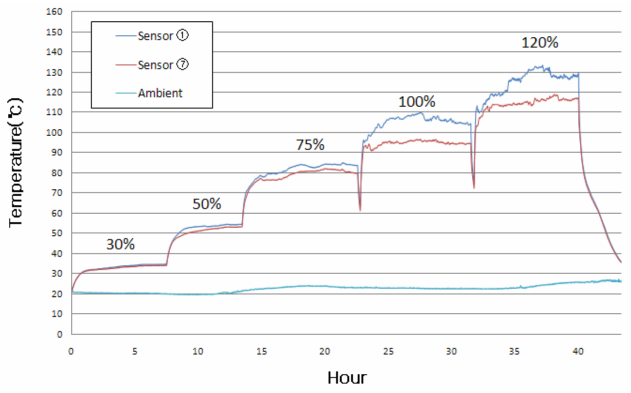

Fig. 8. Hot spot temperature on the low voltage winding

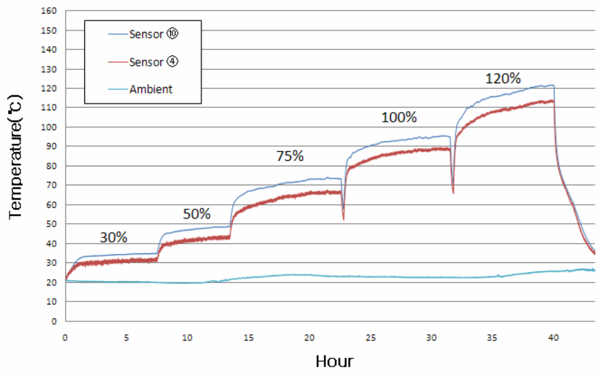

Fig. 9. Hot spot temperature on the high voltage winding

Fig. 8 shows the hot spot temperature on the low voltage winding and ambient temperature as measured by the optical fiber sensors with 30%, 50%, 75%, 100%, and 120% of the rated power. During the test, the ambient temperature was 20~26℃, and the data below was set to 20℃ in this paper. With the rated power, the hot spot temperature on the low voltage winding appeared to be 105.9℃ at the sensor ①, in the direction of liquid flow; 98.0℃ at the sensor ⑦, in the direction perpendicular to the liquid flow.

Fig. 9 shows the hot spot temperature on the high voltage winding and ambient temperature as measured by the optical fiber sensors with 30%, 50%, 75%, 100%, and 120% of the rated power. With the rated power, the hot spot temperature on the high voltage winding appeared to be 92.4℃ at the sensor ⑩ in the direction perpendicular of the liquid flow; and 86.0℃ at the sensor ④ in the direction of liquid flow.

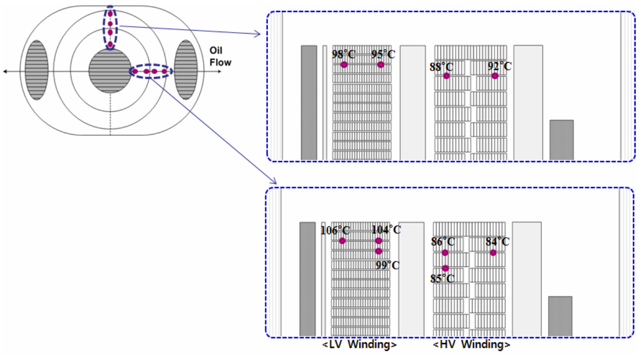

Fig. 10. Temperature at each point of the transformer

Fig. 10 shows the temperature at each point of the transformer with the rated power. As in Fig. 10, the hot spot temperature appeared between turn 2 and turn 3 on the upper side of the low voltage winding, recording 105.9℃. The hot spot temperature also appeared between turn 2 and turn 3 on the upper side of the high voltage winding as in the low voltage winding, and was 92.4℃. The hot spot temperature of the low voltage winding as measured by the optical fiber sensor was 13.3℃ higher than 92.6℃, which is the hot spot temperature calculated by the heat run test.

The power transformer can change in loss of the winding, heat transfer, fluid flow, etc. depending on its design. The hot spot factor (H) should be determined on an individual basis which ranges from 1.0 to 2.1, depending on the transformer size according to IEC 60076-2; however, the power transformer in general is recommended to be 1.3. In this paper, when applying the hot spot temperature measured by an optical fiber sensor to the IEC, the hot spot factor (H) appeared to be 2.0.

4. Conclusion

In this paper, the hot spot temperature of 154kV transformer was measured by the optical fiber sensors and compares the value with the hot spot temperature calculated by the conventional heat run test in the factory test.

The top liquid temperature rise on the rated power measured by the thermocouple in the heat run test appeared to be 49.0℃. This satisfies the top liquid temperature rise limit of 60℃ as in the transformer specification. The average winding temperature rise appeared to be 58.1℃ on the high voltage winding and 57.3℃ on the low voltage winding. This satisfies the average winding temperature rise limit of 65℃ as in the transformer specification. The hot spot temperature at the ambient temperature 20℃ shown in the heat run test was 93.6℃ on the high voltage winding and 92.6℃ in the low voltage winding.

However, the hot spot temperature as measured by the optical fiber sensor appeared between turn 2 and turn 3 on the upper side of the low voltage winding, recording 105.9℃. The hot spot temperature of the low voltage winding as measured by the optical fiber sensor was 13.3℃ higher than the hot spot temperature calculated by the heat run test. Therefore, the hot spot factor (H) in IEC 60076-2 appeared to be 2.0. In order to estimate the transformer life accurately, the hot spot temperature or hot spot factor detected by the paper winding should be applied to the IEEE and IEC standards.

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