New Method of Thyratron Ranging and Diagnosis

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***Abstract*—A thyratron is a very common switching device in many high-power pulse systems. However, it is difficult to diagnose switching characteristics of the thyratron during its operation. A new diagnostic factor of the thyratron has been developed from a convection heat transfer theory. The new diagnostic factor is obtained from a dependence of a thyratron heater current on a thyratron internal gas pressure. We have verified theoretical proprieties of the diagnostic factor and confirmed experimentally that the assumption used in the theory is applicable to typical thyratrons. Using the diagnostic factor, we have designed and constructed an autoranging and autodiagnostic device for the thyratron.**

***Index Terms*—Discharge, gas, high power, switch, thyratron.**

I. Introduction

A THYRATRON is a very common switching device in many high-power pulsed systems. However, it is difficult to diagnose switching characteristics of the thyratron during its operation. A thyratron requires continuous ranging of its internal gas pressure to have an optimum operation condition. The ranging is usually performed manually by a system operator, and thus, the thyratron operation condition strongly depends on the experience of the operator. Furthermore, there is no diagnostic method to detect the gas exhaustion of the thyratron. The diagnostic method is critical in predicting an accurate replacement timing of the thyratron. In order to obtain a stable high-voltage operation with long life, the thyratron should be operated under optimum internal gas pressure. For thyratrons used in the Stanford Linear Accelerator Center (SLAC), the ranging is a time-consuming maintenance process because 245 thyratrons are involved. Effective ranging methods have been investigated, and a method developed at SLAC is the thyratron RF noise detector [1]. However, this method cannot perform the autoranging and thyratron diagnosis. The BA cathode tube manufactured in the English Electric Valve (EEV) contains a barretter controlled reservoir system, which enables an optimization of the gas pressure in the thyratron. However, the operator neither adjusts the gas pressure according to an operational condition nor diagnoses the internal gas state of the thyratron. The C-band main linac of e^+e^- linear collider at KEK will require over 8000 accelerating structures, and 4000 klystrons and modulators [3]. Each modulator will use one or two thyratrons. In such large-scale facilities, the manual maintenance of the thyratron is practically impossible. To overcome such a maintenance problem, a new diagnostic factor of the thyratron has been developed from a convection heat transfer theory. The new diagnostic factor is based on a dependence of a thyratron heater current on a thyratron internal gas pressure. We discuss in this paper a new principle of the thyratron diagnosis, experimental survey of operational characteristics of the thyratron, and a device for autoranging and autodiagnosis of the thyratron.

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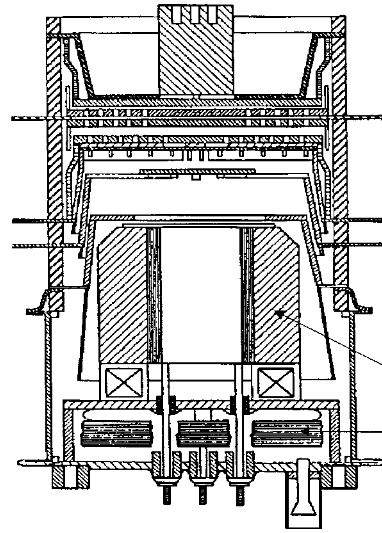

Fig. 1. Typical structure of a thyratron.

II. Principle of Thyratron Ranging and Diagnosis

Fig. 1 shows a typical structure of a thyratron. There are two independent power supplies for a thyratron. One is a heater power supply, and the other is a reservoir power supply that furnishes power for a reservoir to adjust internal gas pressure. Most of electric power supplied to the cathode area is converted into heat.

Therefore, radiation, conduction, and convection heat transfers occur around the thyratron cathode area. Among those heat transfers, the radiation and conduction heat transfer rates are strongly governed by a structure of the device and a temperature of the heater wire. However, an internal gas pressure determines the convection heat transfer rate. To verify these various heat transfer phenomena, a thyratron cathode structure and internal processes of the thyratron should be carefully reviewed. In Fig. 2(a), a cathode structure of the ITT F-303 thyratron is shown. In Fig. 2(b), a portion of the cathode structure is converted into a simple cylindrical model. The model has a heater wire of diameter d stretched along the axis of a tube of diameter D. As shown in Fig. 2, the heater wire diameter is about 1 mm and the tube diameter is simulated as 10 mm.

In Fig. 2(b), if internal gas molecules have average temperatures of T_i on arrival of the wire and T_r on departure from the

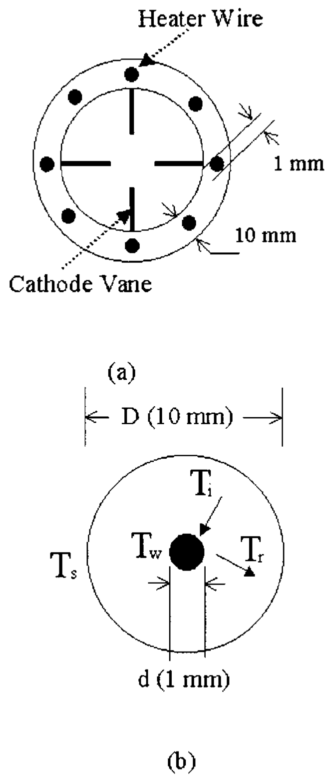

Fig. 2. (a) Cathode structure of ITT F-303 thyratron. (b) Simplified thyratron cathode structure.

wire, the rate of convection energy transfer E from the wire to gas, and subsequently to the outer cylinder, is given by

$$E = k\left(T_r - T_i\right)P \tag{1}$$

where k is a basic constant and P is a gas pressure in Pa [3]. E is in W/m^2. The temperature T_r depends on a wire surface temperature T_w, the tube cylinder surface condition, the temperature T_i, and a type of the gas molecule. T_r, T_w, and T_i are in K. Introducing an accommodation coefficient α and the temperature T_w, (1) can be rewritten as

$$E = \alpha k P\left(T_w - T_i\right). \tag{2}$$

On evaluating constants, (2) becomes

$$E = \frac{\gamma + 1}{4(\gamma - 1)}\sqrt{\frac{2R}{\pi M T_s}}\,\alpha\left(T_w - T_i\right)P \tag{3}$$

where T_s, M, and γ are a temperature of the cylinder surface in K, a mass of the gas molecule in kilograms, and a ratio of specific heat, respectively. R is the universal gas constant.

The radiation heat transfer per a unit area of the heater wire in the structure of Fig. 2(b) can be expressed as

$$Q = \sigma\beta\left(T_w^4 - T_s^4\right) \tag{4}$$

where σ, β are the Stefan's constant and emissivity, respectively. Q is in watts/meter squared.

If ends of a solid bar with an uniform cross-section a in meters squared and a length l in meters are at temperatures T_2 and T_1 in K, conduction heat flow is determined by the following equation:

$$C = \frac{a}{l}\int_{T_1}^{T_2} \Lambda(T)\,dT \tag{5}$$

where $\Lambda(T)$ is a temperatures-dependent thermal conductivity of the solid. C is in Watts.

Then, the electrical energy input to the heater wire, Γ, can be represented by the following equations:

$$\Gamma = \frac{V_0^2}{R_w} = V_0 I_w = QS + ES + C \tag{6}$$

where

V_0 and I_w	voltage and current of the heater power supply;
R_w	heater wire resistance in Ω;
S	surface area of the heater wire in meters squared.

The most important information in ranging and diagnosing thyratrons is the internal gas pressure. In many typical vacuum gages, gas pressure is exactly measured by using a Wheatstone bridge. The bridge measures internal heat losses and converts the information into pressure. This method can be adopted into the thyratron ranging and diagnosis, but it requires a constant current and variable voltage power supply. Therefore, it will require a rather complex power supply to accurately measure the thyratron internal pressure and subsequently range the thyratron. A new method is suggested to measure the internal gas pressure by using a conventional thyratron heater and reservoir power supplies. In the following, the new method is introduced and verified.

In a normal thyratron operation condition, the heater voltage is maintained constant, whereas the heater current changes with the thyratron internal condition. At very low pressure where convection is negligible, (6) can be rewritten as

$$V_o I_1 = Q_1 S + C_1 \tag{7}$$

where

V_o	heater voltage in Volts;
I_1	heater current in amperes at that pressure;
Q_1 and C_1	respectively, radiation and conduction heat transfer rates at the low-pressure condition.

At a certain pressure P, where convection can no longer be ignored, (6) becomes

$$V_o I_2 = Q_2 S + ES + C_2 \tag{8}$$

where I_2 is the heater current in amperes, and Q_2 and C_2 are, respectively, radiation and conduction heat transfer rates at the pressure. To find a pressure dependence of the heater wire temperature, (6) is differentiated with respect to the pressure. The conduction term is not a function of pressure, and the dependence of T_i and T_s on the pressure is found to be small enough to ignore [3]. And the final result is

$$0 = 4K_Q T_w^3 \frac{dT_w}{dP} + K_E \frac{dT_w}{dP} P + K_E\left(T_w - T_i\right) \tag{9}$$

where K_Q and K_E are defined as

$$K_Q = \sigma\beta S,$$
$$K_E = \alpha\frac{(\gamma+1)}{4(\gamma-1)}\sqrt{\frac{2R}{\pi M T_s}}S.$$

Equation (9) is rearranged as

$$-\frac{dT_w}{dP} = \frac{K_E(T_w - T_i)}{4K_Q T_w^3 + K_E P}. \quad (10)$$

The gas mean free path in a high-temperature environment is expressed as

$$\lambda = \frac{3.1 \cdot 10^{-24} T}{\zeta^2 P} \quad (11)$$

where

λ meters;
T gas temperature in Kelvin;
ζ molecule diameter in meters;
P gas pressure in Pascals [4].

A typical thyratron is operated at about 26 Pa of hydrogen gas pressure and 1300 K of the heater wire temperature. From (11), the gas mean free path in a typical thyratron is calculated to be about 2 mm. Because the mean free path is 2 mm in the thyratron, gas molecules do not have many collisions to reach the tube wall. Therefore, we may assume that T_i is approximately the same as T_s. Then, (10) can be approximated as

$$-\frac{dT_w}{dP} \approx \frac{K_E(T_w - T_s)}{4K_Q T_w^3 + K_E P}. \quad (12)$$

The temperature of heater wire is normally operated in the range of 1300 K. If two terms of the denominator in the right side of (12) are compared, the first term with T_w^3 is at least 30 times higher than the second term with P. Therefore, it is safe to ignore the second term with P. Then (12) can be rewritten as

$$-\frac{dT_w}{dP} \approx \frac{K_E(T_w - T_s)}{4K_Q T_w^3} \approx \frac{3.1 \cdot 10^6 (T_w - T_s)}{T_w^3}. \quad (13)$$

Equation (13) has an unit of Kelvin/Pascal. In a typical thyratron, T_s and T_w are about 1000 K and 1300 K. Then, from (13), dT_w/dP is calculated as 0.42. Therefore, if the internal gas pressure of the thyratron is changed from pure vacuum to normal pressure of 26 Pa, the heater wire temperature changes only 10 K. This temperature variation affects only about 5% of the radiation heat transfer rate. Therefore, the variation of radiant heat exchange rate after filling the thyratron with hydrogen gas is small and thus can be ignored. In addition, because the heater wire temperature variation is small, the conduction heat transfer rate variation due to the internal gas pressure change can also be ignored. Then, from (3), (7), and (8), we can get

$$V_o I_e \approx K_E(T_w - T_s)P \quad (14)$$

where $I_e = (I_2 - I_1)$.

Equation (14) tells us that the pressure has a linear relationship with the heater current. Because I_e is a direct function of a total heater current I_w, the following relationship comes into existence:

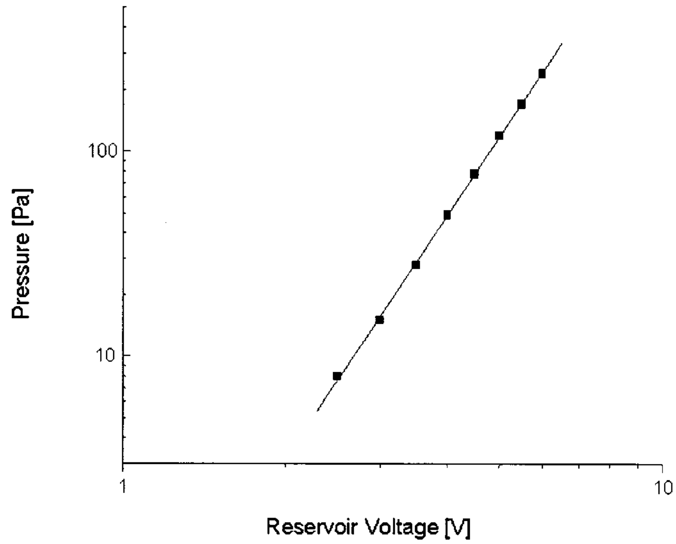

Fig. 3. Variation of the thyratron (ITT F-303) internal gas pressure as the reservoir voltage changes from 2 V to 6 V.

$$I_w \approx BP \quad (15)$$

where B is a proportional constant. Equation (15) implies, if the voltage of the heater power supply is constant and the gas pressure is increased, that more current will flow to maintain a constant temperature of the heater wire. From this simple theory, we introduce a new method of thyratron ranging and diagnosis.

III. Experimental Survey of Thyratron Characteristics

The experiment was carried out to verify the theory given in (15). A thyratron used in the experimental survey is ITT F-303. The thyratron is used in linac modulators of the Pohang light source (PLS). The PLS linac modulator has a 200-MW peak output power and a 400-kV peak output voltage with a 25-kV peak primary DC voltage. During the normal operation of the thyratron, it is not possible to read its internal pressure. We need to get the pressure information from reservoir and heater voltage values. To find the relationship of voltage and pressure, we intentionally installed a vacuum pump and a pressure gauge after breaking vacuum of a thyratron.

Fig. 3 shows a trend of thyratron internal gas pressure as the reservoir voltage increases from 2 V to 6 V. It shows a linear relationship of the reservoir voltage in a log–log plot. Fig. 4 shows a variation of the heater current as the gas pressure increases from 26 Pa to 240 Pa with a fixed heater voltage of 6.3 V. From Fig. 4, we can recognize that the heater current increases linearly as the internal gas pressure increases. This tendency agrees very well with the relation given in (15).

Fig. 5 shows the variation of heater current by changing the reservoir voltage from 0 V to 6 V, whereas the heater voltage is fixed at 6.3 V. For the measurement given in Fig. 5, the thyratron was positioned in the modulator without high voltage applied. The operating point indicated in the Fig. 5 is an initial setting of ITT F-303 thyratron that is recommended by the manufacturer. The operating point has a reservoir voltage of 3.3 V and a heater

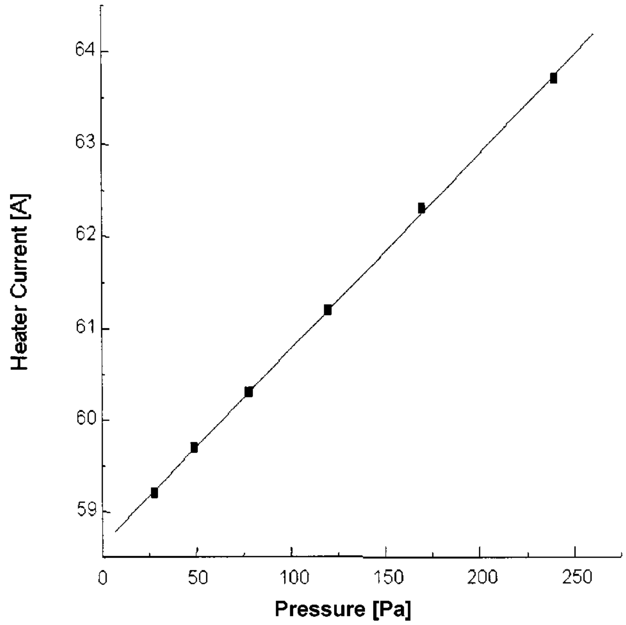

Fig. 4. Variation of the heater current as the internal gas pressure increases from 26 Pa to 240 Pa with a fixed heater voltage of 6.3 V.

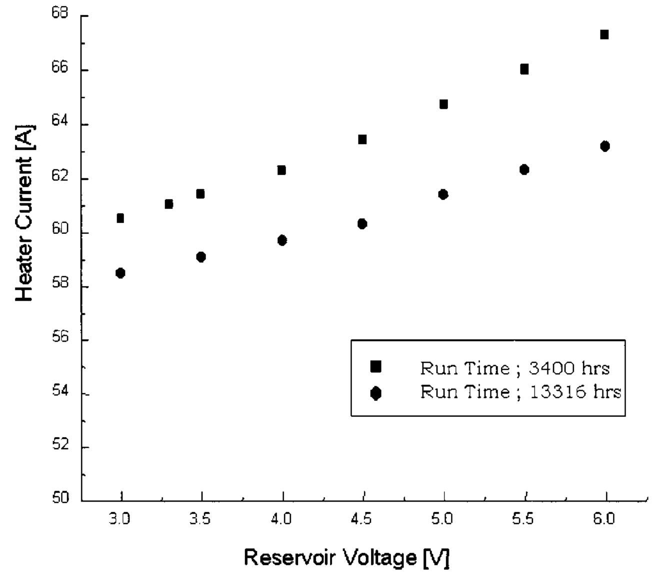

Fig. 6. Comparison of two heater current data as a function of the reservoir voltage for a same thyratron (ITT F-303) measured at a different accumulated high-voltage run-time (3400 h: May 1998, 13 316 h: November 1999). The heater voltage was fixed at 6.3 V.

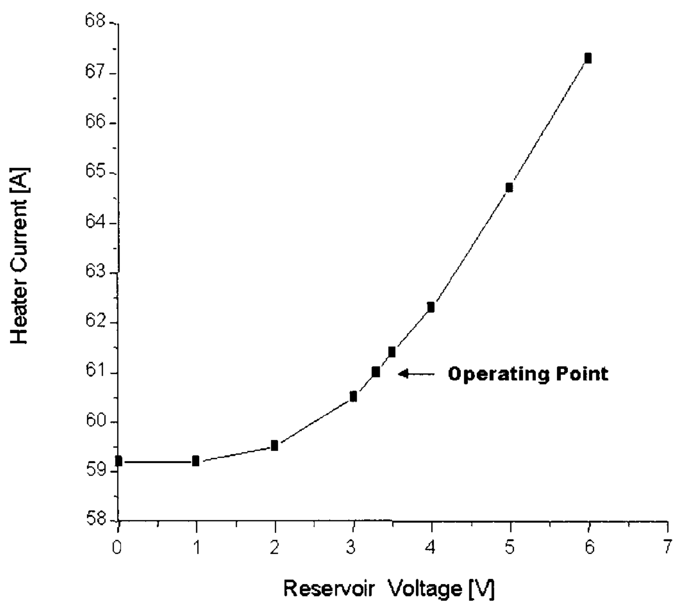

Fig. 5. Plot of a variation of the heater current by changing the reservoir voltage from 0 V to 6 V with a fixed heater voltage of 6.3 V.

current of 61 A. Fig. 6 compares two heater current data as a function of the reservoir voltage. A same thyratron was used to collect the data in Fig. 6, but at a different accumulated high-voltage run-time. The two data were measured with a run-time of 3400 h (on May 1998) and a 13 316 h (on November 1999).

As shown in Fig. 6, the heater current reduces as the high-voltage run-time increases at a given reservoir voltage. In a normal operation mode of the thyratron, if the heater current is lower than the initial setting of 61 A, the reservoir voltage should be increased above its initial setting of 3.3 V so that the internal gas pressure of the thyratron can be maintained. This action is what we called “ranging.” However, if the internal gas is exhausted, the heater current cannot be controlled anymore by increasing the reservoir voltage. At this point, the thyratron is reached at the end of life.

With a fixed heater voltage of 6.3 V and a fixed reservoir voltage of 3.3 V, the variation of the heater current is measured as a function of the high voltage of the modulator. The result also shows that the heater current decreases from 61 A to 60.5 A as the high voltage increases from 0 to 19 kV. It indicates that the internal gas temperature is also affected with high-power switching losses.

IV. Thyratron Autoranging and Autodiagnosis

For a given thyratron, we initially set an optimum heater current according to an operational condition. Internal gas of the thyratron will be gradually exhausted as the thyratron operation time is accumulated. Because the heater current is directly proportional to the gas pressure from (15), the heater current will also decrease for a given heater voltage as the thyratron run-time gets higher. Then, we should increase the reservoir voltage to increase the gas pressure so that the heater current approaches to an initial value. This is a typical manual ranging method to maintain the initial internal gas pressure constant. The same principle can be applied to diagnose the thyratron health. To diagnose, the heater current of a virgin thyratron should be measured by varying the reservoir voltage from 0 V to the maximum voltage with a constant time step. The result should be plotted and kept as a reference for future comparison. After operation, the thyratron heater current should be periodically measured and compared with the reference plot. From the comparison, the following can be diagnosed.

1) The amount of the internal gas can be relatively measured by monitoring the heater current variation.
2) Early perception of the structural deformation, the abnormal cooling, the overheating of the anode, and so on, by checking the irregular variation of the heater current.

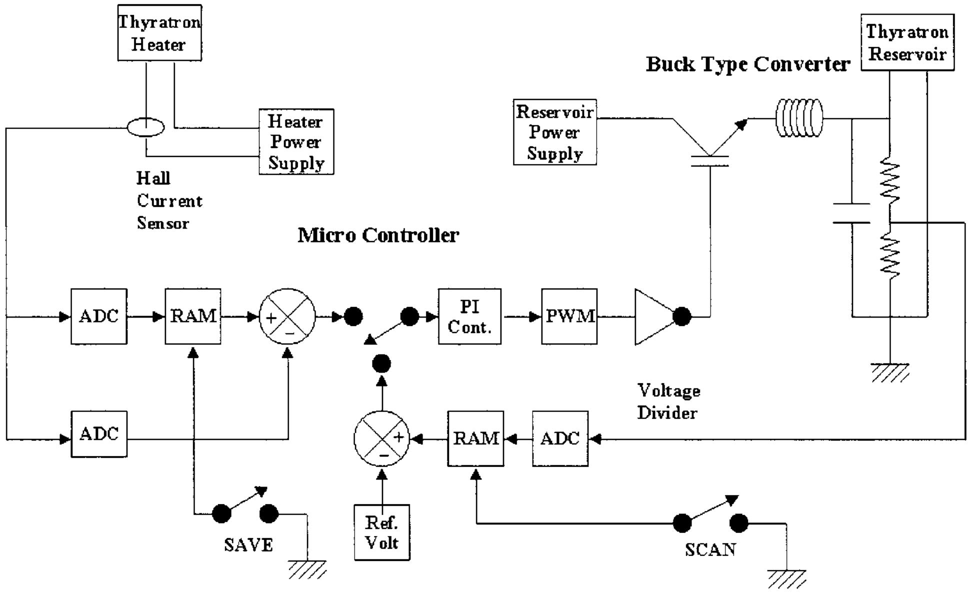

Fig. 7. Circuit diagram of a device for the autoranging and autodiagnosis of thyratron.

3) The exhaustion of the internal gas and the function of the reservoir can be diagnosed so that the exact replacement timing of the thyratron can be decided accurately.

Fig. 7 shows a circuit diagram of a device for the autoranging and autodiagnosis of the thyratron. Necessary data of a virgin thyratron are scanned and memorized in a RAM. If the heater current becomes lower than a set point, the reservoir voltage rises until the heater current approaches a set point. The pressure setting is automatically regulated according to the operational conditions of the modulator. This is the autoranging method that the initial setting of the internal gas pressure is continuously maintained. If abnormal trends are detected by the device, it will give an external warning signal so that the thyratron can be diagnosed.

V. Conclusion

We verify the theoretical propriety of the diagnostic factor for the thyratron, and we investigate how the proposed factor is applied to the thyratron. By the convection heat transfer, the heater current is found to be linearly proportional to the internal gas pressure. Application of this simple principle made it possible for the autoranging and diagnosis of the thyratron. We also carried out an experiment to determine whether the principle used in this theory is applicable. The experimental result shows that the heater current increases linearly as the internal gas pressure increases. The result is in good agreement with the theoretical prediction. Using this diagnostic factor, we have designed and constructed an autoranging and autodiagnosis device for the thyratron.

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