Paper

Computing of Thermal Stability and Permissible Overload of Power Capacitors

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This paper describes the temperature rise and the thermal stability of tank type power capacitors and a analyzing method of the stability and permissible overload factor using a computer. When capacitor is operated at high ambient temperature and under excessive high voltage, the temperature of the dielectric rises higher and in some cases the capacitor looses the thermal balance and finally breakdowns thermally.

We measured the heat radiation coefficient and temperature rise of the capacitor, and clarified that the radiated heat calculated from the heat radiation coefficient and the area of the tank coincided with the generated heat calculated from the output of the capacitor and the loss factor of the dielectric. Furthermore we developed analyzing method of thermal stability and permissible overload factor of capacitors using a computer. By this analysis it becomes possible to know the permissible overload factor and the temperature of the capacitor dielectric without performing the temperature rise test which requires long time and much cost.

Keywords: power capacitors, heat radiation coefficient, temperature rise, thermal stability, permissible overload, computer analysis

1. Introduction

Power capacitors are widely used for regulating the voltage and improving the load power factor of the electric utility systems.

As the output of large tank type capacitor is limited mainly by the thermal stability, it is important to use low loss dielectric especially for high output capacitor.

Dielectric of capacitors was mineral oil (M oil) impregnated paper (P) at the first stage of the development, but loss factor of the paper is rather high, so it was substituted to mixed paper/polypropylene (pp) film (P/F) and at the same time M oil was substituted by synthetic oil such as diisopropylnaphthalene (S oil). A sheet of paper is used between pp films to improve drying of the pp film and impregnation of the oil. S oil has good affinity with pp film and can improve dielectric strength of the capacitor compared with M oil [1][2]. The paper and pp film are strictly quality controlled and completely dried in vacuum at high temperature and impregnated with purified oil, and then completely sealed in a tank. Therefore, the dielectric scarcely deteriorates throughout the long life and the capacitors have very high reliability. However, under the influences of thermal and electrical stresses the dielectric undergoes an irreversible change and this exerts an influence upon the life of the capacitors. Especially when excessive high voltage is imposed on the capacitor, the temperature of the dielectric rises extraordinarily and promotes the aging of the dielectric and in some cases heat generated within the dielectric exceeds the heat radiated from the tank wall, and finally the capacitor breakdowns thermally [3][4].

Temperature rise and thermal stability of power capacitors have been reported by many papers, but these papers dealt with the problem only qualitatively, or reported only some tested results. The paper presented by M. Pierson dealt with this problem quantitatively, introducing indexes which express the quality of the dielectric [5].

This paper clarifies the heat dissipation from the tank wall and temperature rise of tank type power capacitors under normal and excessive load operation, and gives a method to analyze the temperature rise and permissible overload factor of power capacitors using a computer [6].

2. Heat Generation and Radiation of the Power Capacitors

2.1 Heat Generation Loss of the capacitor originates mainly from dielectric loss of the dielectric, and so the generated heat of the capacitor can be calculated by multiplying the output of the capacitor by $\tan\delta$ of the dielectric.

As the output of the capacitor is computed from the rated capacity (Q) and the overload factor (k), the generated heat (W) is given by following formula.

$$W = KQ\tan\delta \quad \cdots\cdots (1)$$

Tan δ–temperature characteristics of the dielectrics

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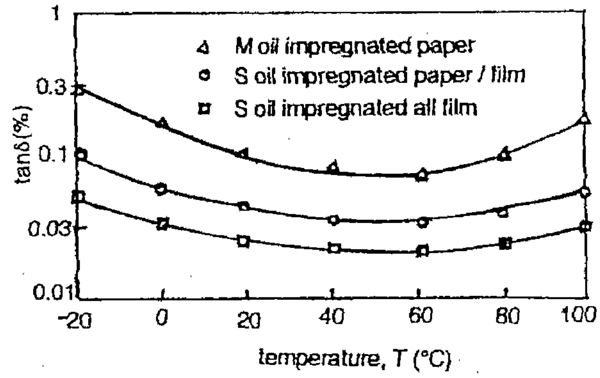


Fig. 1. Typical $\tan\delta$–temperature characteristics of capacitors

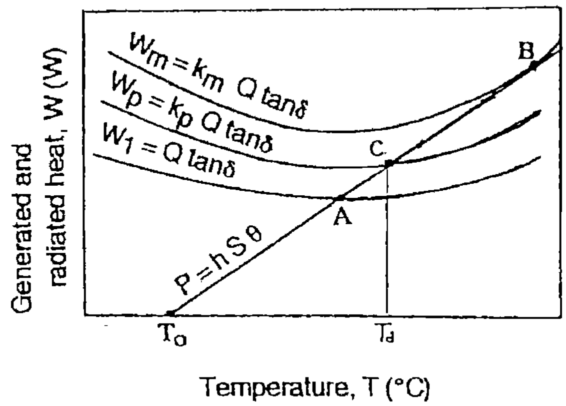


Fig. 2. Heat generated and radiated of power

are as shown in Fig. 1, and can be expressed by a quadratic equation, and are given from the $\tan\delta$ values at three points of the dielectric temperature.

Therefore, the temperature characteristics of the generated heat of the capacitor operated at the rated output ($k = 1$) and overload ($k = k_p$) can be given as curve W_1 and W_p of Fig. 2 , respectively.

2.2 Heat Radiation Heat generated within the dielectric is radiated outside through the tank wall. The radiated heat is proportional with the temperature rise, temperature difference between the wall and the atmospheric air, and the temperature of the wall rises up until the radiated heat becomes equal with the generated heat, and the temperature of the dielectric rises along with that of the wall.

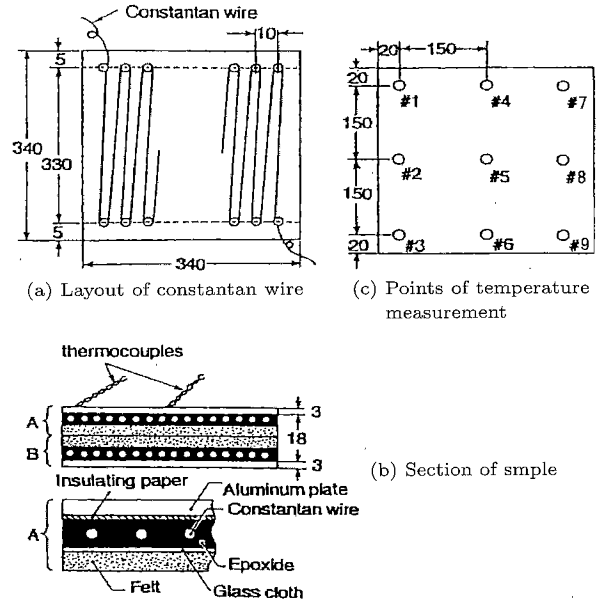
Radiated heat from the wall (P) is determined by area of the wall (S), heat radiation coefficient (h) and temperature rise (θ) of the wall, and given by following formula,

$$P = hS\theta \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

3. Heat Radiation Coefficient

3.1 Measuring Method of Heat Radiation Coefficient Heat radiation coefficient of a tank wall differs by the situation and the color of the wall. The heat radiation coefficient was measured using model of the tank wall as shown in Fig. 3 [3].

An aluminum plate of 3 mm thickness is used as an sample of the tank wall and a sheet of insulating paper of 60 μm thickness is pasted on the plate, and a



(a) Layout of constantan wire

(c) Points of temperature measurement

(b) Section of smple

Fig. 3. Sample used to measure the heat radiation

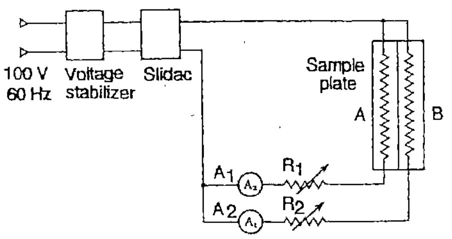


Fig. 4. Electrical circuit used for measurement of the heat radiation coefficient of the tank wall

constantan wire of 55 μm diameter is placed on the plate at interval of 10 mm as shown in Fig. 3(a). The wire is fixed on the plate using epoxy resin on which thick felt is pasted as heat insulator. Two plates constructed as mentioned above are combined as shown in Fig.3 (b). Copper-constantan thermocouples pasted on 6 spots of the plate to measure the plate temperature as shown in Fig. 3(c). To minimize the measurement error the diameter of the wire is selected to be as small as possible, and copper plates ($5 \times 10 \times 0.3\,\mathrm{mm}^3$) is soldered on the spots.

When electric current flow in the constantan wire of sample A supplied from 60 Hz 100 V power source is adjusted by a voltage stabilizer and a slidac as shown in Fig. 4, the temperature of the sample A reaches finally a constant temperature, then the temperature of an aluminum plate of the sample B is adjusted to be the same with that of sample A to shield it thermally and electric power supplied through a resistance R_1 is conducted only to the aluminum plate of sample A.

The measurements were performed in a concrete room where the ambient conditions were stable, and the sample was placed 60 cm or more apart from a wall of the room.

The sample was laid vertically and horizontally and also laid on the concrete floor closely contacted with the floor with pressure of $130\,\mathrm{kg/m^2}$. The plates were painted by black lacquer or blue paint (Mancel Color

7.5 GB 6/1.5) and measurements with non colored aluminum plate were also performed.

3.2 Results of Measurement The measured relations between the mean temperature rise of the plate and the electric power supplied to the unit area of the plate are almost linear as shown in Fig. 5.

The mean temperature rise of the plate (θ) is calculated using following formula,

$$\theta = \{2(\theta_1 + \theta_2 + \theta_3) + \theta_4 + \theta_5 + \theta_6\}/9 \cdots\cdots (3)$$

here, θ_n ($n = 1, 2 \ldots, 6$) are the temperature rise of spot # n of Fig. 3(c), and in formula (3) θ_7, θ_8 and θ_9 are represented by θ_1, θ_2 and θ_3, respectively, which have symmetrical positions with θ_7, θ_8 and θ_9 on the plate.

Deviations between the highest and the lowest temperature rise measured on the 6 spots is less than 7%.

Heat radiation coefficient calculated from the electric power supplied to unit area of the sample plate divided by the temperature rise are as shown in Table 1.

Table 1. Heat radiation coefficient of capacitor wall

Color of tank wall	Situation of tank wall	Heat radiation coefficient, h (W/℃m²)
Black	Side (vertical)	11.5
	Top (horizontal)	12.2
	Bottom (horizontal)	10.0
	Bottom (on floor)	12.5
Blue	Side (vertical)	11.2
	Top (horizontal)	11.7
	Bottom (horizontal)	9.8
Metallic	Side (vertical)	7.7
	Top (horizontal)	8.3
	Bottom (horizontal)	6.0

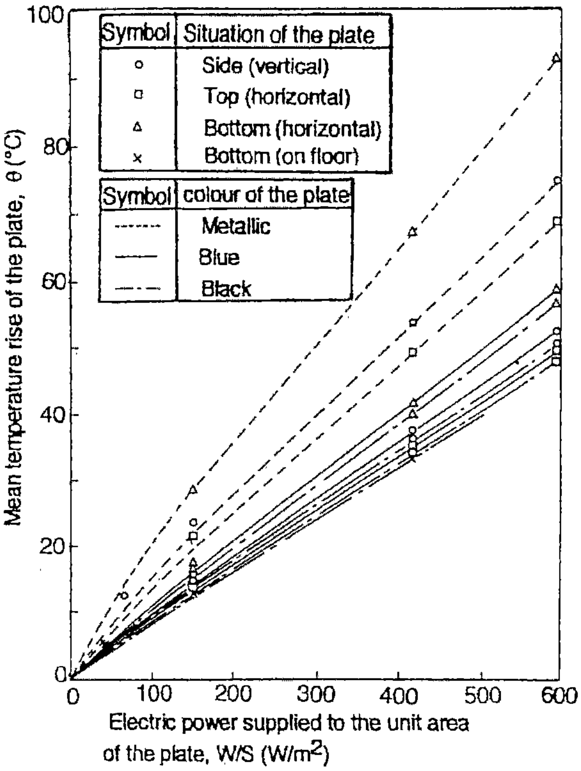


Fig. 5. Relation between electric power supplied to the plate and temperature rise of the plate

4. Temperature Rise Test of Power Capacitors

When tank type power capacitors of large capacity are designed, it is essential to confirm that the capacitors keep the thermal balance and both the temperature rise of the tank wall and the dielectric are under each permissible limits at the permissible overload operation. Therefore, the temperature rise test of capacitors should be done to confirm above mentioned matters when the dielectric or the design are changed. For example, the test results of 60 Hz 1,667 kvar M oil impregnated paper capacitor operated at rated load and 144% overload are shown in Fig. 6.

Overload of 144% is selected considering 110% over voltage, 130% over current and +15% capacitance deviation specified by JIS C4902 [7], and the test was done applying 120% over voltage of rated frequency.

Results of temperature rise tests of various power capacitors are shown in Table 2.

Ratio between mean temperature rise of dielectric and that of tank wall are about 1.8 for M oil impregnated paper capacitors, and that for S oil impregnated paper/pp film capacitors are about 1.5 as shown in Table 2. The test result of four typical capacitors were analyzed dividing the wall to top, side, rib and bottom, and the radiated heat from each portion of the walls and the all portions of the wall were calculated. Each area of the tank wall of capacitors is calculated from the size of the tank and the ribs attached to the side wall of the tank to strengthen it, and the influence of the bushings attached

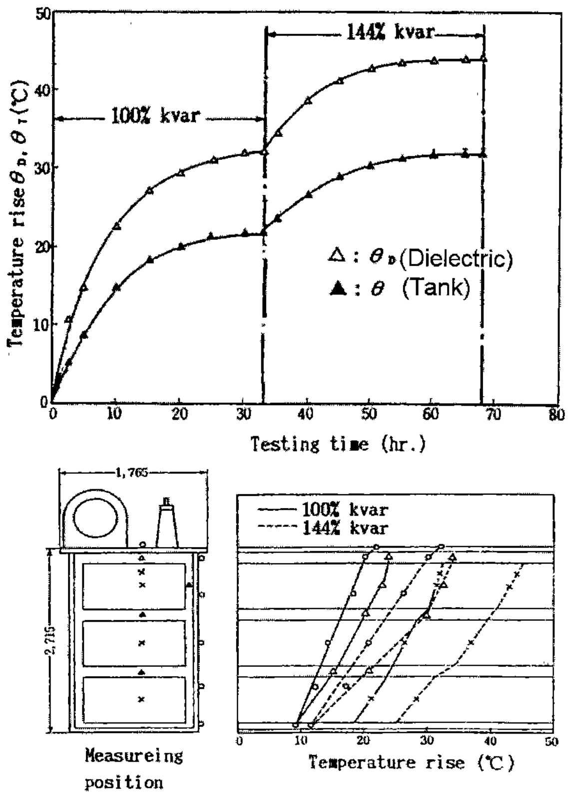


Fig. 6. Results of temperature rise test of 60 Hz 1667 kvar tank type capacitor.

Table 2. Results of the temperature rise tests

Dielectrics	Rating f [Hz]	Rating Q [kvar]	β [%]	Temp.rise(℃) Diel. θ_D	Temp.rise(℃) Tank θ	γ	tanδ [10^{-3}]	βQtanδ [W]
M·P	60	834	100	24.5	12.5	2.0	1.60	1330
	60	1667	100	26.5	14.5	1.8	1.54	2570
	60	1667	144	37.0	20.5	1.8	1.54	3700
	60	3334	100	33.0	19.5	1.7	1.35	4500
Mean						1.83		
S·P/F	60	1667	100	15.5	10.0	1.6	0.50	834
	60	1667	144	21.5	14.0	1.5	0.50	1200
	60	3334	100	16.5	11.0	1.5	0.50	1670
	60	3334	144	25.5	18.0	1.4	0.50	2400
	60	6667	100	19.0	13.5	1.4	0.43	2870
	60	6667	144	25.5	18.5	1.4	0.43	4130
Mean						1.47		

[Note] Dielectrics: M·P:Mineral oil impregnated paper.
S·P/F: Diisopropylnaphthalene impregnated paper/film.
$\gamma=\theta_D/\theta$, θ_D:Temp. rise of diel., θ:Temp.rise of tank.

Table 3. Radiated and generated heats calculated from the results of temperature

Diel. Rating	Tank Size	Tank Area[m²]	θ [℃]	h [W/℃·m²]	hθS [W]	βQtanδ [W]
M · P	L:1.60	U: 0.96	21.5	11.7	241	
60Hz	W:0.60	S:11.9	14.5	11.2	1933	
1667kvar	H:2.70	R: 2.0	14.5	11.2	305	
		B: 0.96	9.6	9.8	90	
		T:15.82			2569	2570
M · P	T:1.83	U: 1.61	26.0	11.7	490	
60Hz	W:0.88	S:13.8	19.5	11.2	3010	
3334kvar	H:2.55	R: 3.6	19.5	11.2	786	
		B: 1.61	12.5	9.8	197	
		T:20.62			4483	4500
S·P/F	T:1.55	U: 0.87	16.5	11.7	168	
60Hz	W:0.56	S:10.8	11.0	11.2	1330	
3334kvar	H:2.55	R: 1.8	11.0	11.2	222	
		B: 0.87	7.0	9.8	60	
		T:14.34			1780	1670
S·P/F	T:1.50	U: 1.58	19.0	11.7	351	
60Hz	W:1.05	S:13.0	14.0	11.2	2038	
6667kvar	H:2.55	R: 2.2	14.0	11.2	345	
		B: 1.61	8.5	9.8	134	
		T:18.39			2870	2870

[Note] Tank size: L:Length, W:Width, H:Hight,
Tank area: U:Upper, S:Side, R:Rib, B:Bottom, T:Total.
θ : Mean temperature rise of the tank wall.
h : Heat radiation coefficient.

to the top of the tank is neglected. The calculated heat radiated from all portion of the wall (h θ S) coincides well with generated heat (β Q tan δ) calculated from the output and the measured tan δ as shown in Table 3. Here, β is the overload factor of the capacitor.

5. Thermal Equilibrium of Power Capacitors

Heat generated in the dielectric when a capacitor is operated at rated capacity is given by Q tan δ and W_1 curves of Fig. 2. On the other hand, heat radiated from the wall is given by Eq. (2) and a line P of Fig. 2. If the radiated heat becomes the same with the radiated heat at point A of the figure, the capacitor operated at rated capacity reaches thermal equilibrium. Curve W_m of the figure shows the case when the line P contacts with the curve W_m (k_mQ tan δ). Therefore, if overload factor exceeds k_m generated heat overcomes radiated heat and temperature of the dielectric rises up boundlessly and the capacitor finally break-downs thermally. Thus, k_m gives upper limit of the permissible overload factor which is determined from the thermal equilibrium.

As mentioned above, generated heat in the dielectric is represented by a quadratic curve and radiated heat from the wall is given by a line with gradient of heat radiation coefficient, and they are given by following equations, when the capacitor is operated at permissible upper limit of ambient temperature T_0.

Heat generation:

$$W = a(\gamma\theta)^2 + b(\gamma\theta) + c \quad\cdots\cdots\cdots (4)$$

Heat radiation:

$$P = hS\theta \quad\cdots\cdots\cdots (5)$$

here, θ is temperature rise of the tank, and γ is ratio between temperature rise of the dielectric and the wall, γθ is temperature rise of the dielectric, and a, b and c are constant determined by the tan δ-temperature characteristic of the dielectric.

When the generated and radiated heat reach thermal equilibrium, following relation is given,

$$a(\gamma\theta)^2 + b(\gamma\theta) + c = hS\theta \quad\cdots\cdots\cdots (6)$$

Solution of this equation is given as follows,

$$\theta = \{-(b\gamma - hS) \pm \sqrt{D}\}/2a\gamma^2 \quad\cdots\cdots\cdots (7)$$

here, D is discrimination equation of the thermal equilibrium and given as follows.

$$D = (b\gamma - hS)^2 - 4a\gamma^2 c \quad\cdots\cdots\cdots (8)$$

(1) If D > 0, the thermal stability is kept, (1 < overload factor < k_m).
(2) If D = 0, the thermal stability is kept to the limits, (overload factor = k_m).
(3) If D < 0, thermal stability is not kept.

6. Overload Limit Restricted from Permissible Highest Temperature of Dielectric

Overload of power capacitors is also limited by permissible highest temperature of the dielectric. The temperature is usually set at 95°C for organic materials such as insulating paper, pp film and M oil. If the temperature is given by T_d, the overload factor of the capacitor is given by k_p as shown in Fig. 2.

7. Computing of Thermal Stability of Power Capacitors

As mentioned above the permissible overload factor which is restricted by the thermal stability (k_m) or the permissible highest temperature of dielectric (k_p) when capacitors are operated at the maximum ambient temperature T_0, can be obtained using a computer by giving the $\tan\delta$ of the capacitor at 3 points of temperature, the rated capacity and the size and color of the wall and the ribs. The maximum ambient temperature T_0 is set to 40°C [7].

For example, Fig. 7(a) and (b) show the results of the computer analysis of permissible overload factor of 3334 kvar M oil impregnated paper capacitor and 6667 kvar S oil impregnated paper/pp film capacitor, respectively, when following data are inputted.

(a) Example 1: M oil impregnated paper capacitor:

Input data: Capacity = 3334 kvar

Tank: Color = Blue, Size (m) = 1.83x 0.88x2.55
Rib: Width (m) = 0.071, Number = 10,
Tan δ = 0.00100 at 40°C
= 0.00128 at 70°C
= 0.00170 at 100°C,

Output data:

When the capacitor is operated at rated capacity,

Temperature of the dielectric = 59.1°C

When operation of the capacitor is restricted by thermal stability,

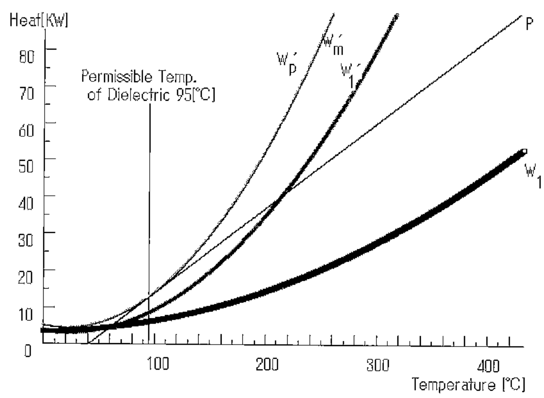
Permissible overload factor = 1.51

Temperature of dielectric = 95.0°C

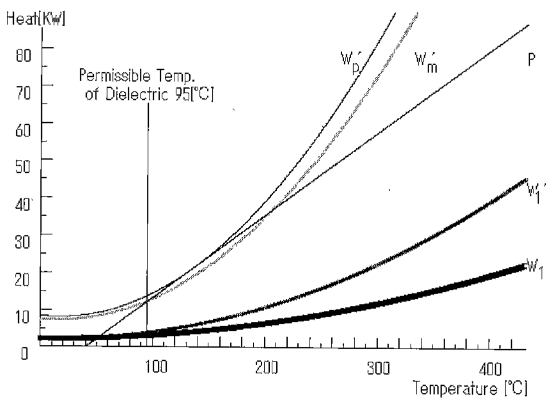
When operation of the capacitor is restricted by permissible temperature of dielectric:

Permissible overload factor = 1.51

(b) Example 2: S oil impregnated paper/pp film capacitor:



(a) M·P 60 Hz 1667 Kvar



(b) S·P/F 60 Hz 6667 Kvar

Fig. 7. Results of computer analysis of permissible overload of the capacitors

Input data: Capacity = 6667 kvar

Tank: Color = Blue, Size (m) = 1.5x0.5x2.55
Rib: Width (m) = 0.054, Number = 8,
Tan δ = 0.00035 at 40°C
= 0.00040 at 70°C
= 0.00048 at 100°C,

Output data:

When the capacitor is operated at rated capacity.

Temperature of dielectric=52.2°C

When operation of the capacitor is restricted by thermal stability,

Permissible overload factor = 3.43

Temperature of dielectric = 135.1°C

When operation of capacitor is restricted by permissible temperature of dielectric,

Permissible overload factor = 3.03

From above mentioned results, we can realize that permissible overload of M oil impregnated paper capacitor is restricted by both thermal stability and permissible temperature of dielectric to 1.51, a little higher than 1.44, and 3334 kvar is almost limit of the rated capacity. On the other hand S oil impregnated paper/pp film capacitor has much margin for the overload and it is possible to manufacture larger capacitors than 6667 Mvar.

8. Conclusion

We clarified the heat radiation from the tank wall and temperature rise of power capacitors, and developed analyzing method of the thermal stability and the permissible overload of the capacitors using a computer.

By this analysis we can know the permissible overload factor and the temperature rise of the capacitors without performing the temperature rise test which requires long time and much cost.

(Manuscript received Aug. 22, 2002,
revised Dec. 16, 2002)

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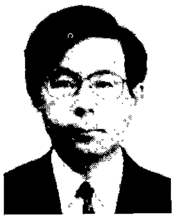

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