12. ENERGY CONSERVATION IN ELECTRIC EQUIPMENT OPERATION

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12.1 Electric Power Management

For electric power conservation, it is necessary to manage the electric power from both electric energy and maximum electric power aspects.

It is important to manage the electric energy from the following two aspects:

(1) Improvement of the electricity intensity

(2) Improvement of the power factor

and for the maximum electric power, it is important to manage from the stand point of improvement of the load factor.

12.1.1 Improvement of the Electricity Intensity

To generally improve the electricity intensity, it is important to get a reasonably clear picture of the transition in this consumption rate, classify each production process and each raw material and associate them with changes in the processing method and for technical improvement. It is also essential to determine the target value for the electricity intensity in each production process, work out a plan starting from a portion which can be improved and carry it out.

Important items to improve the electricity intensity are concretely described as follows:

(1) Placement of measuring instruments

Provide measuring instruments at important points so that the electric power consumption for each hour may be measured and checked periodically. It is necessary to grasp the load condition, maximum electric power and electricity intensity from the results of measurement. If there is any problem, it must be solved quickly.

(2) Electric power management

Optimize voltage and capacity in each distribution line and endeavour to introduce high-efficiency electric equipment, operate them efficiently and reduce troubles.

(3) Equipment management

Optimize capacity for the production equipment, intend to introduce and operate high-efficiency production equipment, and endeavour to prevent troubles by completing maintenance and control. Special attention should be paid to troubles with the electric equipment since they are liable to cause the suspension of operation, equipment damage and accident resulting in injury or death.

(4) Process control

Rationalize the operation processes and improve the layout.

(5) Quality control

Establish an overall company cooperative system for quality control and endeavour to reduce defective ratio.

(6) Participation by all employees

Enhance consciousness for increased productivity and cost, and positively promote for the establishment of a work improvement suggestion system and for thoroughness of QC circle activities.

12.1.2 Improvement of the Power Factor

When AC electric power is provided to a load in a sigle-phase circuit, the electric power at this point is generally less than the product of the voltage and current. In this case, the ratio of the two is called "Power factor", and is expressed by the following equation:

$$\text{Power factor} = \frac{P}{E \cdot I} \times 100\ \% \quad \cdots\cdots (1)$$

where P: Electric power (W)
E: Voltage (V)
I : Current (A)

$$P = EI\cos\phi \quad \cdots\cdots (2)$$

ϕ: Phase difference between voltage and current

$$I = \frac{P}{E\cos\phi} \quad \cdots\cdots (3)$$

Then, the current to get a specified output should be increased in inverse proportion to the power factor, which also applies to the three-phase circuit.

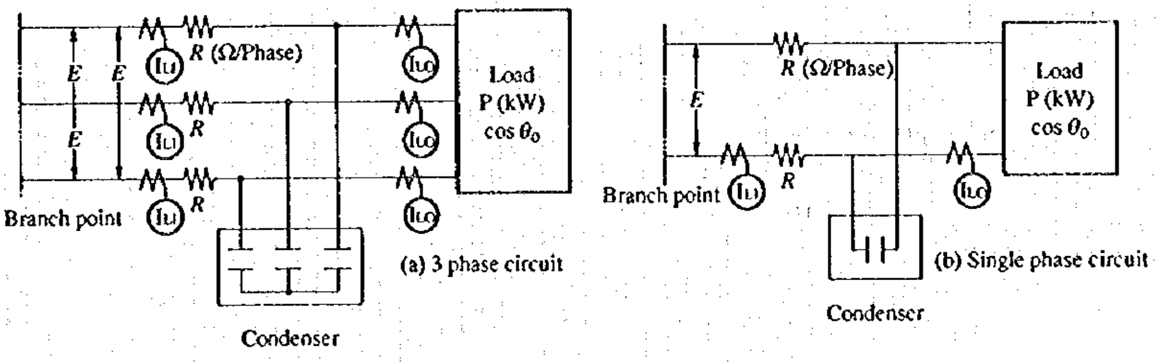
A phase-advancing capacitor is generally provided to improve this power factor. The energy conservation effect due to this is obtained by reducing all of the surplus current and resistance loss of the distribution line or the transformer.

Effects obtained by improvement of the power factor are described below:

(1) Reduction effect of Distribution Line Loss

Since power loss in the distribution line is given by (Line current)² × (Line resistance), reduced distribution line loss (P_L) to be obtained by providing a phase-advancing capacitor to improve the power factor in Figure 12.1 is determined by the following equations:

Figure 12.1 Reduction Effect of Distribution Loss



a. Equation for three phase circuit

$$P_L = 3 \times (I_{LO}^2 - I_{LI}^2) \times R \times 10^{-3} \text{ (kW)} \quad \cdots\cdots (4)$$

where

Before improvement

$$I_{LO}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_0}\right)^2 = \frac{P^2}{3E^2} \cdot \frac{1}{\cos^2\theta_0}$$

After improvement

$$I_{LI}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_1}\right)^2 = \frac{P^2}{3E^2} \cdot \frac{1}{\cos^2\theta_1}$$

$$I_{LO}^2 - I_{LI}^2 = \frac{P^2}{3E^2}\left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right)$$

Hence,

$$P_L = \frac{P^2}{E^2} \times \left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right) \times R \times 10^{-3}(\mathrm{kW}) \quad \text{......} \quad (5)$$

In equation (5), substituting

$$\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1} = k_1$$

$$P_L = \frac{P^2}{E^2} \times k_1 \times R \times 10^{-3}(\mathrm{kW}) \quad \text{......} \quad (6)$$

where,

$$\frac{P^2}{E^2} = 3\cos^2\theta_0 \cdot I_{LO}{}^2$$

Hence,

$$P_L = 3 \times (I_{LO} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3} \ (\mathrm{kW}) \quad \text{......} \quad (7)$$

b. Equation for single phase circuit

$$P_L = 2 \times (I_{LO}{}^2 - I_{L1}{}^2) \times R \times 10^{-3} \ (\mathrm{kW}) \quad \text{......} \quad (8)$$

where

Before improvement

$$I_{LO}{}^2 = \left(\frac{P}{E\cos\theta_0}\right)^2$$

After improvement

$$I_{L1}{}^2 = \left(\frac{P}{E\cos\theta_0}\right)^2$$

$$I_{LO}{}^2 - I_{L1}{}^2 = \frac{P^2}{E^2}\left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right)$$

Hence,

$$P_L = 2 \times \frac{P^2}{E^2} \times \left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right) \times R \times 10^{-3}(\mathrm{kW}) \quad \text{......} \quad (9)$$

$$= 2 \times \frac{P^2}{E^2} \times k_1 \times R \times 10^{-3}(\mathrm{kW}) \quad \text{......} \quad (10)$$

$$= 2 \times (I_{LO} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3}(\mathrm{kW}) \quad \text{......} \quad (11)$$

where

P (kW): Load power
I_{LO} (A) : Present load current
I_{L1} (A) : Line current after improvement of the power factor
E (kV) : Line voltage
$\cos\theta_0$: Present power factor
$\cos\theta_1$: Power factor after improvement

c. Calculation example

Reduced loss in the model system of three phase distribution line is calculated by using the preceding equation (7), as is shown in Table 12.1.

Table 12.1 Calculation Example of Reduction Effect of Loss in 3 Phase Distribution Line due to Power Factor Improvement

Resistance value of distribution line and cable R: (Size of electric wire)	Length of wiring l	Present power factor ($\cos\theta_0$)	Present load current	Load current after improvement		Reduction of loss in wiring	
				$\cos\theta_1 = 0.90$	$\cos\theta_1 = 0.95$	$\cos\theta_1 = 0.90$	$\cos\theta_1 = 0.95$
Ω/km 0.20 (100sq or equivalent)	500 m	0.60	131A	87.3A	82.7A	2.87 kW	3.10 kW
		0.70	131	102	96.5	2.04	2.30
0.13 (150sq or equivalent)	500	0.60	219	146	138	5.18	5.61
		0.70	219	170	161	3.68	4.26
0.10 (200sq or equivalent)	500	0.60	262	175	165	5.74	6.21
		0.70	262	104	193	4.08	4.72
0.08 (250sq or equivalent)	500	0.60	306	204	193	6.25	6.76
		0.70	306	238	225	4.44	5.14
0.06 (325sq or equivalent)	500	0.60	350	233	221	6.12	6.62
		0.70	350	272	258	4.35	5.04

(2) Reduction effect of transformer loss

Generally speaking power loss in transformers consists of "Iron loss" which occurs in iron core, and "Copper loss" which occurs in coil, of which "Copper loss" is greatly affected by the power factor.

a. Equation

Reduced transformer loss (P_t) when the power factor is improved by a phase-advancing capacitor on the secondary side of the transformer as shown in Figure 12.2 is determined by the following equations:

However, it is assumed that total load loss of transformers: Copper loss = 1:0.8.

The equations are the same for both single and three phase.

$$P_t = (\frac{100}{\eta} - 1) \times \frac{4}{5} \times (\frac{P}{L_0})^2 \times (\frac{1}{\cos^2\theta_0} - (\frac{1}{\cos^2\theta_1}) \times L_0(kW) \quad \cdots\cdots (12)$$

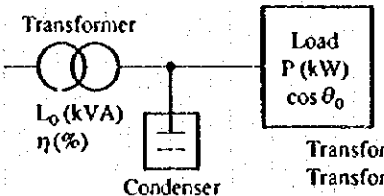
$$= (\frac{100}{\eta} - 1) \times \frac{4}{5} \times (\frac{P}{L_0})^2 \times k_1 \times L_0(kW) \quad \cdots\cdots (13)$$

$$= k_2 \times k_1 \times L_0(kW) \quad \cdots\cdots (14)$$

where,

$$K_2 = (\frac{100}{\eta} - 1) \times \frac{4}{5} \times (\frac{P}{L_0})^2$$

Figure 12.2 Reduction Effect of Transformer Loss



Transformer rated capacity : L_0 (kVA)
Transformer efficiency : η (%)
Load power : P (kW)
Present power factor : $\cos\theta_0$
Power factor after improvement : $\cos\theta_1$

b. Calculation example

The calculation example of reduced transformer loss using preceding equation (14) is shown in Table 12.2.

Table 12.2 Calculation Example of Reduction Effect of Transformer Loss (Pt)

Transformer specification	L_0 = 300kVA η = 98 %			L_0 = 500kVA η = 98.5 %			L_0 = 1,000kVA η = 99 %		
P/L_0	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7
$\cos\theta_0 \rightarrow \cos\theta_1$ 0.60 → 0.90	1.89 kW	2.72 kW	3.70 kW	2.35 kW	3.39 kW	4.61 kW	3.12 kW	4.49 kW	6.11 kW
0.60 → 0.95	2.04	2.95	4.01	2.55	3.67	4.99	3.37	4.86	6.61
0.70 → 0.90	0.99	1.42	1.93	1.23	1.77	2.41	1.63	2.35	3.19
0.70 → 0.95	1.14	1.65	2.24	1.42	2.05	2.79	1.88	2.72	3.69

(3) Effect by reducing bus voltage drop

a. Decreasing bus voltage drop and energy conservation

Since improving the power factor reduces the line current, voltage drop in the distribution line can be reduced, which is, to a large extent, energy conservation. That is, it is because the following various problems which occur because of the voltage drop, can be settled by improvement of the power factor.

1) Life of fluorescent and mercury lamps, etc. becomes short and the brightness lowers.

2) In electric heaters utilizing Joule heat, the operating efficiency lowers because heating capacity decreases in proportion to the square of the voltage.

3) In a constant load state, load current of induction motors increases, efficiency lowers and distribution line loss increases because motor torque decreases in proportion to the square of the voltage.

It should be noted that when more phase-advancing capacitors than required are operated in a light-load time zone such as on holidays, at night, etc., the bus voltage to the contrary rises excessively, thus resulting in shortened life of all electric equipment such as motors, lighting appliances as well as the capacitors themselves. Therefore, unnecessary capacitors must be released by means of an automatic control system, etc. as described later.

b. Equation

Voltage drop reduction value (namely, voltage buildup value) ΔV due to phase-advancing capacitors can be generally determined by the following equation:

$$\Delta V = \frac{Qc}{R.C.} \times 100\% \quad \cdots\cdots (15)$$

where R.C.: Short-circuit capacity of capacitor-connecting bus (kVA)
Qc : Capacity of capacitor (kVA)

c. Example of calculation

Let us determine bus voltage buildup value ΔV, when 500kVA phase-advancing capacitor is connected to a bus with short-circuit capacity of 125 MVA.

$$\Delta V = \frac{500\,(\text{kVA})}{125 \times 10^3\,(\text{kVA})} \times 100 = 0.4(\%)$$

(4) Increased surplus capacity for distribution equipment

The apparent power of distribution equipment such as a transformer and a distribution line will decrease when the line current reduces due to the improved power factor. Namely, the equipment will have a margin in capacity. Therefore,

a. In the existing equipment, it is possible to increase the load without involving equipment expansion such as re-installation of the distribution line and increased transformer capacity,

b. For new equipment, cost can be saved because equipment with a smaller capacity is purchased.

How much load can be increased by improvement of the power factor in the existing distribution equipment varies with the power factor of the extension load in addition to the power factor before improvement ($\cos\theta_0$), and the power factor after improvement ($\cos\theta_1$).

For one thing, the ratio of extensible load capacity P_1 (kW), when the extension load power factor is identical with the load power factor after installation of the capacitor, to the existing load capacity P_0 (kW) (k_3) is determined.

$$k_3 = \frac{P_1}{P_0}$$

Then

$$\frac{P_0}{\cos\theta_0} = \frac{P_0 + P_1}{\cos\theta_1} = \frac{P_0 + k_3 \cdot P_0}{\cos\theta_1}$$

Hence

$$P_0(1 + k_3) = P_0 \cdot \frac{\cos\theta_1}{\cos\theta_0}$$

$$\therefore k_3 = \frac{\cos\theta_1}{\cos\theta_0} - 1 \quad \text{(16)}$$

Example:

When a 100 kW load at a power factor of 70% is improved to 95% of the power factor, $k_3 \fallingdotseq 0.36$. That is, a load of 100 kW × 0.36 = 36 kW (power factor 95%) can be increased with the present equipment as it is.

(5) Reduced electric charge

In general, the electric charge system involves a bonus and penalty system for the receiving power factor.

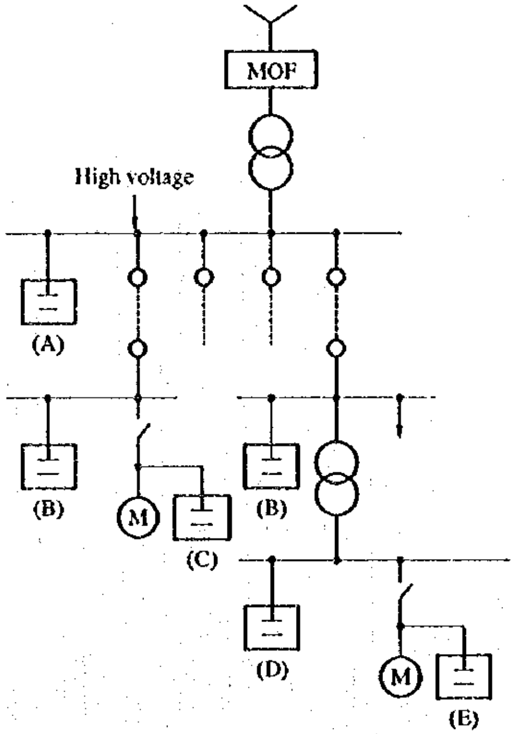
Accordingly, improving the power factor in low power factor factories reduces the electric charge. We have described effects due to installation of capacitors in above items (1) to (5) and will describe problems on selection of capacitor connection and automatic switching control below.

(6) Selection of capacitor connection

a. Connection and effect

There are many points to be considered when connecting a phase-advancing capacitor as shown in Figure 12.3.

Figure 12.3 Connection Points of Condenser



(A) Receiving s/s high voltage bus
(B) Local s/s high voltage bus
(C) High voltage load direct
(D) Low voltage bus lump
(E) Low voltage load direct

1) Receiving power factor improvement

The improvement has almost nothing to do with the connecting point of phase-advancing capacitor.

2) Required capacitor capacity

Generally, since more phase-advancing capacitors are dispersed, the smaller their utilization factor (operating time) will be, the larger the total capacity of required capacitors will be. In Figure 12.3, when capacitors are centralized to (A), a required capacitor capacity may be calculated for mean power of all loads, while when dispersed to (B) to (E), a capacitor capacity to meet load for a restricted area must be calculated.

3) Reduction of power loss

It is needless to say that the closer a capacitor is installed to the end of the distribution line, the greater the reduction will be and the longer the line length is, the greater the reduction will be.

4) Increased equipment margin capacity

Increased equipment margin capacity due to installation of a capacitor takes place in the distribution line, cable and transformer inserted in a series between the capacitor connection and the receiving end. Therefore, the closer the capacitor is connected to the end, the greater the effect will be. However, even if the margin capacity is increased, for example, it is no worse if there is no space to expand or no planning to increase load in the future.

5) Reduction of voltage drop

Since reduction of voltage drop due to a phase-advancing capacitor is determined by power source impedance viewed from the connecting point, the reduction will be larger when it is connected at the end.

b. Determination of capacitor connection

To obtain the maximum energy conservation effect, phase-advancing capacitors should be connected to the end of all of them. However, taking into consideration other conditions such as investment effect, etc., the practical way to determine is as follows.

1) Directly connect to a load with comparatively large capacity (See Figure 12.3, Ⓒ, Ⓔ).

2) Collectively install at point of concentrated small loads.

(See Figure 12.3, Ⓑ, Ⓓ).

3) Connect the capacitor for improving receiving power factor to the receiving high voltage bus (Figure 12.3, Ⓐ).

The above methods are considered and should be determined according to each user's conditions on a basis of this information.

(7) Automatic switching control of capacitors

Operating unnecessary capacitors causes the distribution line and transformer losses due to capacitor current in addition to the difficulty due to rises in the bus voltage, thus nullifying the energy conservation effect. Therefore, a switching control will be required. Especially since capacitors installed at the end of the factory are considered difficult to control manually, it is recommended to use an automatic switching control. The automatic switching control mainly has the following four systems:

a. **System to switch synchronizing to load on-off signal**

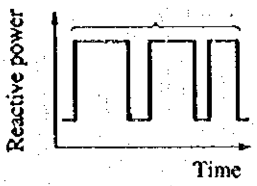
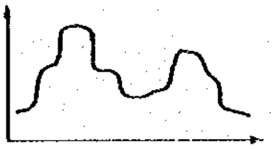
b. **System to switch according to increase or decrease in load current (Current control)**

c. **System to switch according to increase or decrease in line reactive power (Reactive power control)**

d. **System to switch by means of a time switch (Programmed control)**

It is necessary to select a suitable system according to the load fluctuation pattern. One example of selection is shown in Figure 12.4.

Figure 12.4 Condenser Control System

Load fluctuation pattern	(Same every day)  	(Change every day) 
Applied control system	Reactive power control Current control Program control	Reactive power control

12.1.3 Improved Load Factor

Since the load factor is defined as shown in equation (17), it is important for improving load factor to restrain the maximum power in such a manner not to concentrate production in a specified time zone through appropriate factory management or through operation control.

$$\text{Load factor} = \frac{\text{Mean power (kW)}}{\text{Maximum power (kW)}} \times 100\ (\%) \quad \cdots\cdots\cdots\cdots \quad (17)$$

Improving the load factor provides the following advantages:

- Since capacity for the receiving and distribution equipment, etc. can be effectively utilized, the equipment investment can be saved.

- It is possible to know operating conditions of the factory and machine equipment and to eliminate waste by checking the load curve and load factor.

- It is possible to reduce the demand charge by lowering the maximum power.

The method for improving the load factor is shown as follows.

(1) Draw and study the daily-load curve

A graph representing the change of power consumption in relation to time is drawn, and using this daily-load curve, the load shift which would average out the load throughout the day as possible should be determined.

(2) Extend the operating hours

The extension of the facility operating hours is attempted through its mechanization and automatization, for using the facility evenly throughout the day.

(3) Shift load to the light-load time such as late night

The peaks will be reduced through such measures as the operation of the air conditioning and heating systems late at night by using the heat accumulation, using the electric power equipment for only late at night, and the shift of operations of the large-capacity equipment and test equipment to the light-load hours or practicing time-differential operations.

(4) Promote an appropriate maintenance of the installations

It is necessary to promote appropriate preventive maintenances and productive maintenances in order to limit malfunctions to a minimum and to equalize the load.

(5) Improvement of the transport and preparation works

It is necessary to attempt the reduction of idle hours and empty operation, to improve transport, preparations, and layout so that work progresses smoothly, and to conduct appropriate operational control.

(6) Introduction of the load control

Installing demand controller, Load controller, etc would be one method to limit the maximum power and to control load.

The demand controller usually consists of a monitor portion and a control portion; the monitor portion receives metering pulse from a watt hour meter and performs operations and judgements required for demand control, it also displays the present demand value and predicted demand value, and it performs alarm, control instructions and recording, etc. The control portion receives instruction from the monitor portion and stops and returns the predetermined load.

12.1.4 Higher Harmonics Generation and Its Control Methods

(1) Causes for higher harmonics

a. With the advance of power electronics, thyristors etc. are used widely from OA equipment to industrial machines. Thyristor control is easy and the response is fast, but by cutting the waveform as the firing angle is changed, waveform distortion is caused and higher harmonics are caused.

b. During the initial melting phase of an arc furnace for steel making, voltage flicker is caused each time when the electrodes are short-circuited by scrap iron, the voltage waveform gets out of shape, and higher harmonics are caused.

c. An equipment like reactors and rotating equipment with magnetic circuits waveform gets out of shape because of core hysteresis phenomena and this is promoted by magnetic saturation, and higher harmonics are caused.

(2) Influence of higher harmonics

a. Higher harmonics become the cause for capacitor overheating and burning because of an increase of the effective current value.

b. The electromagnetic force of higher harmonics causes abnormal noise for series reactors of capacitors etc.

c. For induction motors, vibration torque is caused by the higher harmonics current, and this becomes the cause for vibrations and abnormal noise.

d. Higher harmonics electromagnetic noise increases, and flicker is caused for fluorescent lamps with light controllers.

e. Waveform distortion causes shift of synchronization with the commercial power frequency, and this becomes the cause for the following malfunction because of control circuit phase deviation.

- Computer stop
- NC equipment stop
- Stop of rotating equipment like rolling mills etc.

(3) Countermeasures for suppression of higher harmonics

The following countermeasures are taken to keep the higher harmonics below the permissible distortion rate for computers.

a. Active filters

In case of rectangular wave current, the difference between the rectangular wave current, synthesized from the fundamental wave and the various higher harmonics, and the fundamental sinusoidal wave current becomes the higher harmonics current. By instantaneous supply of the current with the opposite polarity of this higher harmonics current from the outside active filter, the higher harmonics component is eliminated.

b. AC filter

R, C, L series single shunt filters are used for the sources of fifth to thirteenth higher harmonics. Further, L, R parallel circuits in series with C are used as shunt filters for still higher harmonics.

c. Change to multiphase power transducers

For example, when the number of phases is increased from 3 to 12 phases, the ripple decreases and the higher harmonics are suppressed.

12.2 Transformers

For transformer energy conservation, it is necessary to pay attention to the following:

(1) Transformer efficiency

(2) When there are two or more transformers, operation with an efficient number of transformers.

(3) Selection of transformer taps

12.2.1 Selection of Transformers

(1) Transformer efficiency is expressed by the following equation:

$$\eta = \frac{n\,p\cos\phi}{n\,p\cos\phi + W_i + n^2 W_c} \times 100\% \quad \cdots\cdots (1)$$

Where

η : Efficiency (%)
n : Load factor
p : Rated capacity (kVA)
$\cos\phi$: Power factor
W_i : Iron loss
W_c : Copper loss

Although a transformer has dielectric and stray-load losses, in addition to the above iron and copper losses, they are difficult to measure and are minute, and as such will be ignored. Also, the ratio of copper loss W_c to iron loss W_i at rated load is called "Loss ratio α".

$$\alpha = \frac{W_c}{W_i} \quad \cdots\cdots (2)$$

The loss ratio is generally 2 to 5 as shown in Table 12.3. However, it may exceed 10 in the energy conservation type transformers as described later.

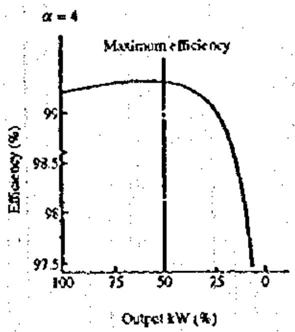
Table 12.3 Efficiency of 3 Phase High Voltage Medium Capacity Transformer

Primary 6.6/3.3 kV, Secondary 400/200 V

Rated capacity kVA	Company A				Company B			
	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio
300	98.2	0.9	4.6	5.1	97.9	2.2	4.2	1.9
500	98.27	1.3	7.5	5.8	98.1	2.7	7.0	2.6
750	98.36	2.0	10.5	5.3	98.2	3.2	10.6	3.3
1,000	98.52	2.5	12.5	5.0	98.2	3.5	14.8	4.2
1,500	98.62	4.5	16.5	3.7	–	–	–	–
2,000	98.69	6.0	20.5	3.4	98.3	7.3	27.3	3.7

From equation (1), the transformer efficiency is at maximum when $n = \sqrt{W_i/W_c}$, namely, output when the iron loss is equal to the copper loss at this point. One example of change in efficiency against output is illustrated in Figure 12.5.

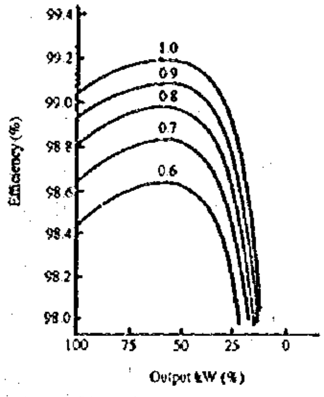
Figure 12.5 Transformer Efficiency (Example)



Also, the transformer efficiency varies with the load power factor in equation (1) and lowering the power factor reduces the efficiency.

This example is shown in Figure 12.6.

Figure 12.6 Relation between Power Factor and Efficiency (Example)



Note: Figure indicates power factor.

The difference of efficiency due to the transformer capacity is shown in Figure 12.7 and Figure 12.8.

Figure 12.7 Example of Efficiency of 50 Hz Single Oil Immersed Transformer

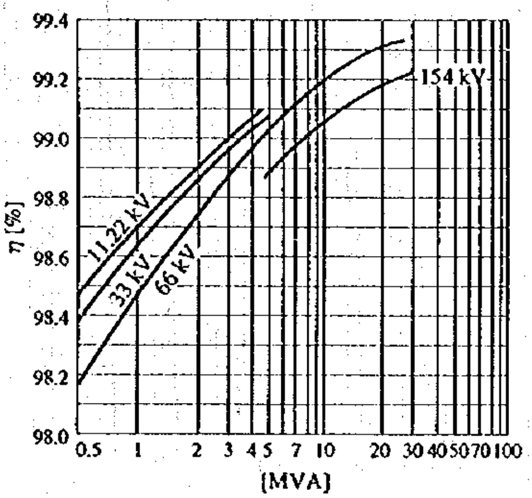
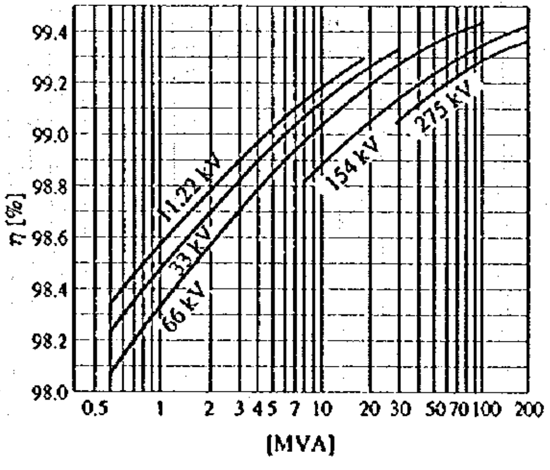


Figure 12.8 Example of Efficiency of 50 Hz 3 Phase Oil Immersed Transformer



(2) All day efficiency of transformers

Although it is of course important to purchase and operate transformers considering the transformer maximum efficiency point, daily efficiency also must not be neglected because the transformer load varies every hour. Equation (3) is called "all day efficiency".

$$\text{All day efficiency} = \frac{\text{Output energy per day (kWh)} \times 100\%}{\text{Output energy per day (kWh)} + \text{Loss energy per day (kWh)}} \quad \cdots\cdots\cdots (3)$$

If the daily pattern for load fluctuation is almost the same, it would be better to operate transformers so that the all day efficiency is better.

(3) Energy conservation type transformers

Some transformers that use the laser treated plate of silicon steel belt for the core material and employ wound core construction are manufactured. They are called conservation type transformers with the iron loss approximately 40% of the conventional types. Anybody purchasing transformers had better keep above for future reference.

12.2.2 Efficient Operation of Transformers

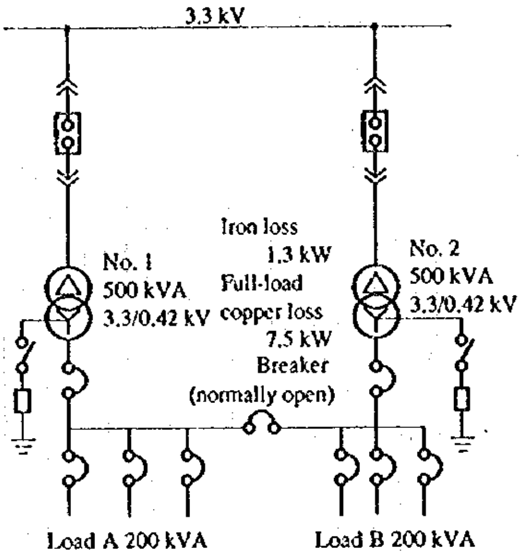
(1) Stopping of light-load transformers

Generally speaking, when there are two or more transformers and each of them has a low load factor, electric power can be saved by stopping low load factor transformers to integrate the load. However, in some cases, loss of transformers with increased load may exceed reduced loss of stopped transformers, causing an adverse effect. Therefore, it is always necessary to confirm by calculating, as shown in the following example.

(Example) When there are two 500 kVA transformers

In the case where each transformer has a load factor of 40% as shown in Figure 12.9, we will calculate the merit for when one transformer is stopped. We presume the transformer's characteristics to be of company A, specified in Table 12.3.

Figure 12.9 Method to Use Two 50 kVA Transformer



At present, for both transformer No. 1 and transformer No. 2, Iron loss = 1.3 (kW)

$$\text{Copper loss} = \text{Full - load copper loss} \times (\frac{\text{Load factor}}{100})^2 = 7.5 \times (\frac{40}{100})^2 = 1.2(\text{kW})$$

Hence,

$$\text{Total loss} = 2\ (1.3 + 1.2) = 5\ (\text{kW})$$

After stop of transformer No. 1,

Iron loss of transformer No. 2 = 1.3 (kW)

$$\text{Copper loss of transformer No.2} = \text{Full - load copper loss} \times (\frac{\text{Load factor}}{100})^2$$

$$= 7.5 \times (\frac{80}{100})^2 = 4.8\ (\text{kW})$$

$$\text{Total loss} = 1.3 + 4.8 = 6.1\ (\text{kW})$$

Stopping one transformer increases the loss by 1.1 kW.

(2) Control of the number of transformers

When transformers with the same rating are operated in parallel, the total loss can be reduced by increasing or decreasing the number of transformers.

Overall loss when N units of transformers are operated in parallel is expressed by the following equation:

$$W_N = N\left\{W_i + \left(\frac{P_L}{N\cdot Q}\right)^2 W_c\right\} \text{ (kW)}$$

where

W_N: Overall loss (kW)
W_i : Iron loss of one transformer (kW)
W_c : Copper loss of one transformer (kW)
P_L : Load capacity (kVA)
N : Number of transformers
Q : Capacity of one transformer (kVA)

Overall loss when (N – 1) units of transformers are operated in parallel is expressed by the following equation:

$$W_{N\text{-}1} = (N-1)\left\{W_i + \left(\frac{P_L}{(N-1)\cdot Q}\right)^2 \cdot W_c\right\} \text{ (kW)}$$

In case of $W_n > W_{N\text{-}1}$, (N–1) units operation is better for loss decreasing, so we get

$$P_L < \sqrt{\frac{N(N-1)}{\alpha}} \times Q \text{ (kVA)}$$

where

$$\alpha = \frac{W_c}{W_i}$$

α: Loss ratio

For example, when three 500 kVA transformers whose α is 3 are operated

$$\sqrt{\frac{N(N-1)}{\alpha}} \times Q = \sqrt{\frac{3\times 2}{3}} \times 500 = 707 \text{ kVA}$$

That is, when the load is 707 kVA or below, the energy can be saved by reducing one of the operated transformers to two units.

(3) Stopping of transformers at night and on holidays

In equipment and factories where operation is not performed at night and on holidays, the electric power can be saved by concentrating only loads for which electricity supply cannot be stopped even at night and on holidays, to certain transformers and stopping unnecessary transformers. However, when there is not much difference in electric power between the daytime and at night, there is no merit.

12.2.3 Selection of Transformer Taps

Low-voltage transformers or main power lines have many loads and it is not easy to supply the voltage close to the rating of each load. However, it is important to optimize the transformer taps and endeavour to get as close as possible.

Observing how motors are being operated in factories, full-load operations are few and 50% to 80% of the load is generally seen. Relation between voltage fluctuation and load state of an induction motor is as shown in Table 12.4 and Table 12.5. When all loads for the transformer are motors, it is desirable to select the taps in the light of these.

Table 12.4 Effect of Voltage Fluctuation on Induction Motor

	Voltage fluctuation	
	90 % Voltage	110 % Voltage
Starting torque, Maximum torque	–19 %	+21 %
Synchronous speed	Remain unchanged	Remain unchanged
% Slip	+23 %	–17 %
Full-load speed	–1.5 %	+1 %
Efficiency (Full-load)	–2 %	Slightly increased
Power factor (Full-load)	+1 %	–3 %
Full-load current	+11 %	–7 %
Starting current	–10 ~ –12 %	+10 ~ +12 %
Full-load temperature rise	+6 ~ +7 °C	–1 ~ –2 °C
Magnetic noise	Slightly decreased	Slightly increased

Table 12.5 Relation between Voltage Fluctuation and Loading State of Induction Motor

		Voltage fluctuation	
		90 % Voltage	110 % Voltage
Efficiency	Full load	–2 %	Slightly increased
	3/4 Load	Remain unchanged	Remain unchanged
	1/2 Load	+6 ~ -2 %	-1 ~ -2 %
Power factor	Full load	+1 %	-3 %
	3/4 Load	+2 ~ +3 %	-4 %
	1/2 Load	+4 ~ +5 %	-5 ~ -6 %

12.3 Motors

For motor energy conservation, the countermeasures are mainly classified into the following two cases:

(1) In the case of energy conservation by newly establishing or by greatly remodelling load and motor equipment.

(2) In the case of energy conservation by intensifying the management aspect of the existing equipment or by remodelling it in a small scale.

Each of these will be discussed below:

12.3.1 In the Case of Newly Establishing Load and Motor Equipment

Although it applies not only to motor application equipment but also to general equipment, it can be stated that the amount of energy used may be determined to a certain degree at the equipment planning stage. If the equipment capacity is too big or unfit for the load equipment, the energy cannot be used in a rational manner. Matters which should be considered at the planning or introducing stage of newly-establishing equipment are described as follows:

(1) Basic expressions relating to motor-driven force applications

Basic expressions which must first be understood when considering the motor energy conservation are shown in Table 12.6.

Table 12.6 Basic and Practical Expressions Relating to Motor Application

Formulation Item	Basic expression	Practical expression	Description of symbols
1 Power and torque	$P = \omega T$	$\begin{cases} N[\mathrm{rpm}] = \frac{60}{2\pi}\omega \\ T_g[\mathrm{kg \cdot m}] = \frac{T}{g} = \frac{T}{9.81} \end{cases}$ $P_k[\mathrm{kW}] = \frac{N[\mathrm{rpm}]}{973} \times T_g[\mathrm{kg \cdot m}]$	P : Power (kW) T : Torque (N-m) T_g: Torque (kg·m) ω : Angular velocity (rad/sec) N : Rotating speed (rpm)
2 Moment of inertia and acceleration torque	$J\frac{d\omega}{dt} = T$	$GD^2 = 4J$ $T_g[\mathrm{kg \cdot m}] = \frac{1}{375}\ GD^2 \cdot \frac{dN}{dt}$	J : Moment of inertia (kg·m²) GD²: Flywheel effect (kg·m²)
3 Acceleration time	$t = \int_0^{\omega_0} \frac{J}{Ta} d\omega [\mathrm{sec}]$	$\overline{Ta} = \frac{\int_0^{\omega_0} Ta(\omega)d\omega}{\omega_0}$: $t_a[\mathrm{sec}] = \frac{1}{365}\ \frac{GD^2N^2[\mathrm{rpm}]}{P[W]}$	t : Time required for acceleration (sec) t_a : Time required for completion of acceleration (sec) Ta: Acceleration torque (kg·m) $\overline{Ta}$: Mean acceleration torque (kg·m)

(2) Load condition in the selection of motors

To select an optimum motor, it is necessary to know the load condition.

How a motor must be under various conditions of load, or what to be the allowable conditions are summarized in Table 12.7. When the conditions shown here are clear, it is possible to select the motor and also to select the control equipment to follow it.

Table 12.7 Conditions for Motor Selection

	Conditions of load	Motor system		
		DC machine	Induction machine	Synchronous machine
Starting conditions	Necessary frequency for starting		Study heat capacity of motor	
	Necessary starting torque • Moment of inertia of load • Possibility of no-load starting	Application of series motor	Application of wound-rotor type IM Study starting current and time according to the above items	
	Necessity of smooth starting	Acceleration restriction	Reactpr starting, soft starter, etc.	Low frequency starting, etc.
Stop conditions	Necessity and its degree of emergency stop (quick stop)	Regeneration system, dynamic braking, etc.	Reversing-phase braking	Brake, etc.
	Necessity of precise stop position	Position control	Difficulty	
	Necessity of holding the stop position		Presence of brake	
Operating conditions	Necessity and its conditions of reverse rotation	Field switching Armature switching	Main circuit switching	
	Rating of load (Continuous, time)	Possibility of reducing frame No. for hourly rating		
	Special function	Restriction is comparatively small	Restriction is large.	
Speed control	Constant speed or variable speed?	For variable speed	For constant speed Variable speed in conjunction with control equipment	
	Speed control range	Scope of application is large.	Study combination with control equipment.	
	Necessity of speed control	Suitable	Change by amount of slip	Synchronize with the power sourc frequency.
Ambient conditions, etc.	Temperature and humidity conditions		Study motor construction.	
	Necessity of explosion-proof construction	Possible, but difficult	Possible	
	Whether good atmosphere or not	Problem on brush commutator	Squirrel cage type is for improper circumstance.	Brushless exciting is possible.
	Problem on personnel for maintenance	Maintenance is important.	In the case of brushless, easy maintenance.	
	Power source condition	Problem on higher harmonics and power factor	Starting current large, Delay power factor	Leading power factor is possible.

Although motor systems are classified into DC, induction and synchronous machines in Table 12.7, induction and synchronous machines here are considered to be constant-speed drive systems for commercial power source. A thyristor motor applied to a synchronous machine and a frequency control method applied to an induction machine belong to the DC machines for system. Main items for selection of motors are described in the following item (3):

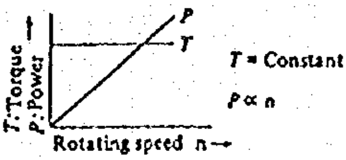
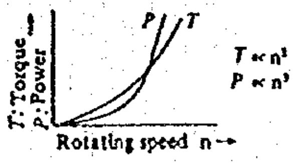
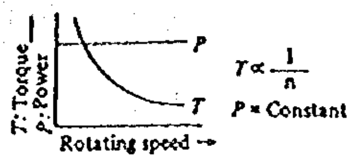
(3) Torque characteristics of load

Motors usually start in a load-coupled state from zero speed, accelerate to a specified speed and enter into a constant speed operation. Since the load has inherent torque characteristics, motors must generate a torque greater than that required by the load over all speed ranges.

Generally, when load and motors are more alike in torque characteristics, motors can be more economically designed.

As examples of typical torque-speed characteristics, there are three types. The first is constant-torque type in which the torque is constant in spite of the speed, the second is torque increasing type in which the torque is in proportion to the speed or its square, and the third is constant-output type in which the necessary torque is in inverse proportion to the speed and torque multiplied by speed is constant. These relations are summarized in Table 12.8.

Table 12.8 Class of Load and Torque Speed Characteristic

Load characteristic		Typical load
Constant torque load		Gravity load, Friction load [Example] Crane, Winding machine, Conveyor, Paper machine, Mixer
Increasing torque load		Fluid load [Example] Blower, Pump
Constant output load		Special load [Example] Winder, Constant cutting machine, Log barker

It is generally important in constant-speed motors such as three phase induction and synchronous motors whether starting torque and maximum torque are greater than the torque required by the load. It is also important in synchronous motors whether pull-in torque is greater than the torque required by the load.

(4) GD^2 of the load

The amount of the load GD^2 (Flywheel effect) is related to length of the starting time and the amount of the heating value during starting, so it is an important factor in the selection of motors.

Assuming the load torque as T_L (k·m), the motor torque as T_M (kg·m) and the sum of the flywheel effect for the load and motor as GD^2 (kg·m²),

$$T_M = \frac{GD^2}{375} \cdot \frac{dN}{dt} + T_L \quad \text{.......} \quad (1)$$

Accordingly, the starting time is

$$t = \int_0^{N_0} \frac{GD^2 \cdot dN}{375(T_M - T_L)} \text{ second} \quad \text{.......} \quad (2)$$

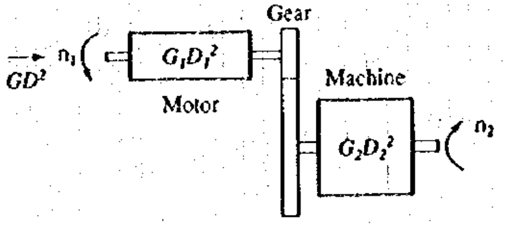
where N_o: Full-load rotation number

The needed time for starting is in direct proportion to GD^2. Since motors are unusually warmed when t is long, the allowable GD^2 of the load is determined for any motors. When GD^2 is great, on the contrary, it is necessary to select large motors fitting for it.

When GD^2 of motors: $G_1D_1^2$, GD^2 of machines: $G_2D_2^2$ and reduction ratio: $n_1/n_2 = n$ as shown in Figure 12.10, GD^2 converted to the motor side is:

$$GD^2 = G_1D_1^2 + \frac{1}{n^2} G_2D_2^2 \quad \text{.......} \quad (3)$$

Figure 12.10 Conversion of Flyweel Effect



This result is important because a reducer is, in most cases, used for industrial load.

(5) Time characteristics of the load

Motors are used in various methods of use such as continuous, short-time and intermittent use, etc. and such hour application duty is called "Duty". When electrical machinery and apparatus are used under specified conditions for use, they are designed so that the allowable maximum temperature is not exceeded, and these conditions are called "Rating of machinery and apparatus".

For the ratings, there are rated output, rated rotating speed, rated voltage, rated current, rated frequency, etc., and for the duty, there are various classes such as continuous rating, short-time rating, periodic rating, etc.

a. Continuous rating

For 24 hour continuous operation, we select, of course, motor with a continuous rating. Generally, when continuously used for more than two or three hours, motors with continuous rating are mostly used because they are nearly the same in price. The motor, while continuously used, is heated from the inside due to copper and iron losses, etc., and at the same time cooled by radiant heat from the surface and operated at a balanced value between these two.

Assuming the heating value every second: Q, Difference between the motor and ambient temperature (temperature rise value): θ, Heating capacity of motor: C, Heat dissipation coefficient: A,

$$C\frac{d\theta}{dt}+A\theta=Q \quad\cdots\cdots (3)$$

Assuming $\theta = 0$ at $t = 0$,

$$\theta=\frac{Q}{A}(1-\varepsilon^{-\frac{t}{T}}) \quad\cdots\cdots (4)$$

where, $T=\frac{C}{A}$

T in the above equation is called "Thermal time constant". If $t =$ in equation (4), $\theta = Q/A$ and the final temperature rise is determined.

This is graphed in Figure 12.11. Also, the thermal time constant normally will be as shown in Table 12.9.

Next, when the motor is separated from the power source and stopped, substituting $Q = 0$ in equation (3) and $\theta = \theta_0$ at $t = 0$,

$$\theta = \theta_0 \varepsilon^{-\frac{t}{T'}}$$

$$\text{where, } T' = \frac{C}{A'}$$

T': Thermal time constant during cooling
A': Heat radiant coefficient during cooling
θ_0: Temperature when cooling starts.

Figure 12.11 Temperature Rise Curve of Motor

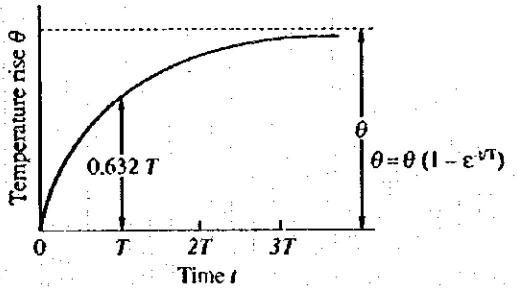


Table 12.9 Example of Thermal Time Constant

Type	Thermal time constant (minute)
Open type	20 - 40
Totally enclosed fan cooling type	50 - 150
Totally enclosed self cooling type	90 - 180

In separately-ventilated motors, the thermal time constant when stopped is the same as when operating because the amount of cooling air does not change even while stopped, but in self-ventilated motors it will be about three times that during operation.

b. Short-time rating

There are 5, 10, 15, 30, 60, 120 minutes, etc. as a standard time in the short-time rating, among which the nearest one to the actual load condition should be selected.

c. Periodic rating

Periodic load means that load and rest period are periodically repeated, which is represented by a crane. For motors with crane, rated motors with % ED expression are used (See Table 12.10).

40% ED indicates a condition for use in which the motor is used at a rated capacity for four minutes in ten minutes.

Table 12.10 Frame Number Application Table

		Load time factor					
		15%ED	25%ED	40%ED	60%ED	100%ED	Number of poles
Frame number	Output	kW	kW	kW	kW	kW	
132M		3	2.5	2.2	1.8	1.5	6
		5	4	3.7	3	2.8	6
160M		7.5	6.3	5.5	4.5	4	6
		10	8.5	7.5	6.3	5.5	6
160L		15	13	11	9	7.5	6
180L		20	17	15	13	11	6
200L		30	25	22	18.5	15	6
225M		40	33	30	25	22	6
250M		50	40	37	30	25	6
		63	50	45	37	33	6
280M		75	63	55	45	37	8
315M		100	85	75	63	50	8
		125	100	90	75	63	8
355L		150	125	110	90	75	10
		185	150	132	110	90	10
400L		220	185	160	132	110	10
		280	220	220	160	132	10

d. Calculation of output by the root mean square method

Rated output of a motor is selected from the timely characteristics of the load, but when the load varies irregularly, it is rather difficult to determine the motor output. However, when the load varies continuously and periodically, the root mean square method is often used as a simple output calculation method.

When the terminal voltage is constant in induction and DC shunt motors, the output is approximately in proportion to the load current. There are copper and iron losses as an exothermic source for motors and the copper loss is far greater than the iron loss. Also, since the copper loss is in proportion to the square of the load current, the loss in motor is almost in proportion to the square of the output.

Assuming the load current as I (t), and the output at this point as P (t),

$$\{I(t)\}^2 R = \{k P(t)\}^2$$

Assuming that it takes time of $t_1, t_2, \ldots\ldots t_n$ for load of $P_1, P_2, \ldots\ldots P_n$ during one period T, the equivalent load as Pa

$$k\{P_1^2 t_1 + P_2^2 t_2 + \cdots + P_n^2 t_n\} = kP_a^2 \cdot T$$

where, $T = t_1 + t_2 + \ldots + t_n$

$$\text{Hence, } P_a = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \cdots + P_n^2 t_n}{T}} \quad \ldots\ldots (6)$$

This P_a is an equivalent continuous load which gives out the same loss of load P which fluctuates periodically. In the case of an intermittent load, it is necessary to determine the equivalent load, taking into consideration generated heat and cooling during starting and stopping, since starting occurs very frequently.

For example, the equivalent load when a motor with a continuous rating is used for intermittent load as shown in Figure 12.12 is determined in the following way:

$$P_a = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + P_3^2 t_3}{t_1\alpha_1 + t_2\alpha_2 + t_3\alpha_3 + t_4\alpha_4}} \quad \ldots\ldots (7)$$

Figure 12.12 Example of Periodic Load

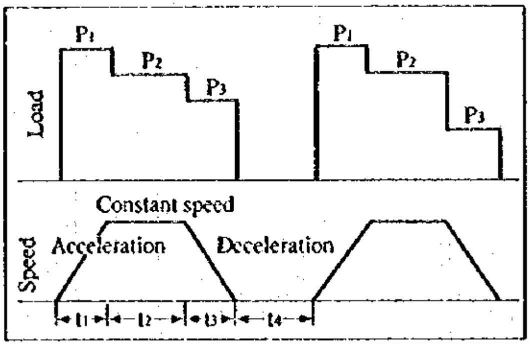


Table 12.11 Example of Cooling Coefficient Values

Type of motor	During stop	During acceleration	During operation	During deceleration
Open type AC motor	0.2	0.5	1	0.5
Enclosed type AC motor	0.3	0.6	1	0.6
Totally enclosed fan cooling type AC motor	0.5	0.75	1	0.75
Separately-cooling AC motor	1	1	1	1

However, α is heat extraction coefficient and its value is as shown in Table 11.

Also,

$$T = t_1\alpha_1 + t_2\alpha_2 + t_3\alpha_3 + t_4\alpha_4$$

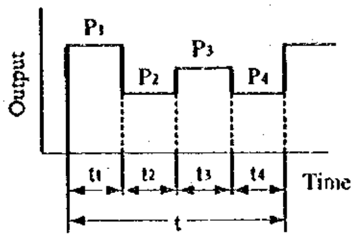
T shown in the above equation is an equivalent period, taking the heat extraction coefficient into consideration.

c. Determination of motor capacity

When the rated output of motors is to be decided, it is oftenly determined by the maximum load. However, it should be determined by calculating the equivalent load as described in the preceding item.

For example, in continuous operation as shown in Figure 12.13,

Figure 12.13 Example of Load Curve (1)



P_1 = 100 kW, t_1 = 10 minutes
P_2 = 50 kW, t_2 = 15 minutes
P_3 = 80 kW, t_3 = 10 minutes
P_4 = 50 kW, t_4 = 20 minutes

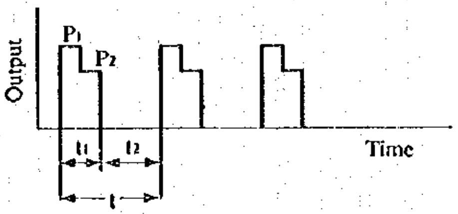
From equation (6), the required motor output P is

$$P=\sqrt{\frac{100^2\times10+50^2\times15+80^2\times10+50^2\times20}{10+15+10+20}}=67.6\ \mathrm{kW}\fallingdotseq 70\ \mathrm{kW}$$

Accordingly, 75 kW should be selected for the motor. In this case, at the maximum load, 100/75 = 1.33. Namely, it will be 133 % overload, but there will be no problem because the maximum torque of the motor is more than 200 %. If the motor is selected at the maximum output of 100 kW, it will be a significant adverse factor for energy conservation.

When a motor for crane is periodically used as shown in Figure 12.14.

Figure 12.14 Example of Load Curve (2)



P_1 = 50 kW 1.5 minutes
P_2 = 30 kW 1.5 minutes
t_1 = 1.5 + 1.5 = 3 minutes, t_2 = 7 minutes,

the root mean square load in operation is

$$P=\sqrt{\frac{50^2\times1.5+30^2\times1.5}{3}}=41.2\ \mathrm{kW}$$

Accordingly, a motor corresponding to 40 % ED 45 kW may be selected from Table 12.10.

(6) Class, efficiency and power factor of motors

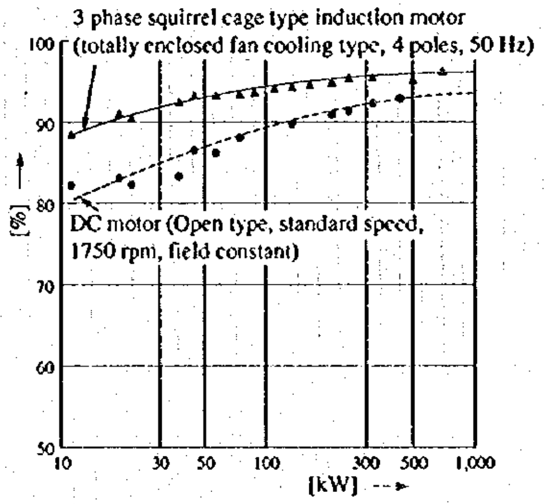
Let us compare the typical DC, induction and synchronous motors with induction motors mostly used in respect to efficiency and power factors.

a. DC and induction machines

Figure 12.15 shows the comparison in efficiency between DC and induction motors. As can be seen from the figure, the efficiency of the DC motor is 5 to 8 % lower than the induction motor for small capacity machines 100 kW or less and 2 to 3 % lower for 300 to 100 kW. This DC motor, being of the separately-ventilated type, must be essentially evaluated including loss of the blower for cooling. Since, however, this value is omitted, the efficiency actually tends to lower further.

The DC motor is capable of operating in accordance with the load characteristic and also in easily controlling the speed or torque because it can be easily provided with various characteristics by means of excitation systems. On the other hand, the DC motor has the following defects; the efficiency is lower than AC motors such as induction and synchronous motors, etc.; it has difficulties in maintenance and in environment-proof because of a current collecting mechanism.

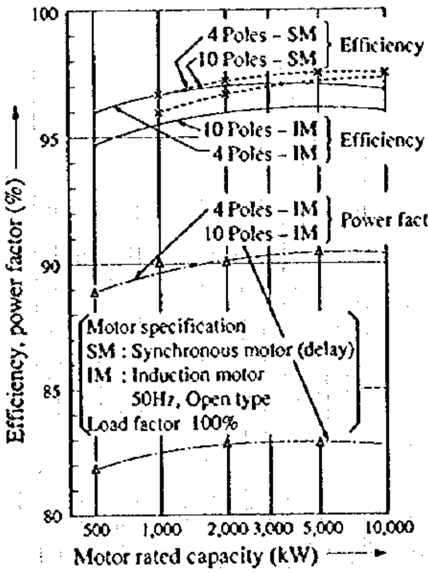
Figure 12.15 Comparative Example of Efficiency for Induction and DC Motor



b. Synchronous and induction motors

Figure 12.16 shows the comparison in efficiency between synchronous and induction motors.

Figure 12.16 Comparative Example of Efficiency and Power Factor between Synchronous and Induction Motors



The efficiency of synchronous motors is generally higher than that of induction motors and the tendency is remarkable in low-speed motors with larger numbers of poles. For example, in the case of 10 MW class, the efficiency of 4 pole synchronous motors is about 0.5% higher than induction motors, while 10 pole synchronous motors have an efficiency of about 1 to 1.5% higher.

Also, the greatest special feature of the synchronous motors is to freely select the power factor, enabling power factor 1.0 or advancing power factor and, at this point, they are quite different from the induction motors. Moreover, it is possible to control the system at a constant power factor by means of the field control, or to restrain voltage fluctuation of the system by performing constant control of the power factor or terminal voltage. Since the power factor considerably lowers with low-speed large capacity induction motors as can be seen from the figure, they are disadvantageous as compared to the synchronous motors in this respect also.

Since, however, the synchronous motors including excitation power source equipment for the field system are expensive, generally selection should be studied, with the following points:

1) For 10 MW or more, study adoption of synchronous motors in respect to efficiency.

2) For low-speed motors with larger numbers of poles even 10 MW or less, study adoption of synchronous motors.

3) When power factor and voltage of the system must be controlled, study adoption of synchronous motors. However, the motor is limited to sufficient enough large capacity to supply the system reactive power (Var).

4) Generally, for MW or less, induction motors are superior in simple starting and power source composition.

5) Generally, for salient-pole synchronous motors, the starting torque is not so large as for induction motors, it shoinly be, therefore, moted that they are diffcult to start up with large inertia moment or torque loads.

c. Induction motor and its number of poles

Figure 12.17 shows the relationship between number of poles and efficiency, power factor of a totally enclosed fan cooled type three phase squirrel cage induction motor with the output capacity as a parameter. In the figure, the efficiency does not vary much with the number of poles, because it is designed so that the efficiency does not vary much with the number of poles for each output capacity.

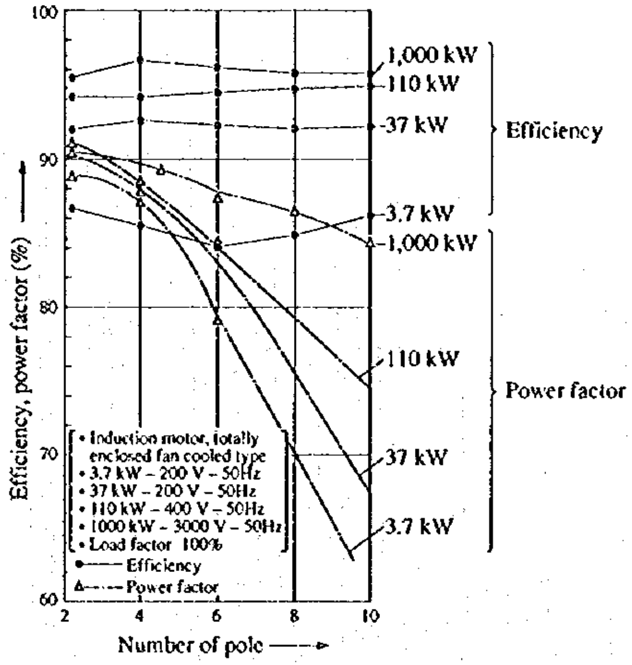
However, the power factor remarkably lowers with increased numbers of poles because the exciting current is in proportion to the number of poles. This tendency is remarkable with the smaller capacity motors with higher exciting current component as compared to load current components. Number of poles of a motor is selected according to rotating speed of the opposite machine. Generally, for motors with the same output, the larger the number of poles is, the larger the volume and weight become.

Since the weight is intimately related to the amount of materials used and material manufacturing expenses, it may represent a tendency of cost. Accordingly, since the larger numbers of poles generally raise the cost, it is better not to make the number of poles unnecessarily larger, otherwise, the initial investment will be larger and uneconomical.

Motors are rarely directly coupled to the opposite load machine and usually, a reducer lies between them.

When a four-pole motor is selected with reference to the reducer, there will be no problem in respect of cost and power factor. But when a motor with larger numbers of poles is selected, it should be determined by taking into consideration the equilibrium between the efficiency merits of the drive system including the reducer and the increased investment amount for the motor.

Figure 12.17 Relation between Number of Pole, Efficiency and Power Factor of Induction Motors

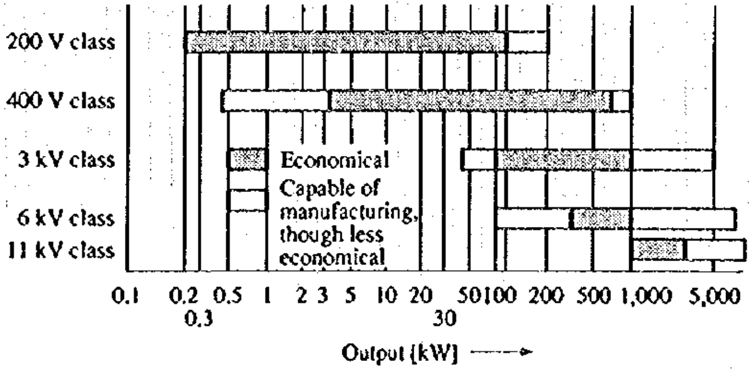


(7) Selection of motor voltage

Determination of the distribution voltage is an important factor for energy conservation because the motor voltage is deeply related to efficiency and cost. It is not desirable to select an especially high rated voltage for a small capacity motor, or to select on the contrary, a low voltage for a large capacity motor.

Figure 12.18 shows the optimum range of motor capacity for each voltage taking into consideration the technical problems and economical efficiency. The range shown with a white frame in this figure is a comparatively economical range containing few problems in manufacturing technique, and the shaded portion is the range which it is possible to manufacture technically if the economical efficiency is ignored to a certain degree.

Figure 12.18 Optimum Output Range of Motor



(8) Adoption of high-efficiency motors

In recent years, high-efficiency motors with iron and copper losses reduced by 20 to 30 % have been sold on the market. They have been developed by improving the low-voltage squirrel cage type induction motors through adoption of high-class steel plate and optimization of design with leaving the frame number and external dimensions as the present standard. Although the initial investment will be somewhat higher, they will deserve studying for adoption for long-time operating motors.

Figure 12.19 and Figure 12.20 show comparison in efficiency between high-efficiency motors and standard type motors which are being manufactured at present. It should be noted in Figure 12.20 that the high-efficiency motors are remarkable in the improvement of efficiency at light load.

Figure 12.19 Efficiency Comparison of 3 Phase Squirrel Cage Type Induction Motor (Output Capacity)

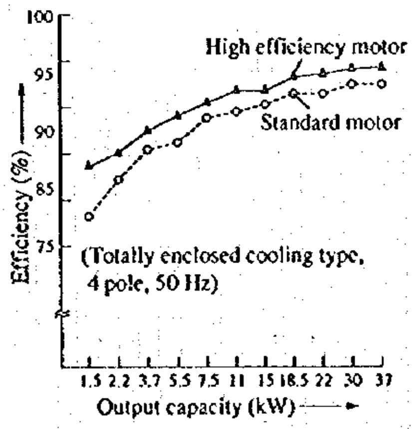
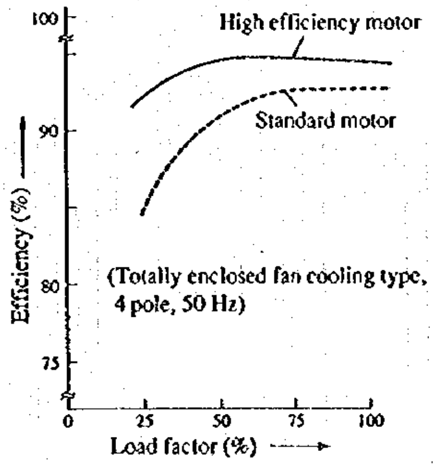


Figure 12.20 Efficiency Comparison of 3 Phase Squirrel Cage Type Induction Motor (Load Factor)



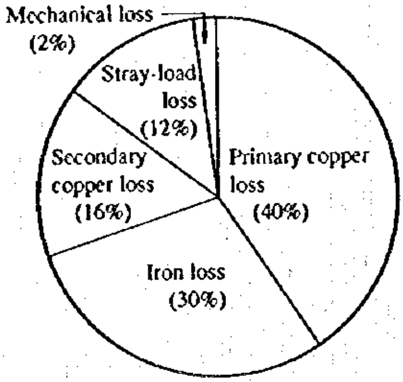
12.3.2 Energy Conservation by Remodelling the Existing Equipment in a Small Scale

(1) Induction motors and voltage control

Although induction motors are generally used because they are low cost and simple to handle, it should be noted that supply voltage has the greatest impact on these motors.

Figure 12.21 shows one example of loss of a three phase induction motor with a comparatively small capacity. As can be seen from this figure, a greater part of the loss is copper and iron losses which account for 86 %. Accordingly, the impact of supply voltage fluctuation on the induction motor will be clarified by investing these two.

Figure 12.21 Loss Analysis Example of Standard 3 Phase Induction Motor



The copper loss is a resistance loss which occurs by current flowing through the induction motor startor winding (primary winding) and rotor (secondary winding) and it is in proportion to the square of the load current. Therefore, it is a loss component much dependent on the load factor.

$$W_c = 3(r_1 + r_2')I'^2_2 (W) \quad \cdots\cdots (8)$$

where

W_c: Copper loss
r_1 : Resistance of primary winding each phase (Ω)
r_2' : Resistance of secondary winding each phase (primary side converted value) (Ω)
I'_2 : Load current (A)

Secondary current, when the motor runs at a rated speed close to the synchronous speed, is as follow from the basic formula of the induction motor.

$$I'_2 \fallingdotseq \frac{\omega_0 T}{3V_1} (A) \quad \cdots\cdots (9)$$

where

ω_0: Synchronous angular velocity
V_1: Supply voltage
T : Load torque

From equation (8) and equation (9), the relation between the supply voltage and copper loss is

$$W_c \fallingdotseq (r_1 + r'_2)\frac{\omega_0^2 T^2}{3V_1^2}(W) \quad \cdots\cdots (10)$$

That is, when the load torque does not change before and after the supply voltage fluctuation, the copper loss will be in inverse proportion to the square of the voltage.

On the other hand, iron loss W_i occurs when the magnetic flux in the iron core changes by means of the revolving magnetic field and consists of eddy current loss W_e and hysteresis loss W_h. The eddy current loss is in proportion to the square of the thickness of the iron plate of the core and the square of the magnetic flux density B, while the hysteresis loss is said to be in proportion to the frequency f and the magnetic flux density to the 1.6th power according to Steinmetz's research. Since, however, silicon steel plate has recently been used for iron plate, considerably high magnetic flux density can be obtained. Therefore, the hysteresis loss is also considered to be practically in proportion to the square of the magnetic flux density.

Since fB are in proportion to the voltage, the iron loss W_i is:

$$W_i = W_e + W_h = k_1(dfB)^2 + k_2 fB^2 = V_1^2\left(k'_1 + \frac{k'_2}{f}\right)(W) \quad \cdots\cdots (11)$$

where

k_1, k'_1: Constant representing the eddy current loss
k_2, k'_2: Constant representing the hysteresis loss

Since a greater part of the motor loss is iron and copper loss, supposing that total loss is a sum of the iron loss W_i and copper loss W_c, the total loss W comes to the following equation from equation (10) and equation (11).

$$W = \left(k'_1 + \frac{k'_2}{f}\right)V_1^2 + (r_1 + r'_2)\frac{\omega_0^2 T^2}{3V_1^2}(W) \quad \cdots\cdots (12)$$

Supply voltage V at which the total loss W is minimized is determined by using a condition of dW/dV = 0 into the following equation:

$$V = \sqrt[4]{\frac{(r_1 + r'_2)\omega_0^2}{3(k'_1 + \frac{k_2}{f})}} \cdot \sqrt{T}(V) \quad \cdots\cdots (13)$$

Since the supply voltage at which the loss is minimized is in proportion to $\sqrt{T}$ from the above equation, it lowers as the load factor lowers.

Figure 12.22 shows a conceptual diagram of the characteristics of copper and iron losses against the supply voltage. The torque may be regarded as the load factor because it is balanced with load torque $T\ell$. Accordingly, copper loss curve W_c rises with the load factor and the iron loss value has nothing to do with the load factor. Since the minimal loss point is the point of intersection of iron loss curve W_i and copper loss curve W_c, it will swift to the right when the load factor is high, and it will swift to the left when the load factor is low.

Figure 12.22 Tendency of Loss against Applied Voltage

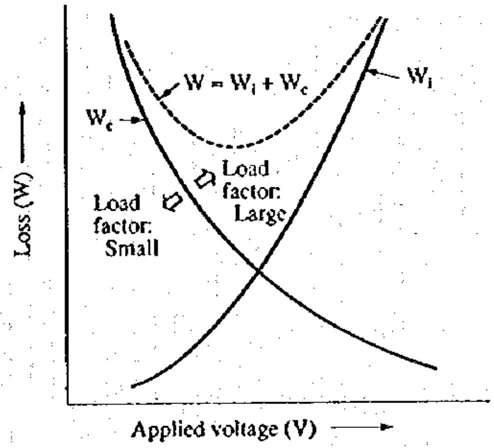


Figure 12.23 shows one example of the efficiency curve when the survey voltage is actually changed with a motor. As shown in the figure, the efficiency during voltage fluctuation exhibits varied tendencies according to the load factor. When the load factor is high, the highest efficiency is shown at the rated voltage, while, when the load factor is low, the efficiency lowers as the voltage increases.

Figure 12.23 Example of Efficiency during Voltage Fluctuation of Induction Motor

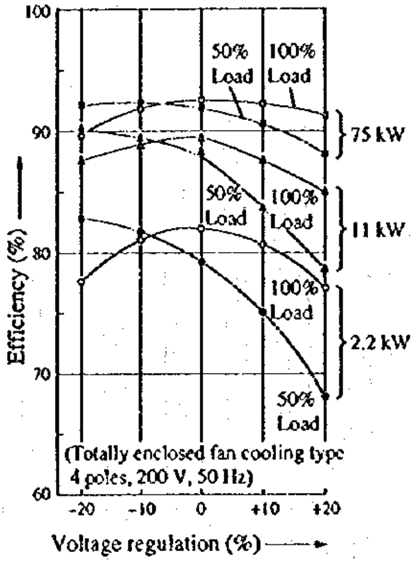


Figure 12.24 Example of Power Factor during Voltage Fluctuation of Induction Motor

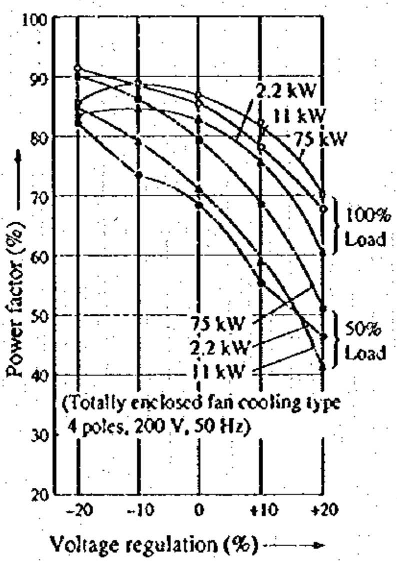


Figure 12.24 shows the change in the power factor of induction motors when the supply voltage fluctuates. The power factor increases as the voltage drops, because the exciting current of induction motors is in proportion to the supply voltage.

What has been described until now is summarized in Table 12.12.

Efficiency and power factor during supply voltage fluctuation have been described in the foregoing. When the above are actually applied to motors in operation within the field, the following items should be studied together.

Table 12.12 Effect of Voltage Fluctuation on Induction Machine

		Voltage fluctuation		
		90 % Voltage	Proportional relation	110 % Voltage
Starting torque Stalling torque		-19 %	V^2	+21 %
Synchronous speed		Remain unchanged	Constant	Remain unchanged
% slip		+23 %	$1/V^2$	-17 %
Full-load speed		-1.5 %	–	+1 %
Efficiency	Full load	-2 %	–	Slightly increased
	3/4 load	Actually no change	–	Actually no change
	1/2 load	+1 ~ 2 %	–	-1 ~ 2 %
Power factor	Full load	+1 %	–	-3 %
	3/4 Load	+2 ~ 3 %	–	-4 %
	1/2 Load	+4 ~ 5 %	–	-5 ~ 6 %
Full-load current		11 %	–	-7%
Starting current		-10 ~ 12 %	V	+10 ~ 12 %
Full-load temperature rise		+6 ~ 7 °C	–	-1 ~ 2 °C
Magnetic noise		Slightly decreased	–	Slightly increased

a. Study when the supply voltage is lowered

To operate with the supply voltage lowered below the rated voltage, it is necessary to check accelerating torque during starting and the value of the peak load because the starting torque and maximum torque decrease at a rate of the square of the voltage as shown in Table 12.12.

Since the load current increases in inverse proportion to the voltage even if the total loss decreases, the motor copper loss increases, thus increasing the winding temperature and the line loss of distribution line, etc. Care should be taken. Therefore, the lower limit of the supply voltage should be determined within a range not to exceed the motor rated current.

b. Study when the supply voltage is raised

When operated with the supply voltage raised above the rated voltage, saturation of the magnetic flux increases the exciting current remarkably, causing lowered power factor, unusual magnetic noise and an unusually heated iron core due to increased iron loss, etc. Also, since the motor output torque increases at a rate of the square of the voltage, it is necessary to check whether the machine is ruined by excessive torque.

c. Study of entire equipment

Many motors are usually connected to the same distribution system and operated, but the individual motors are rarely operated under the same load conditions. Some of them are operated at close to the rated load and the rest may be operated at a load 50 % or below. Since it is not possible to determine the supply voltage uniformly under such a condition, it is necessary to study the entire equipment.

1) When motors operated at light load hold an overwhelming majority, lower the distribution voltage and replace a few heavy-loaded motors with one rank higher capacity. In this case, if there are any unused motors available, study whether they are utilized or whether they are exchanged between respective equipment.

2) When motors operated at heavy load hold an overwhelming majority, maintain the distribution voltage at the motor rated voltage value and lower the output capacity of a few light-loaded motors by one rank. Also in this case, study utilization of any unused motors and exchange between respective equipments.

3) When large-capacity motors are operated at heavy load and other small-capacity motors at light load, separate the distribution system for only large-capacity motors from others and lower the supply voltage for the light-loaded motor group.

Besides the above, various combinations are considered and, as such, study on a case-by-case basis. In any case, when replacement and installation of new motors are involved, it should be determined by taking into consideration the equilibrium between the investment amount and conservation energy charge due to improvement of the efficiency.

Another problem with voltage control is the unbalanced voltage.

When unbalanced voltage is applied to a three phase AC motor, unbalanced current of zero-phase-sequence, positive-phase-sequence and negative-phase-sequence component current flows. Of these, the zero-phase-sequence component current, its resultant magnetomotive force being zero, induces no voltage in the secondary winding and, as such, no torque is generated. However, the magnetic field due to the negative-phase-sequence component rotates at synchronous speed in the opposite direction to the magnetic field due to the positive-phase-sequence component current, thus inducing a voltage having a frequency of ω_0 (2-S) where s represents sliding in the secondary winding - then current flows and torque is generated. This torque is called "Negative-phase-sequence component torque".

This negative-phase-sequence component torque increases the copper loss remarkably, because the torque is going to rotate the motor in the reverse direction. As a result, the motor efficiency lowers.

Therefore, it is necessary to minimize the unbalance factor of supply voltage as much as possible and it should be controlled within 1 to 2 %. When a single phase load is applied to a three phase AC power source, the current during each phase becomes unbalanced and voltage drops as each phase differs, causing unbalanced voltage. Therefore, it is important to electrically arrange a single phase load properly so that each phase is balanced.

(2) Prevention of idle running and reduced starting loss

Since a motor is sure to be connected to the opposite machine, electric power consumed at no-load running will be about two to three times that of the motor itself. Accordingly, it is important for electric power conservation to stop the motor when unnecessary. Also, in this case, it is desirable to stop the motor cooling fan and field system for the DC motor. At this time, the precautions are as follows:

a. Deterioration and output drop of motors due to multi-frequency starting should be restricted within a range so that they can be used as usual.

   In the case of large-capacity motors 100 kW or more and motors with high GD^2 as a load such as blower, etc., it is recommended to consult with the motor manufacturer.

b. Electric energy during starting should not exceed the electric energy during idle running.

Generally, to re-start a motor, care should be taken, because certain starting methods cause a considerable amount of loss. Starting loss of induction motors and its countermeasures are described as follows:

1) Starting loss of three phase induction motors

Internal loss W_ℓ of a motor when accelerated from a state of slip S_1 to a state of S_2 is generally expressed by the following equation:

$$W_\ell = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (S_1^2 - S_2^2)(1 + \frac{r_1}{r_2'}) \frac{T_m}{T_m - T\ell} \quad \cdots\cdots\cdots (14)$$

The loss from state of stop to synchronous speed is calculated as

$S_1 = 1, S_2 = 0,$

$$W_\ell = \frac{1}{2}\cdot\frac{GD^2}{4}\omega_0^2\left(1+\frac{r_1}{r_2'}\right)\frac{T_m}{T_m - T\ell} \qquad \text{(15)}$$

Where

r_1 : Primary resistance of induction motor (Ω)
r'_2 : Secondary resistance of induction motor (Primary side converted value) (Ω)
T_m: Accelerating torque of induction motor (Mean value) (N·m)
T_ℓ : Mean torque of load in acceleration (N·m)
ω_0: Synchronous angular velocity

2) Reducing method of starting loss

Equation (15) shows that the following will reduce the starting loss.

① Start with a higher motor generated torque.

② From the standpoint of operation efficiency, it is desirable to start with the motor torque as high as possible. Starting with reduced voltage or with reduced current to restrain the starting current lowers the motor torque thus increasing the loss.

Therefore, it is desirable to directly start as far as the power source circumstances permit.

③ Increase the secondary resistance when starting.

When a wound-rotor type induction motor is used, inserting a high external resistance when starting will not only greatly reduce the entire motor loss including the external resistance, but also restrain rotor heat and starting current.

④ Change the synchronous angular velocity ω_0.

Changing the synchronous angular velocity ω_0 of induction motor together with a rise in the motor speed greatly reduces the loss during starting.

To change this ω_0, there are two methods; one is to switch the synchronous angular velocity to step-wise using a pole change motor, and the other is to continuously change the power source frequency together with the speed.

Taking the case of two-step pole change induction motors, we will explain. First, starting with the low-speed side winding, accelerate to the synchronous angular velocity ω_{OL} of the low-speed winding (Number of poles: P_L), and switching to the high-speed winding side, accelerate to the synchronous angular speed ω_{OH} of the high-speed winding (Number of poles: P_H). Total loss of the motor during this period $W_{2\ell}$ will be determined as follows. For simplification, it is assumed in equation (14) that $r_1 = 0$, $T_\ell = 0$.

$$W_{2\ell} = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_{OL}^2 (1^2 - 0^2) + \frac{1}{2} \cdot \frac{GD^2}{4} \omega_{OH}^2 \left\{ \left(\frac{\omega_{OH} - \omega_{OL}}{\omega_{OH}} \right)^2 - 0^2 \right\} (J) \quad \text{.............. (16)}$$

Assuming pole ratio $n = \frac{P_L}{P_H} = \frac{\omega_{OH}}{\omega_{OL}}$

$$W_{2\ell} = \frac{1}{2} \cdot \frac{GD^2}{4} \cdot \omega_{OH}^2 \left(1 + \frac{2}{n^2} - \frac{2}{n}\right)(J) \quad \text{.............. (17)}$$

Assuming the reduction factor for the loss when started with only the high-speed winding from the beginning as Ka, Ka is expressed by the following equation:

$$K_a = \frac{\text{Loss during starting with pole change}}{\text{Loss during starting with only high-speed winding}} = 1 + \frac{2}{n^2} - \frac{2}{n} \quad \text{.............. (18)}$$

The pole ratio at which the loss is minimized in the above equation is determined by a condition of $dK_a/dn = 0$ and the loss will be 1/2 when $n = 2$. Moreover, increasing numbers of poles changing steps will reduce the loss further.

The following measures are effective in preventing idle running.

- Installation of an idle running alarm device
- Automatization of the process and equipment
- Reduction of the waiting time for handling the treated matter by improving the equipment layout and jigs and tools

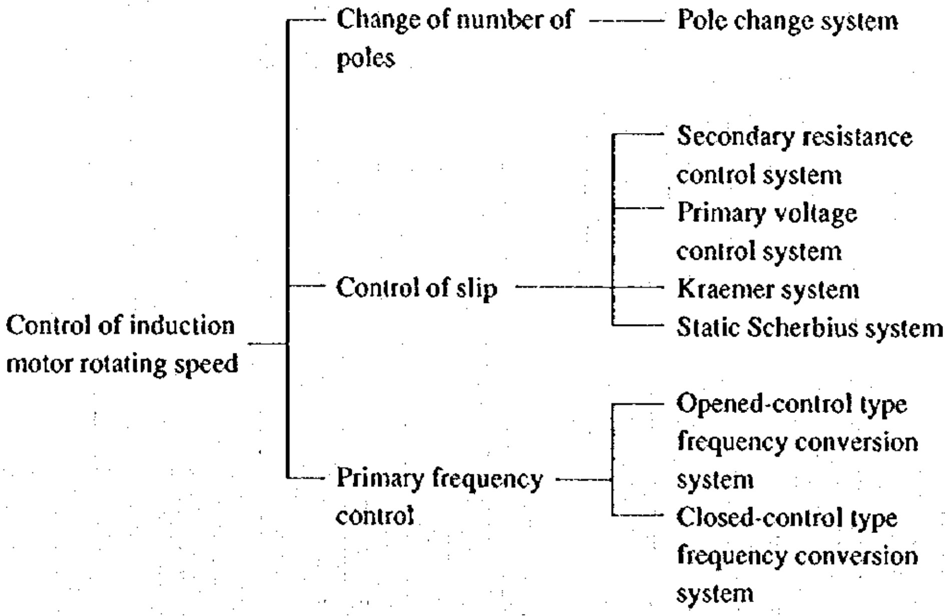
(3) Control of induction motor rotating speed

Control of induction motor rotating speed is widely used for energy conservation of pump, fan, blower and motor for crane. Induction motor rotating speed is generally expressed by the following equation:

$$N = \frac{120f}{P}(1 - S) \quad \text{.............. (19)}$$

As can be seen from the above equation, the induction motor rotating speed is controlled by any changing of the number of poles P, changing slip S or changing power source frequency f. Rotating speed control systems classified by these control factors are as shown in Figure 12.25.

Figure 12.25 Classification of Rotating Speed Control



Of these, the primary frequency control system (VVVF) can be materialized from the standpoint of remodelling the existing equipment and as such it will be described.

The primary frequency control system controls the primary voltage and frequency of the motor at the same time, by means of a frequency converter, to change the synchronous speed.

This control system is mainly divided into opened-control and closed-control types. Of these, the opened-control type is open-loop control in which the converter frequency is determined based on frequency instructions from a setting apparatus irrespective of changes in state such as the motor rotating speed, torque, etc. On the other hand, the closed-control type is closed-loop control in which the converter frequency is controlled according to changes in state of the motor. The opened-control type has V/f constant control in which the ratio of the motor primary voltage V to frequency of (V/f) is constant. The closed-control type has slip frequency control and vector control.

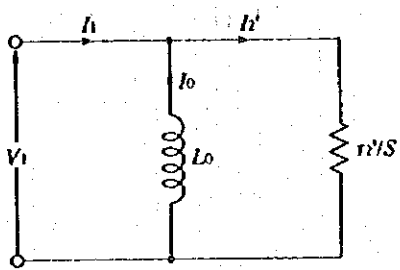
For a characteristic equation during primary frequency control of induction motor, approximations and simple equivalent circuits can be obtained if attention is given to the following points.

Exciting circuit is represented by exciting inductance L_0. Since operated at close to the synchronous speed with this system, the characteristic equation is approximated by a condition of $S \fallingdotseq 0$.

The simple equivalent circuit prepared under this condition is shown in Figure 12.26.

Therefore, approximation of the characteristic equation can be expressed by the following equations:

Figure 12.26 Simple Equivalent Circuit of Induction Motor at Slip $\fallingdotseq$ 0



Equivalent circuit during operation near synchronous speed

$$I_1 = I_0 + I'_2 \, [A] \quad \text{......} (20)$$

$$I_0 = \frac{V_1}{\omega_0 L} [A] \quad \text{......} (21)$$

$$I'_2 = \frac{SV_1}{r_2'} = \frac{S\omega_0}{r_2'} \frac{V_1}{\omega_0} [A] \quad \text{......} (22)$$

$$T = \frac{3SV_1^2}{\omega_0 r_2'} = 3\frac{S\omega_0}{r_2'}\left(\frac{V_1}{\omega_0}\right)^2 [N \cdot m/rad] \quad \text{......} (23)$$

On the other hand, assuming the voltage factor as Kv, the magnetic flux ϕ is

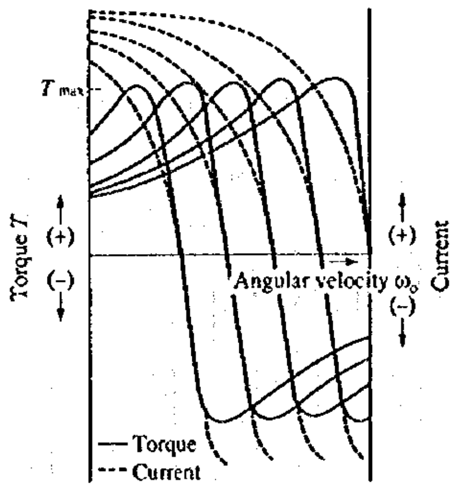
$$\phi = \frac{V_1}{K_v \omega_0} = K_1 I_0 [W_b] \quad \text{......} (24)$$

where

$$K_1 = \frac{L_0}{K_v}$$

When control (V/f constant control) is performed so that the ratio of voltage V_1 to frequency ω_0 in the above characteristic equation is constant, the motor torque, current I_0, I_2 and magnetic flux ϕ become constant at constant slip frequency $S\omega_0$. Figure 12.27 shows torque-speed characteristic curve at this point and the maximum torque T_{max} becomes constant against speed ω_0.

Figure 12.27 Torque-Speed Characteristics of V/f Constant Control



Inverters are usually used for the VVVF system. Characteristics of rotation control by an inverter are shown below.

a. Can easily control a squirrel-cage induction motor without any additions except VVVF
b. Can apply stepless rotation control effectively in a wide range.
c. Power factor is high. Power capacity can be small for starting up.
d. Can reverse rotation direction electroniclly.
e. Can start and stop high-frequently.
f. Can apply breaking control electrically.
g. Suitable for rotation control of a motor placed in a severe environment.
h. Can control rotation of multiple motors at a time.
i. Can easily obtain constant torque characteristics and constant output characteristics.

As problems raised from introduction of an inverter, the following can be named: troubles by harmonic waves, troubles by speed control of general purpose motors, and troubles by operation switching between direct and inverter operations. Table 12.13 shows troubles and measures accompanied with the introduction of an inverter.

Table 12.13 Troubles and Measures Accompanied with Introduction of Inverter

No.	Trouble	Measures
I	Trouble by harmonic waves	
1	• Metallic sound is generated from motor.	• Insert an AC reactor between inverter and motor.
2 3	• Condensive capacitor or fluorescent lamp is heated. • Input transformer generates heat or causes vibration.	• Insert an AC reactor to the receiving side.
4 5	• AM broadcast on radio cannot be heard due to noise. • Electronic devices such as measuring instruments cause error.	• Install a noise filter. • Place an inverter in an iron case and earth the case. • Earth the motor frames. • Place input/output cables in an iron pipe and earth the pipe.
6	• Earth leakage breaker operates erroneously.	• Shorten connecting wire between inverter and motor. • Use breaker dedicated to inverters.
II	Troubles by speed control of general purpose motors	
7	• Resonance occurs between motor and the other machine. As a result vibration and noise are generated.	• Use tire-type coupling between motor and the other machine.
8	• Self-cooling efficiency of motor lowers. Temperature rises.	• Fit a forced cooling fan.
III	Troubles by operation switch between direct and inverter operations	
9	• Life of relay shortens due to frequent switching.	• Review control method.
10	• The device stops due to instantaneous power cut when switching.	• Check sequence control circuit.
11	• Adjust time of motor after switching is too long.	• Increase the capacity of inverter.

(4) Other countermeasures

Diagnose the present equipment capacity. When the equipment capacity is too large as compared to the production scale, it is important for energy conservation to reduce the rotating machine and equipment output. For example, with motors being used as-is, the power to drive the load can be reduced by changing the power transmission mechanism (diameter of a pulley, or reduction ratio of gear etc.). Also, when there are stand-by motors, the energy can be saved by replacing them with smaller motors or lower rotating speed motors.

12.4 Compressors

Energy conservation countermeasures for pneumatic systems are mainly divided into for air compressor, piping and air-operated apparatus.

Power used for compressors is generally given by the following equation:

$$L = \frac{(a+1)K}{K-1} \cdot \frac{P_S Q_S}{6120} \cdot \left[\left(\frac{P_d}{P_S}\right)^{\frac{K-1}{K(a+1)}} - 1\right] \cdot \frac{1}{\eta_c \eta_t} \quad \text{(1)}$$

L : Required power (unit kW)
P_s : Absolute pressure of intake air (unit; kg per square m)
P_d : Absolute pressure of discharge air (unit; kg per square m)
Q_s : Amount of air per unit time converted to a state of intake (unit; cubic m per minute)
a : Number of intercoolers
K : Adiabatic coefficient of air
η_c : Overall adiabatic efficiency of compressor
η_t : Transfer efficiency

Values η_c and η_t shall be given by the manufacturer.

Accordingly, to reduce power for compressors,

(1) Lower temperature of intake air. Also, improve the cooling effect in the intercooler.

(2) Lower the discharge pressure. Also, reduce the amount of air used.

(3) Select compressors and systems with good efficiency.

(4) Prevent air leakage from the compressor proper and piping, etc.

(5) Intensify management for the entire system for compressed air.

The above items are important. Respective items will be described below.

12.4.1 Intake Air Temperature and Intercooler

When intake temperature rises, air density generally becomes smaller and the actual volume of air sucked with the same power reduces. Since this relation is in inverse proportion to the absolute temperature of intake air, for example, changing intake side temperature from 35 °C to 25 °C reduces power cost by 3.3 %.

Therefore, the air intake opening should be located at a cool place where it is not exposed to the direct rays of the sun.

Insufficient cooling in the intercooler brings air compression close to adiabatic compression and increases the compression power on the second stage and after. Since lowered efficiency of the intercooler is caused possibly by lowered heat transfer efficiency due to adherence of scale or slime, or insufficient amount of cooling water, it is necessary to clean the inter-cooler and work out other appropriate countermeasures.

12.4.2 Discharge Pressure and Amount Used

In equation (1), lowering discharge pressure of the compressor reduces the axial power greatly.

Table 12.14 shows an experimental example of a compressor actually in use and the required power could be reduced by about 4 % by lowering the service pressure 1 kg/cm².

Table 12.14 Actual Measurement Example of Compressor Performance

(1) Discharge pressure and motor input (kW)

Pressure (kg/cm²G) Load (%)	7	6	5	4	3
100	226	216	205	190	166
50	156	150	144	134	120

(2) Load (flow rate) and motor input

Load	(%)	0	50	100
Discharge amount	(m³/min)	0	20	40
Input	(kW)	44	132	220

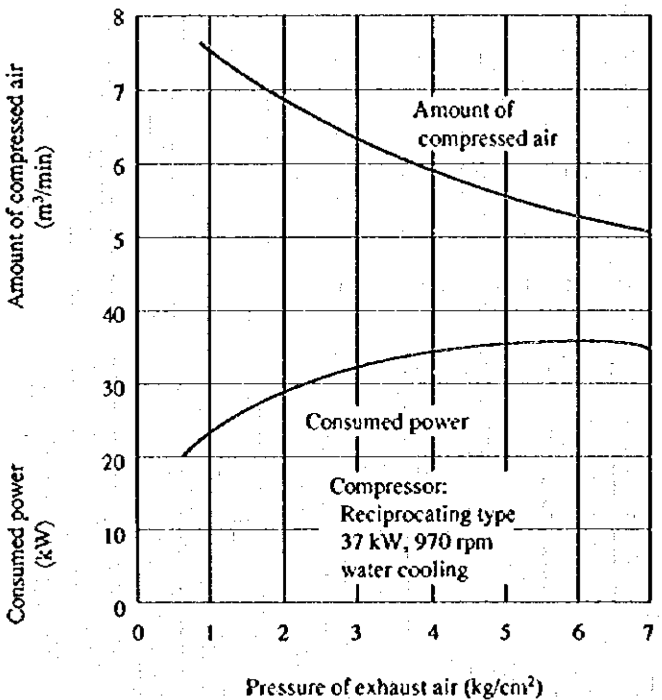
(3) Compressor specification

Discharge pressure	(kg/cm²G)	7
Discharge amount	(m³/min)	40
Capacity adjustment	(%)	0, 50, 100 3 stage
Motor		3.3 kV 220 kW

Figure 12.28 shows an example of characteristics of 37 kW air compressor.

Generally, when the same operation is performed, many machines and tools having the same capacity differ in the pressure of air required by them. Therefore, if possible, study thoroughly and standardize service pressure of machines and tools in the whole factory to the lower one, to reduce the required electric power.

Figure 12.28 Characteristics of 37 kW Air Compressor



When there is equipment requiring high compressed air such as pressing machines in the factory, it is economical to install a booster for exclusive use.

Also, since reduction in the amount of air used is almost in proportion to reduction in the power cost, it is better not to use compressed air for cooling, cleaning, etc., if possible, and it is also better to control the condition for use thoroughly by re-checking the nozzle diameter, etc.

12.4.3 Selection of Kinds of Machines and Operation Systems

The air compressors have the following tendencies from the standpoints of efficiency and it is important to take them into consideration when selecting the kinds of machines:

(1) The larger the compressor capacity is, the higher the efficiency will be.

(2) The more the number of compression stages is, the higher the efficiency will be.

(3) When operated with the load factor nearer to 100 %, the efficiency will be higher.

Therefore, in a factory where small-scale operation is performed during holidays, operating a large-capacity compressor causes a great power loss and, therefore, it is advisable to separately install a small-capacity compressor which is capable of operating at a load close to 100 % on holidays.

Also, when two or more compressors are operated in parallel, it is important to control the number of the compressors in order to make the compressor load factor as high as possible. When the load fluctuates, operate the rotary type compressor at base load and operate the reciprocating type compressor to correspond to the fluctuating load. This serves for energy conservation in the respect of efficiency of both types. Table 12.15 shows classification of air compressors by pressure range.

Table 12.15 Classification of Air Compressor

Type	Class	Main pressure range (kg/cm^2)	Applications
Reciprocating compressor	General purpose compressor	7 ~ 8.5	2 stage compressor for 100 kW or more
	Intermediate pressure compressor	10 ~ 100	Standard type for 1,000 kW or less
	High pressure compressor	150 ~ 1,000	For petroleum refining, petrochemical and general chemical industry processes
	Superhigh pressure compressor	1,500 ~ 3,500	For synthetic chemistry such as ammonia, methanol and hydrogenation. Mostly large scale such as several thousand kW.
	Oilless compressor	7 ~ 8.5	Mainly, ethylene compressor for synthesis of polyethylene and ethylene.
Rotary compressor	Variable profile compressor	1 Stage 2 Stage	Oxygen gas, air for food processing industry and instrumentation, etc.
	Screw compressor	1 Stage 2 Stage	Air capacity 2~60 m^3/min.

12.4.4 Air Leakage from Clearance, Hole, etc.

(1) Air leakage

Flow rate Q when air flows out from a vessel with a pressure of P_1 inside into a space at pressure of P_2 is given from Bernoulli's equation

$$Q = S\sqrt{\frac{2g(P_1 - P_2)}{\gamma}} \text{ [m}^3\text{/S]} \quad \cdots\cdots (2)$$

where

g : Acceleration of gravity 9.8 (m/S^2)
γ : Specific weight of air (kg/m^3)
S : Effective cross section (m^2)
P_1, P_2: Absolute pressure inside and outside vessel (kg/m^2 abs)

Actually, compressibility and adiabatic expansion become problems and as a practical equation,

$$Q = C \cdot S \sqrt{\frac{2g(P_1 - P_2)}{\gamma}} \, [\mathrm{m^3/S}] \qquad (3)$$

where

C: Discharge coefficient

Since the loss due to this air leakage is very great, it is necessary to check the piping, etc. for leakage and, if any, to repair and correct immediately. The leakage is in proportion to $\sqrt{P_1 - P_2}$ in equation (3) and, as such, reducing the service pressure surely reduces the leakage. Figure 12.29 shows the blow-off air amount from a small diameter orifice.

Figure 12.29 is used to determine the blow-off air amount when there is a sufficient large capacity receiver tank and piping as compared with the size of the blow-off nozzle. It is assumed that pressure in the tank and piping remains unchanged during blow-off at normal temperatures. The blow-off air amount is converted to a standard condition (20 °C, 1 atmospheric pressure).

To apply practically, use selectively a value multiplied by 0.97 to 0.65 because values in Figure 12.30 are based when discharge coefficient c = 1.

Figure 12.29 Compressed Air Pressure and Blow-Off Air Amount from Nozzle

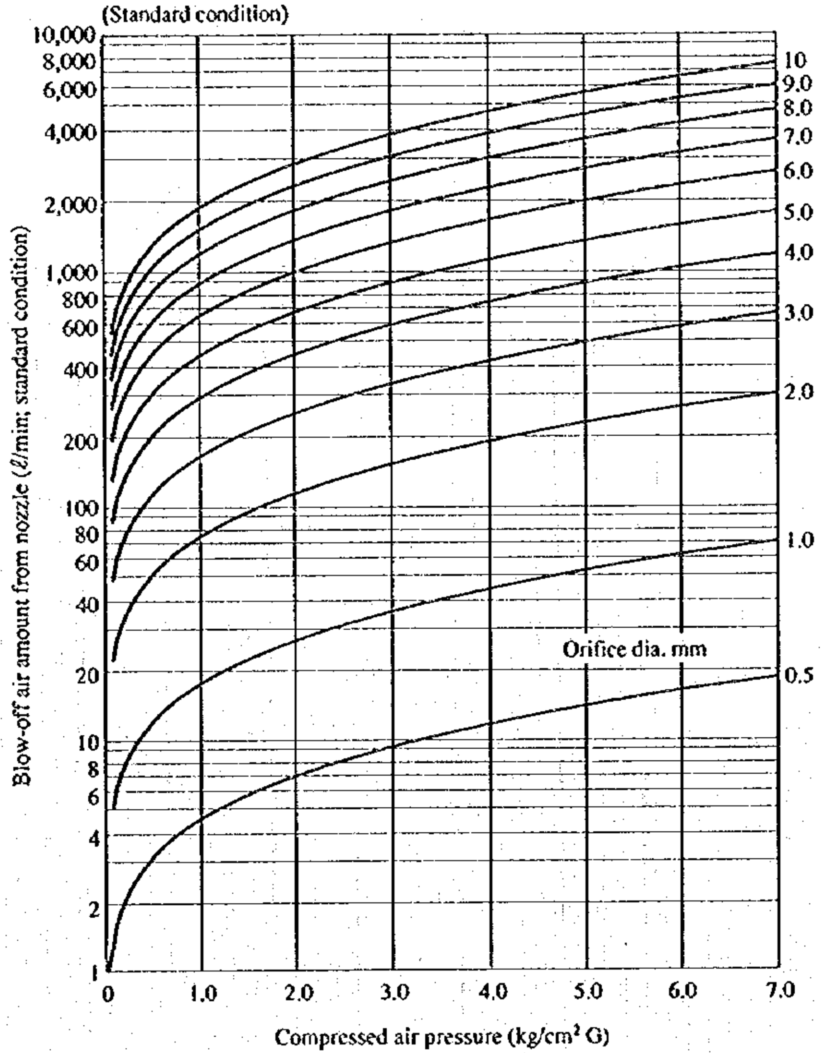
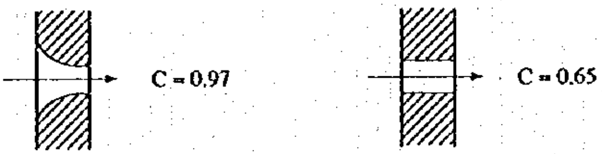


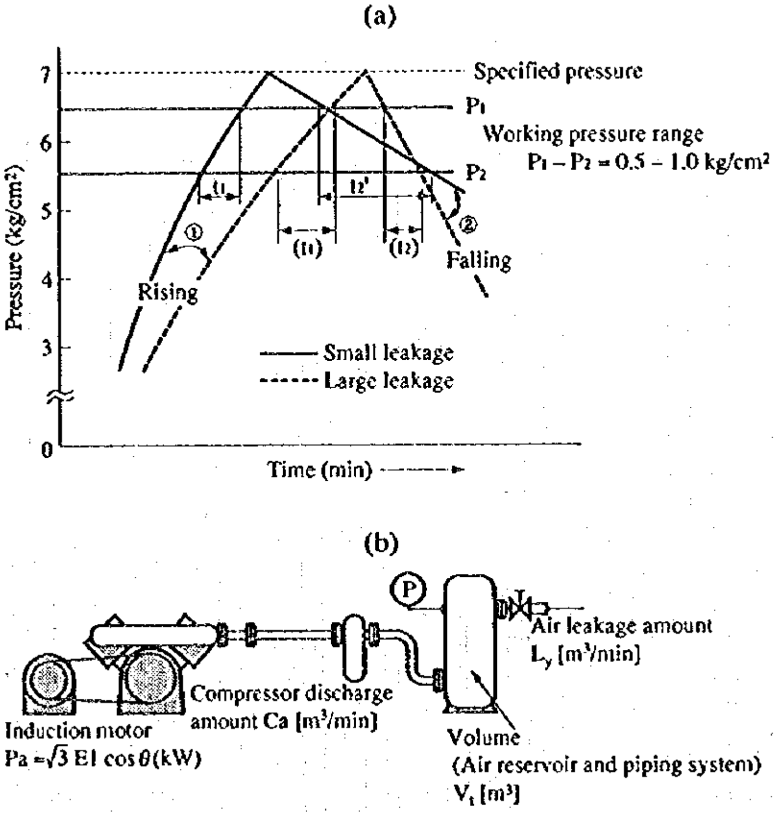
Figure 12.30 Shape of Orifice and Value of Discharge Coefficient



(2) Measurement of air leakage

It is possible to measure air leakage of the compressed air piping system in the following way: first, operate a compressor with the end closed and the pressure gradually rises as shown by (①) in Figure 12.31 (a). Stop the compressor at the specified pressure and let stand as-is, then the pressure will lower the air leakage as shown by (②). In the case of (a), it shows that the solid line has less leakage than the dotted line.

Figure 12.31 Pressure - Time Curve



C_a: Compressor discharge amount
L_y: Air leakage amount
t_1 : Tmie required for pressurizing
t_2 : Time required for lowering

Assuming that pressure range (P_1 to P_2)is treated as a pressure to be practically used, and t_1, t_2 are treated as shown in the figure, the following equation is formed.

Assuming volume of compressor equipment, piping system, etc. as V_t,

$$V_t = t_1 (C_a - L_y) = L_y t_2 (m^3)$$

When air leakage L_y is determined from the above equation,

$$L_y = \frac{C_a t_1}{t_1 + t_2} (m^3/min)$$

Air leakage factor L_p (%) is

$$L_p = \frac{L_y}{C_a} \times 100 = \frac{t_1}{t_1 + t_2} \times 100(\%)$$

Air leakage is measured by measuring compressor equipment (compressor proper, intercooler, air tank, etc.), piping system, pneumatic machine, control circuit, etc. in the group unit using the sound and the daubed soapy water.

12.4.5 Management of Compressed Air Equipment

Precautions for management of compressed air system are as follows:

(1) Management of compressor

To operate compressors in a stable condition at all times, items to be daily checked are:

a. Is cooling water for compressors, aftercoolers, etc. well supplied?

b. Is not generated heat of compressors unusually high?

c. Is the pressure switch for unloader normally operating? Also, is the set value for the pressure switch proper?

d. Does not the compressor give unusual noises?
Also, is the vibration within a normal range?

e. Is the amount of the lubricating oil normal?
Is normal lubricating oil used?

f. Is not the intake side filter clogged?

g. Does the safety valve normally operate?
Is the set value for the safety valve normal?

h. Is the indicated pressure on the pressure gauge normal?
Also, is not the pressure gauge out of order?

i. Is the air tank drain ejector operating normally?

j. Is the intercooler operating normally?

(2) Control of pressure

To control pressure, it is necessary to know the following points:

a. What is the minimum pressure of the line required?
: the minimum pressure to get stable control.

b. What is the maximum pressure of the line?
: the maximum pressure to get stable control.

c. What is the proof pressure of the line?
: the pressure at which the control equipment will be damaged.

Set the pressure switch, safety valve and relief valve after knowing the above matters. Items to check in this case are as follows.

a. Are the set values for the pressure switch, safety valve and relief valve in the air tank and piping proper?
Are they operating normally?

b. Is the check valve to prevent back flow of air operating normally?

c. Is the regular operating normally?

d. Is the pressure gauge used in the line normal?
Is not the indication out of order?

(3) Control of drain

For the drain valve installed where drain collects, always discharge drain at least once a day (preferably in the morning when the equipment is operated).

Check Items:

a. Discharge drain by means of the drain valves installed in the air tank, piping down portion, end of the piping and air filter.

b. Is the automatic drain apparatus operating normally?

c. For the air filter and automatic drain apparatus, etc., clean the internal elements periodically.

(4) Control of pipe

Since air leakage causes energy loss and lowered pressure, take care to prevent leakage as much as possible.

Check Items:

a. Does not air leak due to looseness of joints?

b. Does not air leak due to breakage of pipe, hose or tubes?

c. Can the stop valve, etc. be securely closed?

12.5 Blowers (Fan and Blower)

12.5.1 Characteristics of Blowers

Although blowers and compressors have the same principles, below 1 mAq, 1 mAq to below 10 mAq (1 kg/cm^2) and 10 mAq, or the above in discharge pressure are usually called "Fan", "Blower" and "Compressor" respectively.

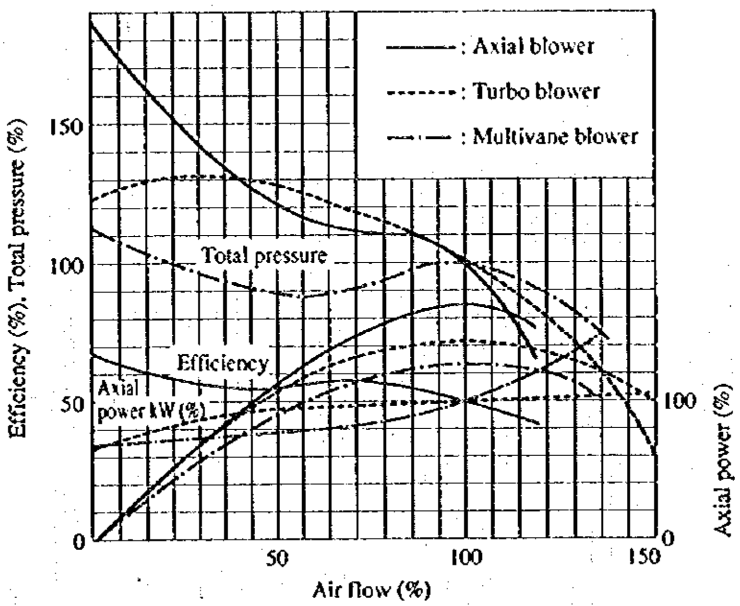
For classification, they are mainly divided into turbo types and displacement types according to the operating principle, and the turbo type is further classified into an axial-flow system and centrifugal system.

Table 12.16 and Figure 12.32 show characteristics of blowers and the characteristic curves respectively.

Table 12.16 Characteristic Comparison of Blowers

System Item	Axial flow system	Turbo system	Multivane system	Radial system
Range of use	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2
Efficiency (%)	80 - 92	70 - 85	50 - 60	60 - 70
Efficiency curve	When varied from the planned air capacity, rapidly decreases.	Shows no rapid decrease.	Comparatively smooth	Shows no rapid decrease.
Starting	Fully open damper.	Fully close damper.	Fully close damper.	Fully close damper.
Noise (dB)	39 - 55	32 - 44	22 - 41	28 - 42
Limit surging air capacity (%) (against air capacity at maximum efficiency point)	70 - 80	30 - 60	60 - 80	50 - 70
Applications example	For ventilation fan (buildings, architecture, tunnel), for boiler forced draft, for induced exhaust, for mine blower	For various blowers for steel mills, for dust collecting tunnel ventilation, for boiler forced draft, for induced exhaust, for cement kiln exhaust	For various blow and exhaust for steel mills, for boiler forced draft, for building and tunnel ventilation.	For various blow and dust collection for steel mills, for boiler induced draft, exhaust for gas re-circulation, for cement kiln exhaust

Figure 12.32 Characteristic Curve for Various Blowers



(1) Turbo types

The turbo types have two systems: centrifugal system, and axial-flow system. In the former, centrifugal force is involved in rotation of impellers housed in the casing which provides the gas with speed energy, while in the latter, pressure and speed energy are provided while the gas is being flowed in the direction of rotation by rotating impeller blades with the blade section in the straight pipe. "Turbo type blowers" is a general term for these types.

(2) Displacement types

In the displacement types, the gas is sucked in a chamber with a specified volume, the inlet port is closed and the gas is pressed out to the discharge opening separately provided while the chamber is being pushed, lessened and compressed. This operation is repeated. The gas is pushed out by means of piston reciprocating operation or rotary operation of cocoon type (roots type) rotor.

12.5.2 Required Power of Blowers

(1) Air power (L_T)

Air power means effective energy given to air by a blower in unit time.

$$L_T = \frac{K}{K-1} \cdot \frac{P_{t1} \cdot Q}{6,120} \left\{ \left(\frac{P_{t2}}{P_{t1}}\right)^{\frac{K-1}{k}} - 1 \right\} \text{[kW]} \quad \text{.......... (1)}$$

where

P_{t1}: Absolute pressure on suction side (kg/m² abs)
P_{t2}: Absolute pressure on discharge side (kg/m² abs)
Q : Air flow (m³/min)
K : Specific heat ratio (1.4 for air)

When the pressure ratio is 1.03 or below, it may be calculated by the following equation:

$$L_T = \frac{QP_T}{6{,}120} [\text{kW}] \quad \cdots\cdots (2)$$

where

P_T: Total pressure of blower (mmAq)

(2) Axial power (L)

Axial power is obtained by dividing the air power by the blower efficiency (η_F).

$$L = \frac{L_T}{\eta_F} (\text{kW}) \quad \cdots\cdots (3)$$

The efficiency varies with the air flow as shown in Figure 12.32, but is generally displayed by that during rated air flow. Its approximate figures are shown in Table 16.

(3) Motor output

Induction motors with simple construction and low-cost are generally used for blowers. Squirrel cage type induction motors are used for comparatively small-capacity blowers. In this case, since the inertia (GD^2) of the blower impeller is great, it is necessary to select after due consideration. The motor output (L_M) is determined by the following equation:

$$L_M = L \times \phi \frac{1}{\eta t} (\text{kW}) \quad \cdots\cdots (4)$$

where

ϕ: Allowance rate
η_t: Transfer efficiency

Values of ϕ and η_t are from Table 12.17 and Table 12.18.

Table 12.17 Value of η_t

1 stage parallel shaft type gear reducer with transfer power of 55 kW or less	1 stage parallel shaft type gear reducer with transfer power of 55 kW or more	Constant speed type fluid coupling with transfer power of 100 kW or less	Constant speed type fluid coupling with transfer power of 100 kW or more
0.95	0.96	0.94	0.95

V-belt	Flat belt	Direct-coupled
0.95	0.90	1.00

Table 12.18 Value of ϕ

Propeller fan	Disk fan	Multivane fan	Turbo fan	Plate fan	Profile type fan
1.30	1.50	1.30	1.15	1.25	1.15

12.5.3 Electric Power Conservation for Blowers

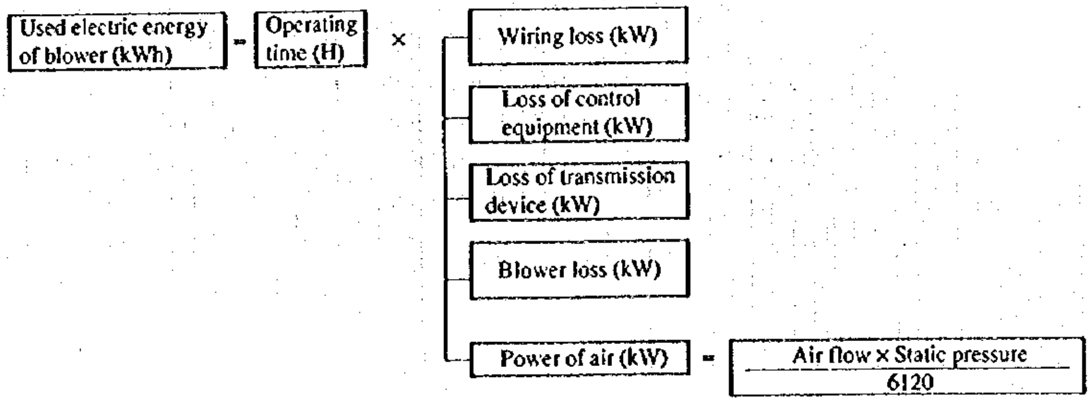
Factors for blower electric power conservation are shown in Figure 12.33.

Namely, the fundamental conception of the electric power conservation is:

- Reduce the operating time.
- Adopt high-efficient equipment.
- Reduce air power.

These will be described as follows:

Figure 12.33 Factors for Blower Electric Power Conservation



(1) Reduce the operating time

Too early start of blowers before the factory operation starts, or very late stop of blowers after close of the factory is often seen in factories. Also, blowers in operation, although the entire factory is at a stop because of some troubles, are often seen in general factories. Since such useless operation of blowers is a significant adverse factor for energy conservation, it is necessary for the factory manager to give special attention.

The most direct method to eliminate this useless operation of blower is ON-OFF operation of blowers. Countermeasures and precautions for prevention of general idle operation for motors were described in the section for Motors. However, blowers generally have great GD^2 and special precautions for ON-OFF operation are as follows:

a. Check the motor for mechanical and electric life

When new equipment is established, the daily number of times for start-up as the conditions is indicated to the manufacture and the equipment fit for the condition is ordered. Therefore, there will be no problem. However, when the blower being almost continuously operated at present is going to be changed to operate to this system, it is necessary to carefully study problems concerning mechanical strength and heat, etc. of the motor caused by frequent start-up.

b. Voltage drop of power source

Since the blower has been started while other loads are at a stop, voltage drop to the starting current has not become a problem. However, when ON and OFF is repeated while other loads are in operation, troubles by voltage drop of power source may occur.

Electric machinery and apparatus are generally designed to perform their functions even at a voltage drop of about 10% and they are likely to cause trouble at a voltage drop of more than that. Therefore, in this case, appropriate countermeasures such as reactor starting or adoption of VVVF will be required.

c. Life of starting equipment

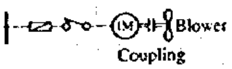
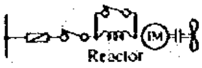
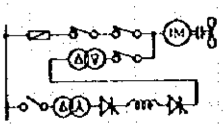
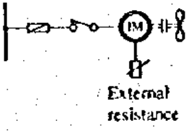
Reactors for start-up and starting compensator are generally of a short-time rating and when they are changed to very frequent use, the temperature of winding in these equipment will increase, possibly resulting in insulation deterioration and a burning accident. Therefore, for very frequent use, it is necessary to carefully study the temperature rise beforehand.

d. Others

Precautions other than the foregoing are for generated heat for power source cable and life of switches, etc.

Table 12.19 and Table 12.20 show comparison of various starting systems when an induction motor is used for a blower, and general life of switches respectively.

Table 12.19 Comparison of Various Starting Systems

Starting system	Composition diagram	Starting current	Starting torque	Voltage when starting	Electro-magnetic force	Armature heating capacity	Problems when starting at multi-frequency
Direct starting		100 (6 to 7 times full-load current)	100 (About 150 % on rated torque)	100	100 (In proportion to square of current)	$100\left(\frac{GD^2 \cdot N_0^2}{730}(J)\right)$	Power voltage drop, Motor life, Breaker life
Reactor starting		50,65,80	25, 42, 64	50, 65,80 (Standard tap)	25, 42, 64	100	Reactor heating capacity, motor life, breaker life
Closed circuit transition auto-transformer starting		25, 42, 64	25, 42, 64	50, 65, 80 (Standard tap)	25, 42, 64	100	Starting compensator heating capacity, motor life, breaker life
VVVF Starting		17 or less (Any value below rated current)	70 or less (Any value below rated torque)	0 - 100 (In proportion to speed)	2 - 3 (Large when there is inrush current)	Hardly any	Transient torque (when switched from VVVF to main power source), inrush current (when switched from VVVF to main power source), effects from higher harmonic (motor temperature rise, occurrence of shaft voltage, resonance of pulsating torque and shaft torsion, surging voltage when commutating)
Secondary side resistor starting (limited to wound-rotor type)		18 - 40 (Optional)	80 - 200 (Optional)	100	3 - 16	Hardly any (Consumed by external resistance)	External resistance heating capacity, breaker life, slip ring heating capacity, mechanical life of brush lifting mechanisms, life of motor for brush lifting

Note (1) Value at direct starting is regarded as 100 %.

(2) Starting torque is generated torque of motor and shall be (Starting torque + Stalling torque)/2.

Table 12.20 Life of Switch (when not repaired)

	Mechanical life		Electrical life (rated current opening and closing)
Oil breaker	10,000 times		2,000 - 5,000 times
Vacuum breaker	10,000 times	Possible also for 50,000 times	10,000 times
Gas (SF6) breaker	10,000 times		10,000 times
High voltage electromagnetic contactor	5 million times (Class 1)		500 thousand times (Class 1)

(2) Adopt high-efficiency equipment

Remarkable points are:

a. Efficiency of blowers

b. Efficiency of power transmission equipment

c. Efficiency of motors.

Especially for blowers, it is necessary to select the optimum type according to fluctuation range for air flow, pressure and temperature.

Recently, new products with higher efficiency by improving shape of blade, even of the same type, have been developed.

(3) Reduce air power

As described in the section for compressors, lowering the air flow, pressure and intake temperature reduces the required power. In the case of a blower, it is generally used with an excessive air flow. For example, when dust collecting effect is sufficient at reduced air flow, the blower is operated at full capacity because the proper air flow is not decided. Also, when a blower for cooling has no problems, even if the air flow is reduced according to the season, it is operated at full capacity. These examples are often seen.

That is, to reduce the air flow, it is necessary to study the following:

- What is the proper air flow?

- To acquire this proper air flow, what is the most efficient method?

- Does not air leak from piping and at the place for use?

There are two methods to reduce the air flow; fixed type, and variable type of rotation numbers.

a. Fixed types

Table 12.21 shows method for fixed types.

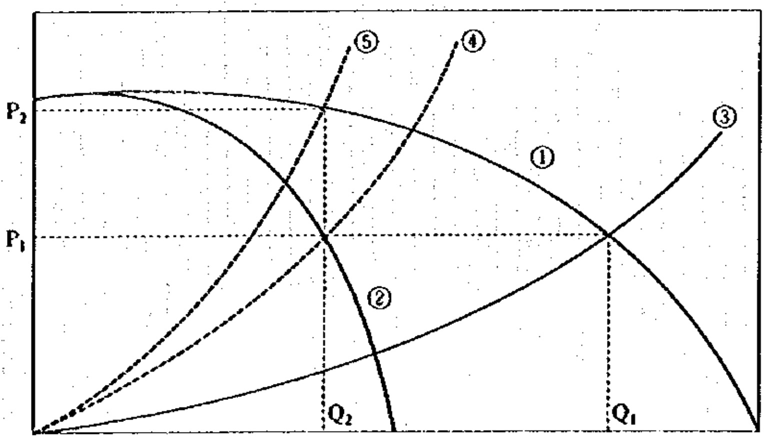
Table 12.21 Method to Reduce Blow Air Capacity (Fixed Type)

Main classification	Sub-classification
Reduction in blowing capacity	When blowers are operated, reduce the number. Replace blower. Blower impellers (replace or cut)
Damper, vane opening adjustment	Reducing damper opening Reducing vane opening
Change in rotating speed	Replace motor. Replace belt-driven pulley. Insert or replace reducer.

1) Reduction in units

In case two blowers with the same specifications are operated in parallel, when the required air flow is changed from Q_1 to 1/2 of Q_1 as shown in Figure 12.34, it is necessary to change the resistance curve of the piping system including damper from (3) to (5). The required power at this point is in proportion to $P_2 \times Q_2$. On the other hand, when the operated blowers are reduced to one unit and the resistance curve is changed to (4) the required power at this point is in proportion to $P_1 \times Q_2$. That is, the difference in blowing power between two units and one unit operation is in proportion to $P_2 \times Q_2 - P_1 \times Q_2 = Q_2 \times (P_2 - P_1)$ and it gives a great energy conservation effect. Since, in fact, the difference in efficiency is added to this, this effect will be greater.

Figure 12.34 Performance Curve during Parallel Operation



2) Replacement of impellers

When the blower output becomes too high and the damper is exceedingly narrowed down after the amount of air used is reduced, or when the gas specific weight becomes higher, the wind pressure is too high and the motor is overloaded, it is desirable to replace the impellers.

Assuming the diameter of impeller as D, the air flow as Q, the pressure as P and the axial power as L, the following relations generally exist.

$$Q \propto D^2$$

$$P \propto D^2 \quad \text{...} \quad (5)$$

$$L \propto D^4$$

Accordingly, diminishing the diameter of the impeller as required will bring very great energy conservation. In this case, it is of course necessary after working to adjust the balance. If there is a large amount of working in the case of multi-stage block, the blade in the 1st stage or 2nd stage may be removed. Adjustment of blowing capacity by this method is limited to about 20%.

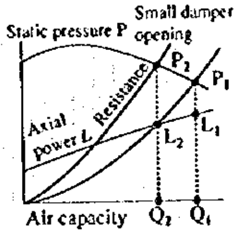
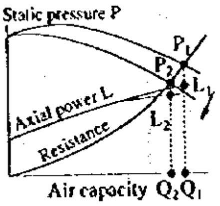
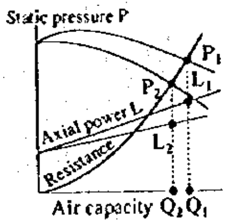
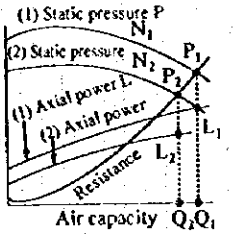
3) Damper, vane opening adjustment

The damper is installed vertically to the air duct shaft direction to change the opening and when installed on the outlet side, the opening changes the resistance curve and, when installed on the inlet side, the opening changes the static pressure curve.

The vane means a movable blade which is installed at the inlet of the blower and provides the gas entering the blower impeller with swirl in the direction of rotation. Accordingly, adjusting the vane changes the wind pressure-air flow curve.

Special features of this method are shown in Table 12.22, in which the rotating speed control method is specified for comparison.

Table 12.22 Damper, Vane Opening Adjustment

Method	Discharge damper opening adjustment	Intake damper opening adjustment	Intake vane control	Changing the rotating speed
Principle	Change blower resistance curve by intentionally increasing resistance of the piping system.	Since damper resistance is provided on intake side, it serves as a negative pressure and pressure curve slightly changes. Axial power curve also changes slightly.	Reduce the impeller work done by intentionally changing gas flowing angle against blower impellers, thus changing the pressure and power curves at the same time.	Air capacity is in proportion to the rotating speed, the pressure to square of the rotating speed, and the axial power to cube of the rotating speed.
Diagram of principle	 When damper is closed, resistance increases and operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2). Note: Operating point is a point of intersection of pressure and resistance curves.	 When damper is closed, pressure curve falls and operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2).	 Reducing vane lowers pressure and axial power curves. Operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2). Reduction in axial power is far larger than damper opening adjustment.	 Changing the rotating speed from N_1 to N_2 shifts the pressure and axial power curves from (1) to (2), and the operating point from (P_1, L_1, Q_1) to (P_2, L_2, Q_2).
Special features	1) Surging area is wide and effective air capacity control cannot be performed. 2) Axial power does not lower much even in low air capacity area.	1) Surging area is narrower than for discharge damper. 2) Axial power lowers almost in proportion to air capacity.	1) Same as at left. 2) Axial power lowers almost in proportion to air capacity and tends to lower much more than the intake damper.	Axial power lowers most and this is the best method for electric power conservation.

4) Change in rotating speed (change of motor or diameter of pulley)

Assuming the rotating speed of blower as N,

$$
\begin{aligned}
Q &\propto N \\
P &\propto N^2 \quad \text{...} \quad (6) \\
L &\propto N^3
\end{aligned}
$$

Since there is the above relation, when it is possible to replace with a motor with lower rotating speed, energy can be greatly saved. However, in this case, once it is changed, it cannot be easily returned to the original position unlike the damper adjustment. Therefore, carefully investigate the resistance curve of load, etc. and be careful so that the air flow is not insufficient after replacement. Also, in the case of belt-drive, it is an effective method to lower the rotating speed by changing the diameter of the pulley.

b. Variable types

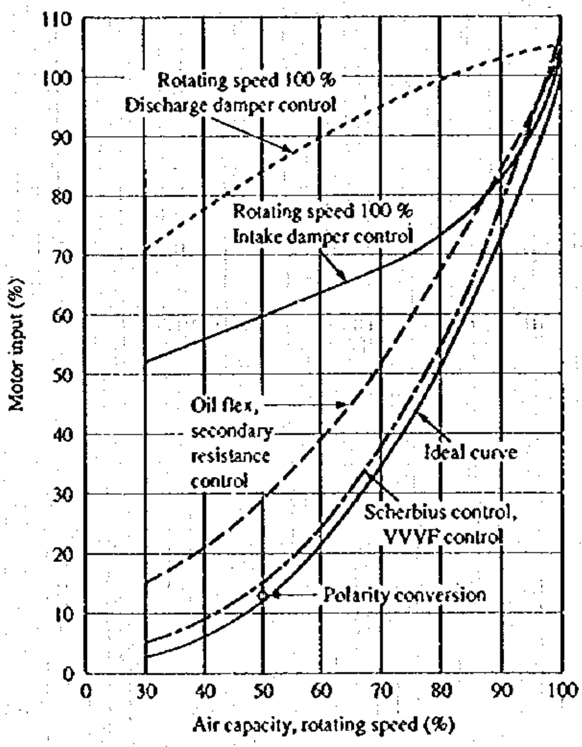
In variable control systems of air flow, there are various systems as shown in Table 12.23, of which we will describe the eddy current joint control and Scherbius control.

Table 12.23 Method to Control Air Flow (Variable System)

Discharge damper control (Variable)	Intake damper control (Variable)
Intake vane control (Variable)	Change in number of poles
Eddy current coupling control	Secondary resistance control
VVVF control	Scherbius control
	Others

Figure 12.35 shows motor input (%) of various variable air flow control methods specified in Table 12.23.

Figure 12.35 Comparison of Blower Motor's Input



12.6 Pump

As electric power consumed by pumps in various facilities is huge, improvement of their efficiency is one of the most important concerns for electric power conservation. So far the head of pumps was designed to allow considerable excess on account of the secular increase of line resistance of piping facilities. Also, many of these pumps have excess capacity in prospect of future increase of supply or drainage quantity, so the flow rate is adjusted by valves.

In these cases, while pump efficiency itself is high, efficiency of the pump facilities as a whole is low, resulting in wasteful consumption of electric power.

12.6.1 Type and Construction of Pumps

Pumps are classified into turbo pumps, positive displacement pumps and other pumps, as shown in Table 12.24. The turbo pump rotates the impeller in the casing to give fluid energy. Centrifugal pumps, mixed flow pumps and axial flow pumps belong to this category. As there is no seal between the impeller and casing in the pump body, the discharge varies largely by pressure.

Whereas the positive displacement pump is that which delivers fluid from the suction side to the discharge side by means of displacement or change of enclosed space which is generated between the casing and inscribed movable members. Reciprocating pumps and rotary pumps belong to this category. As there is a seal line provided between the casing and the movable members, keeping leakage at a minimum, discharge is hardly affected even when the discharge pressure is varied.

Other pumps include jet pumps and air lift pumps, both of which are used for pumping of water.

Table 12.24 General Classification of Pumps

- Pumps
  - Turbo pumps
    - Centrifugal pumps
    - Mixed flow pumps
    - Axial flow pumps
  - Positive displacement pumps
    - Reciprocating pumps
    - Rotary pumps
  - Other types
    - Jet pumps
    - Air lift pumps

However, as pumps, turbo pumps are used for the most. So, the following descriptions mainly refer to turbo pumps:

(1) Centrifugal pump

In this type of pumps, flow discharged from the impeller is mainly within a plane perpendicular to the pump shaft, and there are volute pumps which give water a velocity energy by centrifugal force of the impeller, and convert it to a pressure energy in the volute chamber, and diffuser pumps which convert the velocity energy to a pressure energy by means of the guide vane type diffuser. The specific velocity of pump Ns is 100 - 700.

(2) Mixed flow pump

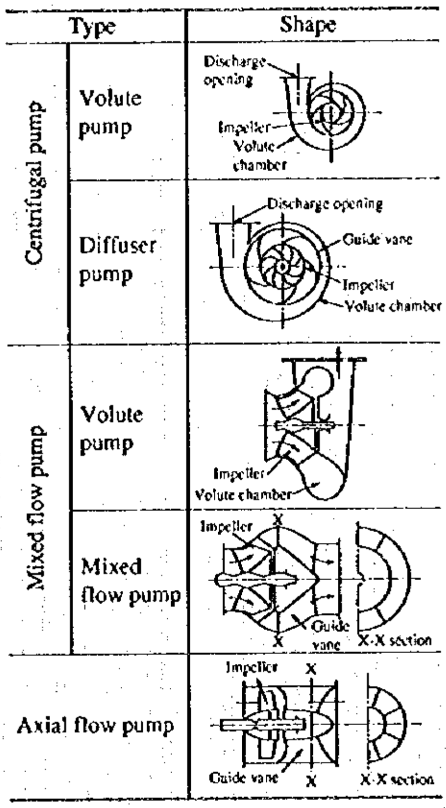
In this type of pumps, velocity energy and pressure energy is given to water by centrifugal force of the impeller and lift of the vane, and the water flows in from the axial direction to the impeller and discharged to a conical plane having the center line of the pump shaft as its axis. Generally, these pumps have a guide vane type diffuser on the discharge side of the impeller, but some pumps have a direct volute type casing. The specific velocity of pump N_s is 700 - 1,200.

(3) Axial flow pump

The propeller shaped impeller gives water a velocity energy and pressure energy by lift of the vane, and the water flows in from the axial direction to the impeller and discharged into a cylinder which is provided coaxially with the pump shaft. The specific velocity of pump N_s is 1,200 - 2,000.

Shapes of these pumps are shown in Figure 12.36.

Figure 12.36 Pump Shapes



12.6.2 Characteristic Curves and Operating Points of Pumps

(1) Specific velocity

Specification of a pump is decided basically by discharge Q (m^3/min), total head H(m) and rotating speed N (rpm). Q and H are decided by purpose and N by selection of suitable model. For pumps, generally the specific velocity is understood as a guideline for characteristic classification. The specific velocity N_s is a value set to be constant for impellers with similar shape, irrespective of the size and rotational speed of each pump, and is used as the model number of impellers.

Specific velocity N_s is determined by the following formula:

$$N_S = N\cdot Q^{\frac{1}{2}}/H^{\frac{3}{4}} \quad \text{……………………………………} \quad (1)$$

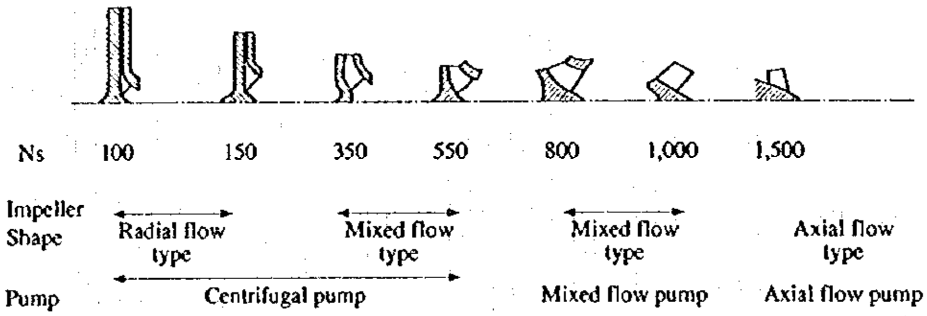
N: Revolution/min

Q: Discharge at max. efficiency point (m^3/min) (Provided, 1/2Q for double suction)

H: Total head at max. efficiency point (m)
(Provided, total head of each stage for multistage pumps)

As it is clear from formula (1), when N_s is small, this means a pump with small flow rate and high head, and when N_s is large, this means a pump with large flow rate and low head. Figure 12.37 shows the relationship of N_s and impeller shape.

Figure 12.37 N_s and Impeller Shape



(2) Operating point of pump

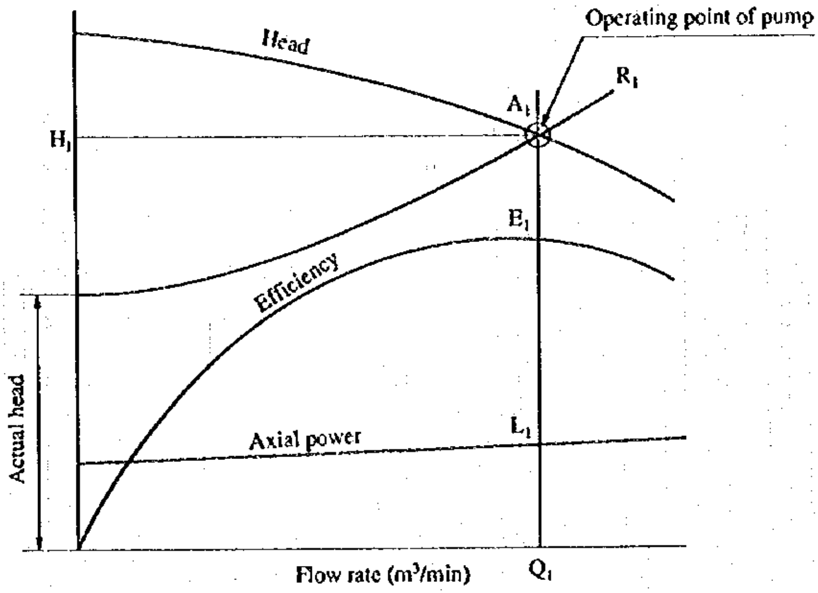
Pumps are not always operated under constantly fixed conditions. However, in each operating state, stable operation is performed at that point of time. This indicates that the state of pipe connected before and after a pump, and of the whole pump system including the water level condition at the suction side and discharge side are in a balanced state. Factors that determine the operating point are pressure loss of the line itself, the throttling of valves in the line, and difference of water level between the suction side and discharge side, etc. which are not related to the pump characteristics.

Generally, performance of volute pumps is shown in Figure 12.38.

Each pump uses a feed pipe to supply water, and the resistance increases almost proportionately to the velocity squared inside the pipe. A resistance curve R_1 of Figure 12.38 is the addition of the line resistance of the feed pipe to the actual head of the pump and a pressure required at the end of the feed pipe, and the pump operates with the flow rate Q_1 and head H_1 at a point of intersection A_1 of this resistance curve R_1 and performance curve of the pump. In this case, the axial power of pump is a point of intersection L_1 of a vertical line drawn from the point A_1 with the power curve, and the pumping efficiency is a point of intersection E_1 of the same vertical line with the efficiency curve.

Admitting that the actual head and the pressure at the end of the feed pipe are necessary, electric power can be saved by minimizing the resistance of the feed pipe, since the total head H_1 of the pump can be reduced accordingly.

Figure 12.38 Performance Curve of Pump



12.6.3 Necessary Power and Pump Drive Motor

(1) Necessary power

The theoretical power of a pump is given by the following formula:

$$P = 0.163 \cdot \gamma Q \cdot H \ [\mathrm{kW}] \quad \cdots\cdots (2)$$

γ : Weight of fluid per capacity (kg/L)
Q : Discharge of the pump (m³/min)
H : Total head of the pump (m)

An output (axial power) which is required of the motor is given by the following formula:

$$P = 0.163 \cdot \gamma \cdot Q \cdot H \frac{100}{\eta}(1+\alpha) \quad \cdots\cdots (3)$$

η: Efficiency of the pump (%)
α: Tolerance

The approximate values of η and α are shown in Figure 12.39 and Table 12.25.

Figure 12.39 Standard Efficiency General Purpose Pumps

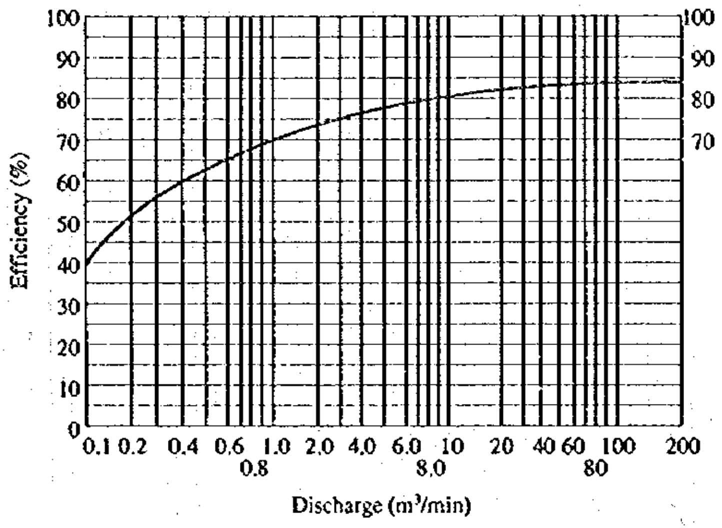


Table 12.25 Tolerance of Pumps

Pump type		Tolerance (%)	
		Fluctuation of head is relatively small.	Fluctuation of head is relatively large.
Volute pump	Highhead	15	20
	Medium, low head	10	15
Mixed flow pump		15	20
Axial flow pump		20	25

(2) Pump drive motor

In selecting the motor, it is necessary to grasp the torque characteristics of the pump at start and during acceleration, as well as the operation system. To start a pump from the stationary state, the motor should have a power exceeding the static friction torque of the bearing, but when the pump is rotating, a dynamic friction which is smaller than the static friction is generated, and a load torque is generated as the pump is accelerated.

Relationship of rotating speed and load torque of each pump is different depending on the pump type and opening state of the discharge valve. In particular, it should be noted that the starting-torque characteristic differs according to opening state of the discharge valve.

Axial power of the pump when the discharge valve is closed shows a minimum for models with 650 or less of N_s, and exceeds 100% of rated load torque and even reaches 200% for models with 650 and over of N_s. For the centrifugal pump of which N_s is 100 ~ 700, the starting torque is small when the valve is closed at start, and for the mixed flow pump of which N_s is 700 ~ 1,200, the starting torque is 150 % ~ 200 % when the discharge valve is closed.

Therefore, for the centrifugal pump, start from the state with the discharge valve closed, and for the mixed flow pump and axial flow pump which are not operable with the valve closed, special care is needed to start. To start axial flow pump small capacities, a method in which the discharge valve closes in the beginning and opens with the increase of rotating speed up to 100 % torque at the rated speed is adopted.

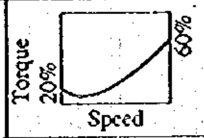
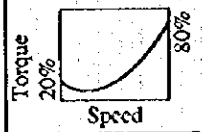
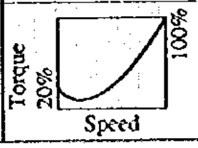
For the case of large-capacity axial flow pumps, sometimes a movable vane is adopted (partly for adjustment of the flow rate) to allow start at 100 % torque with the discharge valve closed. Therefore, the pump torque at the rated speed during start may be considered to be 40 % ~ 80 % for centrifugal pumps, and 100 % for mixed flow pumps and axial flow pumps.

Additionally, vertical type pumps have large static friction due to the thrust bearing, with some reaching up to 40 % torque.

The above may be summarized as shown in Figure 12.40.

Each pump drive motor should be selected by considering the given start conditions. Generally, squirrel cage motors are often used, and while inconveniences such as start delay do not occur in the case of direct-input start, start delay may occur due to torque drop during acceleration in the case of start under reduced voltage such as reactor start.

Figure 12.40 Start Characteristics of Pumps

Pump type		Start torque characteristics	GD_2
Centrifugal pump	$N_s \leq 300$		Small
	$300 < N_s \leq 450$		Small
Mixed flow pump Axial flow pump			Small

However, when wound-rotor induction motors are used, start jam does not occur. In the case of synchronous motors, sometimes almost 100 % pull-in torque is required.

12.6.4 Resistance of Feed Pipe

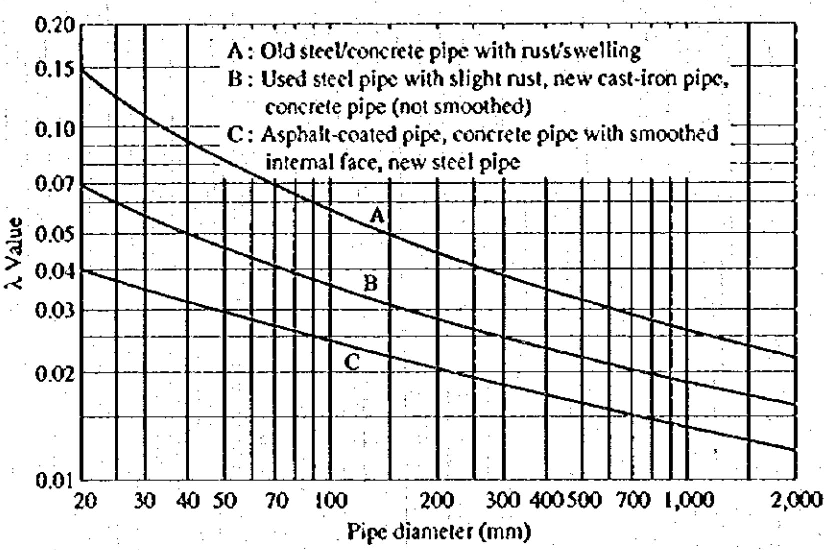
Generally, resistance of feed pipes is calculated by Darcy's formula (formula (4)) when the feed pipe is rather short.

$$H_f = \lambda \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \quad \cdots\cdots\cdots \quad (4)$$

H_f: Resistance of feed pipe (m)
λ : Loss factor
L : Length of feed pipe (m)
D : Inside diameter of pipe (m)
v : Velocity in pipe (m^3/s)
g : Gravity acceleration 9.8 m/s^2

The value of λ is normally set as $\lambda = 0.02 + 1/2{,}000D$, which is multiplied by a modulus determined by the smoothness of the internal face of the feed pipe. For this calculation, the loss factor by Colebrook's experimental formula, as shown in Figure 12.41, will facilitate the procedure.

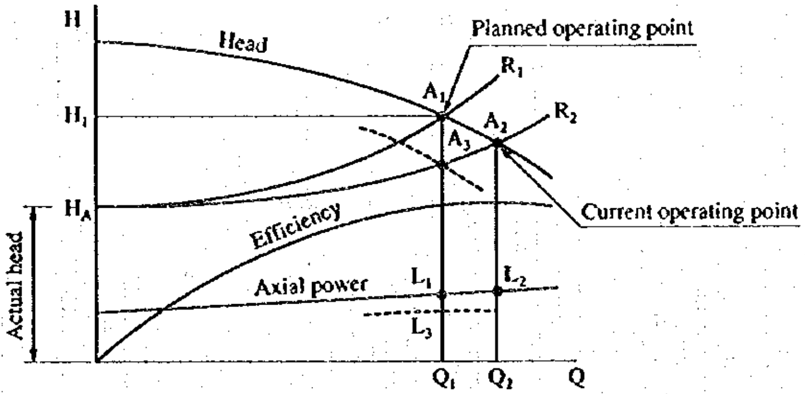
Figure 12.41 λ Values by Colebrook



12.6.5 Pump Performance when the Outside Diameter is Worked Upon

Volute pumps, like the frame number of motors, fabricate impellers according to the pump specification, within the ranges of a certain flow rate and head as a single barrel. Therefore, in cases where specifications are prepared in prospect of the future but have too much leeway performance for the time being as previously mentioned, it is economical to first fabricate the impeller according to a broken line in Figure 12.42, and then make a new one when the flow rate later becomes insufficient due to increase of line resistance.

Figure 12.42 Pump Performance and Resistance Curve



Also, when impeller is rebuilt by increasing the size of the feed pipe to shift the resistance curve from R_1 to R_2, with the same actual head, it allows the operating point of the pump to change from A_1 to A_3, thus saving electric power by $(L_1 - L_3)$.

Change of performance when the outside diameter D_1 of the impeller of an operating pump is worked to D_2 as shown in Figure 12.43 is illustrated in Figure 12.44. When the outside diameter of the impeller is worked from D_1 to D_2 in Figure 12.43, the flow rate, head and power are obtained by equations (5), (6)and (7), respectively.

Figure 12.43 Working the Impeller of Its Outside Diameter

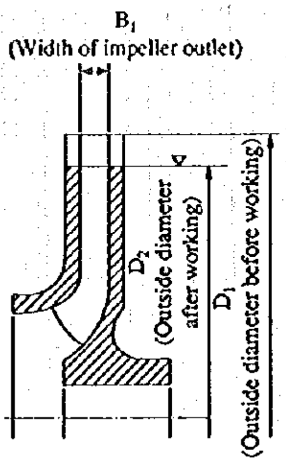
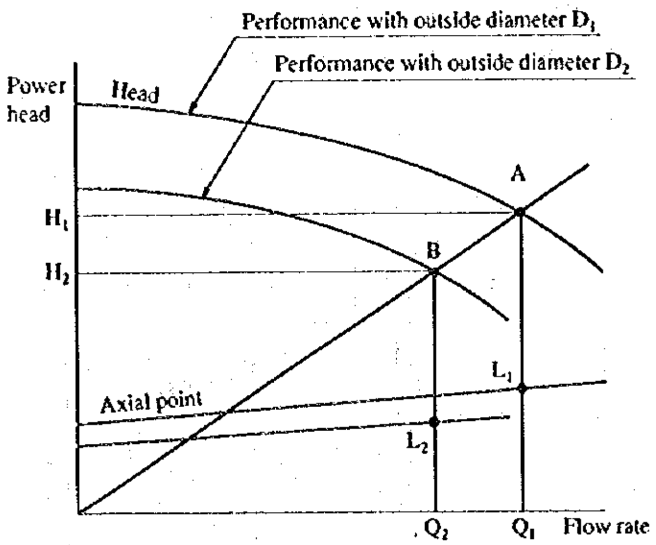


Figure 12.44 Change of Performance by Working on Impeller Diameter



Connect an optional point A, on the Q-H curve of outside diameter D1, to the origin with a line, and obtain a point B from $H_2 = (D_2/D_1)^2 \times H_1$, or $Q_2 = (D_2/D_1)^2 \times Q_1$. Determine several points for the performance of outside diameter D_2 in the same manner, and prepare the Q-H curve of outside diameter D_2 by connecting these points. Likewise, calculate the power from $L_2 = (D_2/D_1)^4 \times L_1$, and obtain a point L_2 on the vertical line BQ_2. Determine several points in the same manner, and prepare the power curve by connecting these points.

- Points to be noted on working the diameter of the impeller

a. As the impeller is balanced during fabrication, it should be re-balanced after worked.

b. For cases when the work ratio of the outside diameter of the impeller, $(D_1 - D_2)/D_1 \times 100$ %, exceeds 20 %, the equations (5), (6) and (7) will sometimes not apply, not enabling pumping.

c. Note that working on the outside diameter is not necessarily available depending on the materials of the impeller, such as pressed stainless steel.

12.6.6 Rotating Speed Control of Pump

Rotating speed control may be adopted for purposes as process control, flow rate control of pumps, or energy conservation. As methods of rotating speed control for pump drive motors, there are various methods as described in 12.3.2, (3). To perform rotating speed control, relations of the equations (8), (9), (10) are established by supposing the rotating speed of the pump to be N_0 and N_1, the flow rate Q_0 and Q_1, the pump head H_0 and H_1, and the axial force L_0 and L_1:

$$\frac{Q_1}{Q_0} = \frac{N_1}{N_0} \qquad (8)$$

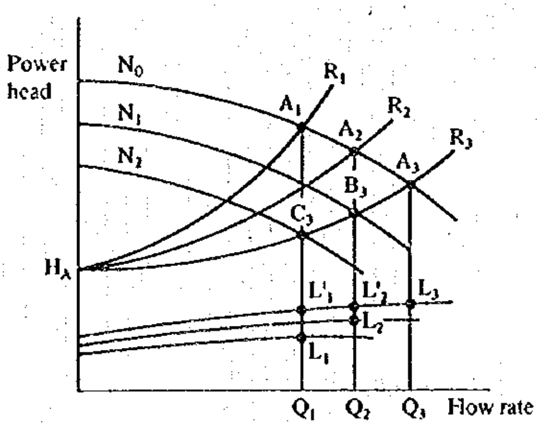
$$\frac{H_1}{H_0} = \left(\frac{N_1}{N_0}\right)^2 \qquad (9)$$

$$\frac{L_1}{L_0} = \left(\frac{N_1}{N_0}\right)^3 \qquad (10)$$

Figure 12.45 shows changes in characteristics of the pump when the rotating speed is changed, where the flow rate, head and axial power are changed in a manner so that the expressions (8), (9) and (10) show their relations to the rotating speed. When the resistance curve of the feed pipe is R_3 in Figure 12.45, and when the rotating speed of the pump is changed from N_0 to N_1 and N_2, the operating point of the pump is changed from A_3 to B_3 and C_3, and the flow rate from Q_3 to Q_2 and Q_1.

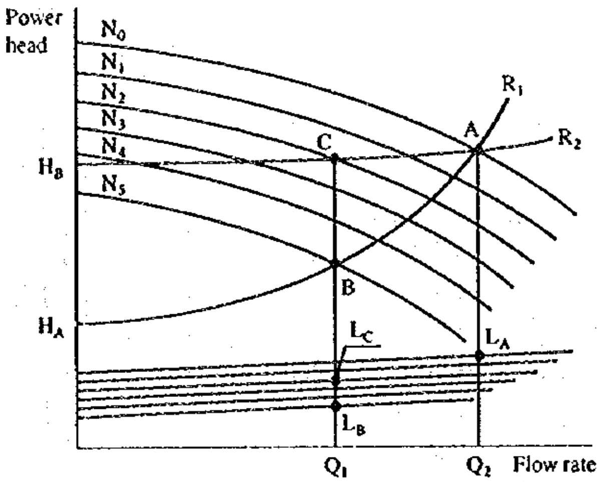
If the rotating speed of the pump is left as N_1 when the necessary flow rate is Q_1, the resistance curve must be changed from R_3 to R_1 by throttling the valve, when the operating point of the pump is A_1 and the axial power is L_1'. When the rotating speed is changed to N_2, it will change the operating point to C_3 and axial power to L_1 while leaving the resistance curve as R_3. Therefore, a considerable amount of electric power can be saved.

Figure 12.45 Changes of Characteristics by Change of Rotational Speed



Provided, however, it should be noted that, as the above description applies only when the actual head is small like H_A and the line resistance is large as shown in Figure 12.46, rotating speed would not result in a significant electric power conservation if made when the line resistance is small and the actual head is as large as H_B.

Figure 12.46 Difference of Axial Power by Actual Head Power



- Method to determine rotating speed to change flow rate from Q_0 to Q_2

Suppose that the pump is operating on the operating point A of Figure 12.47. The resistance curve can be determined from the actual head Ha and the total head H_0. On the resistance curve, the total head is H_2 and operating point C when the discharge is Q_2.

A curve CB is a quadratic curve passing the origin, obtained as follows:

Supposing the quadratic curve to be,

$$H = a \times Q^2$$

the modulus a is obtained from the point C,

$$a = H_2/Q_2^2$$

When factors of Figure 12.46 are substituted,

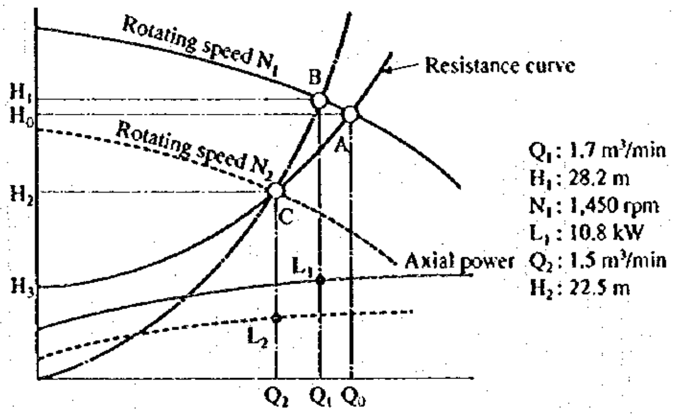
$$a = 22.5/(1.5)^2 = 10$$

Therefore, curve CB is expressed as,

$$H = 10 \times Q^2$$

The point of intersection of this curve with the pump performance curve at the rotating speed N_1 would be point B. From the figure, the discharge Q_1 = 1.7m³/min, total head H_1 = 28.2 m, and axial power L_1 = 10.8 kW.

Figure 12.47 Change of Pump Performance by Rotational Speed



To determine a rotating speed of the pump for reaching the operating point C required by the facility, it is calculated by equation (9), as,

$$N_2 = \frac{N_1}{(H_1/H_2)^{1/2}} = \frac{1,450}{(28.2/22.5)^{1/2}} = 1,295 \text{ rpm}$$

Here, the axial power is obtained from equation (10), as

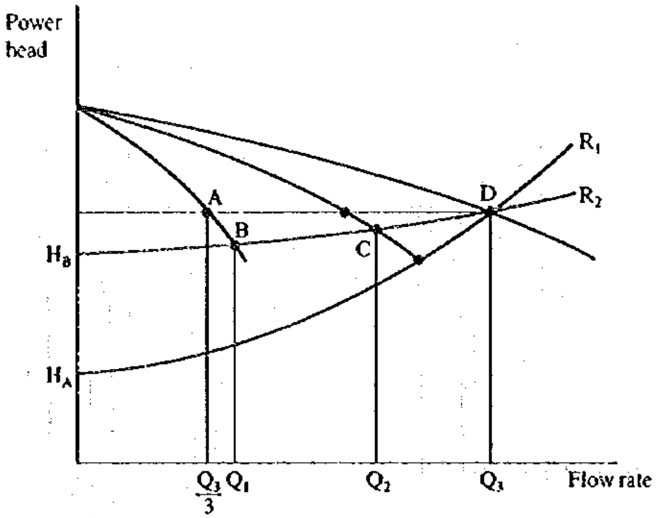
$$L_2 = L_1 \times \left(\frac{N_2}{N_1}\right)^3 = 10.8 \times \left(\frac{1,295}{1,450}\right)^3 = 7.7 \text{ kW}$$

As the axial power is 11.0 kW at point A of Figure 12.46, it is reduced to 7.7 kW by changing the rotating speed.

12.6.7 Pump Unit Control

When flow control is performed by operating the valve of one large-capacity pump when the required volume of water varies seasonally or by time, i. e. by day or by night, or when the rotation number of the variable speed motor is controlled, the pump efficiency will be low in zones with small flow rates as shown in Fig. 12.38. In such a case as shown in Figure 12.48, the number of pumps may be made multiple to perform parallel operation for cases requiring a large volume of water and use only one pump in cases requiring a small volume of water, so that operation can always be performed in zones with high pump efficiency, resulting in electric power conservation. However, it is necessary to make sure of the operating point in order to avoid overload of motor.

Figure 12.48 Parallel Operation Characteristics of Pump



If the actual head is H_B and the resistance curve of the feed pipe is R_2, the flow rate is Q_3 when 3 pumps are in operation. Therefore, if only one pump is used, the pump must be operated at the flow rate $Q_3/3$. However, since the flow rate is smaller and resistance of the feed pipe smaller when only one pump is used, the operating point of the pump is B, consequently resulting in a flow rate Q_1 larger than $Q_3/3$. Therefore, study should be made so the motor is free of overloading even when the pump is operated at the flow rate Q_1.

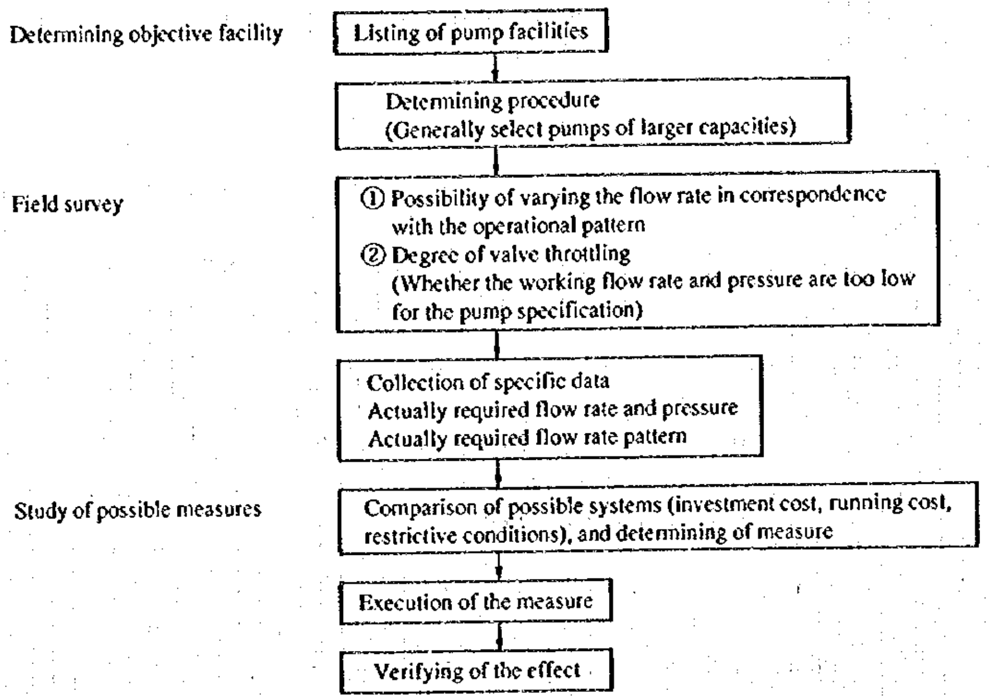
Also, for pumps with small actual head H_A, and the resistance curve of the feed pipe R_1, the flow rate of a pump, when only one pump is to be operated, will exceed the max. flow rate of the pump, requiring an additional resistance by throttling the discharge valve.

12.6.8 Electric Power Conservation Measures of Pump

Since both gas and liquid are fluid and the basic theories are the same, the method which was discussed about the blower thus applies similarly. However, an exception is that the valve control is performed only on the discharge side and not on the suction side. Valve control on the discharge side is the worst method for power conservation purpose.

The electric power saving flow of pumps is shown in Figure 12.49.

Figure 12.49 Electric Power Saving Flow of Pumps



The 3 factors of electric power conservation of pumps are (1) reduction of required flow rate, (2) reduction of pipe resistance, and (3) efficient flow rate control.

(1) Reduction of required flow rate

The first to be done is to reduce the required flow rate. Pumps should be those that meet the required flow rate, however actually in most cases the pump performance is larger than the actually required head and flow rate, because of the following reasons.

a. In many cases pumps having considerable excess capacity in their total head are installed in prospect of an increase of secular loss of piping.

b. Many facilities are installed with excess capacity of flow rate in prospect of a future increase of supply and drainage quantities.

c. Because of the current JIS test standard which states that the actual flow rate-head curve should not be below the prescribed head by means of the flow rate as decided by pump specifications, most pumps have capacities above the flow rate and head as set by the specifications.

(2) Reduction of pipe resistance

Although pipe resistance is mostly fixed at construction and rebuilding of existing facilities is difficult, factors which form the resistance may be described as follows:

a. Friction loss of direct pipe

According to Darcy's formula (formula (4)), friction loss of a direct pipe is proportionate to (resistance modulus of pipe) × (velocity)^2 × (pipe length)/(pipe diameter).

b. Loss at piping elements

Suction port, bends, acute expanded portions, acute shrinked portions, orifices, diverting points, confluent points, effluent outlet, etc.

c. Loss at valves

In short, piping should be arranged closest to the direct pipe with large diameter and short length, excluding unnecessary accessories from the piping for practical purposes in order to reduce the resistance.

(3) Efficient flow rate control

When the required flow rate is reduceable, methods of electric power conservation of pumps are discussed as follows:

a. Intermittent operation

When water use is clearly distinct between periods of need and no need, pumps may be stopped during unnecessary periods.

That is, pumps may be run by intermittent operation. It is a simple method, but turning on and off within short cycles too frequently should be refrained to avoid water-hammer effects.

b. Pump unit control

A method varying the number of pumps according to the fluctuation of flow rate aims at reducing the axial power of pumps so they can be operated with relatively favorable efficiency meeting the fluctuation range of flow rate.

The control system is simple and risks can be avoided by increasing the number of pumps, but discharge changes by stages. Therefore, when the resistance curve is steep, there exist many problems such as discharge does not increase so much even when there are more pumps, and so on.

c. Rotating speed control

In spite of high initial investment cost, this method offers several such advantages as great reduction in electric power costs and smooth pump operation even at low flow rate. This method is effective for pumps with large capacities, and for cases with large head fluctuation ranges.

d. Replacing pumps

Replacing pumps with those meeting the required flow rate when the discharge load is stable but the flow rate has dropped lower than before, or when the flow rate fluctuates seasonally, is simple method but has some problems such that flow control is not available, and it takes much time for replacement.

Additionally, sometimes only motors are replaced for the purpose of reducing the flow rate by changing the revolution.

e. Replacing the impeller

It is applicable for volute pumps operated under fixed discharge load, and afford efficient changes of pump performance. However, disassembling and assembling of pumps are necessary.

12.7 Lighting

12.7.1 Factory Lighting

(1) Purpose of factory lighting

Good lighting facilitates various visual operations and has the following effects:

a. Improved operation efficiency

Proper illuminance diminishes nerve strain, reduces defective products and improves the operation efficiency.

b. Improved operation safety

Since things can be clearly seen and the visual range is widened, employees are careful for their operation and any disasters due to mistakes, etc. can be prevented.

c. Thorough shop management

It becomes easier to point out any defects in the operation and shop, morale for proper arrangement and environmental hygiene is enhanced, and management for the operation and equipment, etc. can be thoroughly achieved.

d. Improved operator's morale

A shop with a well-ordered working environment including lighting enhances the employees' pride and responsibility for their appointed tasks, and excites their desire to work.

(2) Good factory lighting

Good factory lighting has the following factors:

a. Proper illuminance and illuminating distribution
b. Free from flickering and glare
c. Color rendering properties of light source should not be exceedingly improper.
d. Good economical efficiency

For proper illuminance, the necessary value is determined by content of the operation, size of the object and color, etc. Values specified in Table 12.26 are recommended as illuminance standard values in Japan. For the aged, these standard values should be somewhat increased.

Also, flickering and glare cause eye fatigue, hindering the operation and lowering the efficiency. Color rendering properties may also hinder some operations.

Table 12.26 Illumination Standard for Factory

Illumination (lx)	Place	Operation
3,000 2,000	Instrument panel and control panel in control room, etc.	Exceedingly fine visual operation in manufacture of precision machines and electronic parts, printing factory, etc., such as ∘ assembly a, ∘ inspection a, ∘ test a, ∘ selection a, ∘ design, ∘ drawing.
1,500 1,000	Design and drawing rooms	Fine visual operation in selection and inspection in textile mills, typesetting and proofreading in printing factory, analysis, etc. in chemical industry, such as ∘ assembly b, ∘ inspection b, ∘ test b, ∘ selection b.
750 500	Control room	Ordinary visual operation in general manufacturing processes, etc., such as ∘ assembly c, ∘ inspection c, ∘ test c, ∘ selection c, ∘ packing a, ∘ desk work in warehouses.
300 200	Electricity room and air conditioning machine room	Rough visual operation such as ∘ packing a, ∘ wrapping b, ∘ restricted operation
150 100	Entrance/exit, corridor, passage, warehouses involving operation, staircases, lavatories	Very rough visual operation such as ∘ wrapping c, ∘ packing b, c ∘ restricted operation
75 50	Indoor emergency staircases, warehouses, outdoor power equipment	Operation such as ∘ loading, unloading, load transfer, etc.
30 20 10	Outdoor (for passage and safety guard within compound)	

12.7.2 Energy Conservation for Lighting

As an equation for general lighting in a factory and office, the following equation is well known.

$$E = \frac{N \times F \times U \times M}{A} (lx) \quad \cdots\cdots (1)$$

where

E : Illuminance (lx)
A : Area of room (m^2)
N : Number of lamps
F : Luminous flux emitted from one lamp (lm)
U : Utilization factor (See Note 1)
M: Maintenance factor (See Note 2)

Note 1: Utilization factor is the ratio of luminous flux applied to the working plane against the full luminous flux from the lamp, and varies with luminous intensity of the luminaire, installed position, room condition, etc.

Note 2: Maintenance factor is the predicted lowering rate (figure) of initial illuminance with lapse of the working time. This varies with how well the equipment will be maintained, which is determined at the design stage.

Determining the energy required for lighting by transforming equation (1),

$$W \cdot H = \frac{N \times F}{\eta} \times t = \frac{A \times E \times t}{U \times M \times \eta} [Wh] \quad \cdots\cdots (2)$$

where W•H: Watt-Hour

η: Lamp efficiency
t : Lighting time (hour)

Since the actual electric power consumed for lighting contains the distribution line loss for lighting added to this equation (2), the following can be considered for energy conservation for lighting:

- Reduce the lighting time.
- Reduce the distribution line loss.
- Keep the illuminance proper.
- Use high-efficient luminaires.
- Improve the utilization factor.
- Improve the maintenance factor.

12.7.3 Concrete Measure for Energy Conservation

(1) Reduce the lighting time

Concrete measures are:

a. Lights-out while unnecessary, including noon recess

b. Individual lights-out near windows

c. Provide many switches for individual lights-out.

d. Lights-out in quiet areas

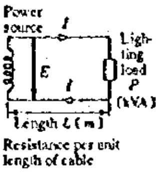
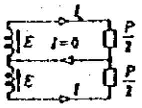
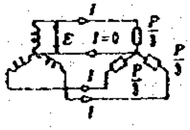
e. Adopt automatic switches or timer switches for outdoor lamps, etc.

In any case, these countermeasures much depend upon the employees' consciousness and therefore, it is necessary to endeavour to enhance it.

(2) Reduce the distribution line loss

Since the distribution line loss greatly varies with the distribution system (See Table 12.27), it is desirable to compare and study well for determination when establishing new equipment. Besides, to increase voltage level in the distribution line and to improve power factor, etc. must be studied.

Table 12.27 Comparison of Loss by Wiring System

Wiring system	Connection	Loss calculation	Loss ratio
Single phase two wire system		$P = EI \times 10^{-3}[kVA]$ $LossW = I^2 \times 2LR_1 = \left(\frac{P}{E} \times 10^3\right)^2 \times 2LR_1 = \frac{2P^2LR_1}{E^2} \times 10^6[W]$	100%
Single phase three wire system		$\frac{P}{2} = EI \times 10^{-3}[kVA]$ $W = 2I^2LR_1 = \left(\frac{P}{2E} \times 10^3\right)^2 \times 2LR_1 = \frac{P^2LR_1}{2E^2} \times 10^6[W]$	25%
Three phase three wire system		$\frac{P}{3} = E \times \frac{1}{\sqrt{3}} \times 10^{-3}[kVA]$ $W = 3I^2LR_1 = \left(\frac{P \times 10^3}{\sqrt{3}E}\right)^2 \times 3LR_1 = \frac{P^2LR_1}{E^2} \times 10^6[W]$	50%
Three phase four wire system		$\frac{P}{3} = EI \times 10^{-3}[kW]$ $W = 3I^2LR_1 = 3\left(\frac{P \times 10^3}{3E}\right)^2 \times LR_1 = \frac{P^2LR_1}{3E^2} \times 10^6[W]$	16.7%

NOTE: Each cable size is same.

(3) Keep the illuminance proper

Although it is of course important to secure illuminance required for the operation, it is important for energy conservation to reexamine the lighting level and provide local lighting for passages, places where persons do not much enter and outdoor lighting, etc.

Also, when establishing a new factory, adoption of natural daylight should be positively considered.

(4) Use high-efficient luminaires

Luminaires here mean stabilizers, lamps and light reflectors. Table 12.28 shows one example of stabilizers' characteristics. To diminish the distribution line size, the current when starting should be smaller, and to reduce the distribution line loss, the power factor should be higher. However, the weight and cost increase in inverse proportion to these and, therefore, it is necessary for selection of kinds of luminaires to study the economical efficiency.

The recent advance of the electronic technology has allowed a wider use of high-efficiency luminars with their luminous efficiency enhanced by using an inverter as a stabilizer and lighting fluorescent lamps at a high frequency of 10 to 50 [kHz].

Features of these luminars include easy timming, smaller-size and lighter-weight stabilizers, reduction of heat loss and so forth.

Table 12.29 and Table 12.30 show features and general applications of various lamps.

Table 12.28 Example of Stabilizer Characteristic (for 400W Mercury Lamp)

	Non-dimming type			Dimming type			
	Low power factor type	High power factor type	Constant power type	Constant power type		General type	
Input voltage (V)	200	200	200	200		200	
Voltage tap (V)	200, 220	200, 220	200	200		200,	220
Input current (A)				Normal	Dimmed	Normal	Dimmed
When staring	5.7	4.0	2.3	2.3	–	3.8	–
When stabilized	3.3	2.3	2.3	2.3	1.3	2.4	1.3
Input power (W)	425	425	435	435	255	432	255
Power factor (%)	64	90	95	95	95	90	95
Weight (kg)	4.6	5.2	10.0	13.5		7.0	
Volume ratio (%)	100	160	270	340		220	
Price ratio (%)	100	150	240	310		260	

Table 12.29 Special Features and Applications of Various Lamps

Class of lamps	Special features	Scope of size (W)	Main performance of standard quality				Applications
			Efficiency (lm/w)	Color temperature (K)	Color rendering index (Ra)	Life	
Incandescent lamp	• Stable light color • Possible to light as-is. • Instantaneous lighting high luminance	Several W ~ Several kW	100 W				Residence, store, office
			15	2,850	100	1,000	
Tungsten halogen lamp	Small-size, high efficiency and long life lamp	Several 10 W ~ Several kW	For general use 500 W				For floodlamp, for automobiles, for projection, for photography, for copying machine, studio
			21	3,000	100	2,000	
Fluorescent lamp	• High efficiency and long life • A wide variety of light colors • Little glare	4 ~ 220 W	White 40 W				Residence, office, store
			82	4,500	69	10,000	
Mercury lamp	High efficiency, long life, high luminance lamp	40 ~ 2 kW	400 W				For floodlamp (baseball ground, golf course)
			51	5,800	23	12,000	
Fluorescent mercury lamp	Mercury lamp with luster improved	40 ~ 1 kW	400 W				Roads, factory, street lighting, arcade lighting
			56	4,100	44	12,000	
Choreless mercury lamp	Mercury lamp requiring no stabilizer	160, 250, 500 W	500 W				For works, stores
			27	3,000	42	6,000	
Halide lamp	Higher efficiency and lustrous lamp than mercury lamp	250 ~ 1 kW	400 W				Gymnasium, factory, shopping street, open space, park
			80	4,500	65	9,000	
High lustrous halide lamp	High lustrous, high luminous lamp	250 ~ 400 W	400 W				Gymnasium, lobby, hall
			50	5,000	92	6,000	
Low pressure sodium lamp	Highest efficiency, yellow, luminous lamp	35 ~ 180 W	180 W				Tunnel, high-way, switch-yard
			175	—	—	9,000	
High pressure sodium lamp	Highest efficiency, luminous lamp for general lighting	150 ~ 1,000 W					Gymnasium, high-ceiling factory, warehouse, roads, open space
			120	2,100	29	12,000	

Note: Efficiency of fluorescent and mercury lamps is of 100 hrs value.

Table 12.30 Selection of Lamps from Standpoint of Typical Applications

Class of lamps		Incandescent lamp			Fluorescent lamp			Mercury lamp				Halide lamp		Sodium lamp		
		General lamp	Reflector lamp	Halogen lamp	General fluorescent lamp	High color rendering properties	High output type	Transparent mercury lamp	Fluorescent mercury lamp	Reflector mercury lamp	Stabilizer built-in type	General type	High lustrous type	High pressure	Low pressure	Xenon lamp
Residence		◎	○	△	◎	○	×	×	×	×	×	×	×	×	×	×
Office	General office	△	△	△	◎	△	○	×	×	×	×	△	△	×	×	×
	High-ceiling office, lobby	○	○	○	○	△	○	×	○	○	△	◎	○	×	×	△
	Single room, drawing room	○	○	△	◎	○	×	×	△	×	×	△	△	×	×	×
Store	General stores	◎	◎	○	◎	◎	○	×	○	△	△	△	△	×	×	×
	High-ceiling stores	○	○	○	○	○	◎	×	○	○	○	◎	○	△	×	△
	Exhibits, showcase	◎	◎	◎	◎	◎	○	×	△	△	○	○	○	×	×	△
Factory	Low-ceiling factory	△	△	○	◎	○	○	×	△	△	△	△	△	△	×	×
	High-ceiling factory	△	△	○	△	△	◎	×	◎	○	○	◎	○	○	×	△
	Warehouse	○	△	○	◎	△	○	△	◎	○	○	○	△	○	×	×
School	Class room	△	△	△	◎	○	△	×	△	×	×	△	△	×	×	×
Hospital	Operating room	○	○	△	◎	◎	△	×	×	×	×	×	×	×	×	×
Theater, hall	Spectator's seats	◎	◎	◎	◎	○	△	×	△	△	△	○	○	×	×	△
	Stage	◎	◎	◎	◎	○	○	×	△	△	△	△	△	×	×	△
Art museum, museum	General	◎	◎	○	○	◎	△	×	△	△	△	○	○	×	×	△
	Exhibits	◎	◎	○	○	◎	△	×	×	×	×	○	○	×	×	△
Roads	Automobiles exclusive roads	×	×	×	△	×	×	△	◎	×	×	△	×	○	○	△
	Automobiles exclusive tunnel	×	×	×	△	×	×	△	○	×	×	△	×	○	◎	×
	Streets	△	×	×	○	×	×	△	◎	△	△	△	△	○	△	×
	Shopping streets	○	×	○	○	△	◎	×	◎	△	△	◎	△	○	×	×
	Roads in resident area	○	×	×	○	×	×	△	◎	△	×	△	×	○	×	×
Parking zone	Indoor	△	△	△	◎	×	○	×	○	△	△	△	△	○	×	×
	Outdoor	△	△	△	○	×	×	△	◎	○	△	△	△	○	△	△
Open space, park, garden		○	△	△	○	△	×	△	◎	△	△	○	△	○	×	△
Floodlight lighting	Structure	○	○	○	×	×	×	△	◎	◎	○	○	○	○	△	○
	Advertisement, signboards	○	◎	◎	○	○	○	△	◎	◎	△	○	○	△	×	○
Sports	Indoor	○	○	◎	○	○	○	△	◎	○	△	◎	○	△	×	△
	Outdoor	○	○	○	×	×	×	△	◎	○	△	◎	○	◎	×	○

(5) Improving utilization factor

The utilization factor means the ratio of the luminous flux entering the work area to the total luminous flux going out of the lamp. It varies depending on the installation location of a luminar, the room condition, etc.

Table 12.31 shows an example of the utilization factor. Room index RI in this table is calculated in the following equation:

Table 12.31 Example of Coefficient of Utilization Table

Ceiling	80%									50%								
Wall	60%			30%			10%			60%			30%			10%		
Floor surface	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%
Room index	Utilization factor																	
0.60	.45	.42	.40	.31	.30	.30	.26	.25	.25	.41	.39	.38	.30	.29	.29	.25	.25	.25
0.80	.56	.51	.49	.41	.39	.38	.35	.34	.33	.51	.48	.47	.39	.38	.37	.34	.33	.33
1.00	.63	.57	.55	.47	.45	.44	.41	.40	.35	.57	.53	.52	.45	.44	.43	.40	.39	.38
1.25	.71	.63	.60	.55	.52	.50	.48	.46	.45	.64	.59	.57	.52	.50	.49	.46	.45	.44
1.50	.76	.66	.64	.61	.56	.54	.54	.51	.50	.68	.63	.61	.57	.54	.53	.52	.50	.49
2.00	.85	.75	.70	.71	.65	.62	.64	.59	.57	.76	.70	.67	.66	.62	.60	.60	.58	.56
2.50	.91	.79	.74	.78	.70	.66	.71	.65	.62	.80	.73	.70	.71	.67	.65	.66	.63	.61
3.00	.95	.82	.76	.83	.74	.70	.77	.69	.66	.84	.76	.73	.76	.70	.68	.71	.67	.65
4.00	1.01	.86	.80	.91	.79	.75	.85	.76	.71	.88	.80	.77	.28	.75	.72	.78	.72	.70
5.00	1.09	.88	.82	.96	3.8	.77	.91	.79	.78	.91	.82	.79	.88	.78	.78	.82	.76	.73
10.00	1.13	.93	.86	1.08	.90	.84	1.05	.89	.82	.97	.87	.83	.94	.85	.81	.92	.84	.80

Light output ratio: 83 %, Light source: 40 W 3,400 lm Fluorescent lamp, reflector used

$$RI = \frac{W \times L}{H(W + L)} \quad \text{..........} \quad (3)$$

Where

W : Width of room (m)
L : Depth of room (m)
H : Height of light source from the working plane (m)

The room index has a higher value when it is a square room. And the utilization factor will be higher with the higher reflectivity of the inner wall and floor and the higher room index.

(6) Improving maintenance factor

The maintenance factor means the estimated rate of the initial luminos flux lowering due to dirt on the luminaires with laspe of the working time.

To improve the maintenance factor, first adopt luminaires with less lowering of luminous flux with lapse of the working time and secondly periodically clean the luminaires and replace the lamps. However, under the actual circumstances of the factory with much expenditures in labor cost, it will be unavoidable to replace the lamps and clean the luminaires when the lamps are burnt out. Therefore, the first countermeasure is to use luminaires with less lowering rate.

Figure 12.50 and Figure 12.51 show the lowering tendency of the luminous flux of lamp itself and the lowered luminous flux when dirt accumulates on luminaires respectively.

Figure 12.50 Lumen Maintenance Characteristic of Various Light Sources

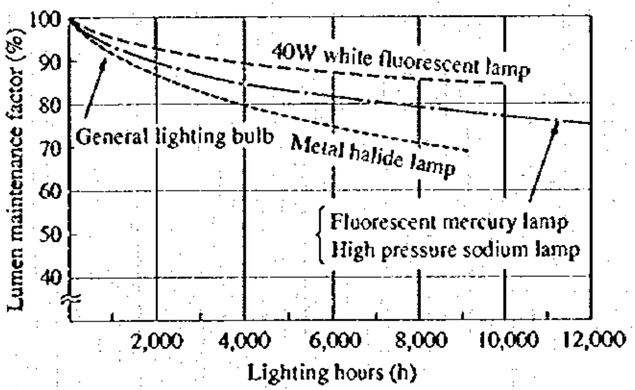
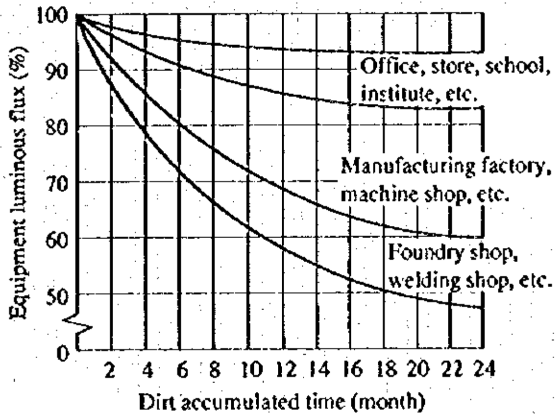


Figure 12.51 Lowered Lumen When Dirt Accumulated on Lamp and Lighting Equipment



(7) Others

Other precautions for lighting are not to fluctuate the supply voltage. Although motors, etc. are capable of operating smoothly even at ±10 % fluctuation, lamps are manufactured to perform their best functions and ensure the longest lives at the rated voltage. Therefore, it is desirable to separate illuminating circuits from motor circuits and also to restrict the voltage fluctuation with ±5 %.

Also for ambient temperatures, it is important not to deviate from the manufacturer's specified value.