Chapter VII

Heating & Power Rating of Motor

The power rating of the motor for a specific application must be carefully chosen to achieve economy and reliability. Use of insufficient motor rating results in over loading, which results in poor reliability and it lowers the production in the industry. On the other hand if the power rating of the motor is more than the required rating, it results in extra initial cost, extra loss of energy and is uneconomical. Furthermore, induction motor and synchronous motor operates at low power factor at light loads. So motor rating should be selected properly for the given applications.

Copper losses, iron losses, frictional losses produce heat inside the motor. As the temperature increases beyond the ambient temperature, a portion heat flows out to the surrounding medium. As motor temperature increases, the heat out flow will increase. The temperature of the motor becomes constant (reaches steady state), where heat generated is equal to heat dissipated to the surrounding medium. The steady state temperature depends on losses and power rating of the machine. As the power rating of the machine increases, the temperature rise will increase. This is called thermal loading of the machine.

Steady state temperature is not same at all parts of the machine. It is more in the windings than any part of the motor. Usually the winding is surrounded by insulation. Among the various materials used in the machine, insulation has lowest temperature limit. Depending up on the temperature limit, insulating materials used in the machine are divided into classes. Following table shows the types of insulation levels and their temperature limit.

Class of insulation →	γ	A	E	B	F	H	C
Temperature Limit →	90^0C	105^0C	120^0C	130^0C	155^0C	180^0C	Above 180^0C

Class of the insulation can be chosen by properly estimating the temperature rise of the machine, ambient temperature, climatic conditions and etc..

Conduction *is heat transfer between part of the same material or different material which are adjacent to one another.*
Convection *is heat transfer from one material to another via a medium, such as air or water.*
Radiation *is heat transfer without any medium and through electromagnetic waves, such as between the Sun and the Earth.*
Evaporation *is heat absorption by liquids which then becomes a gas, such as when you boil water or simply leave a cup of water around and it is evaporated after a while.*

Thermal model of motor for heating and cooling:

Thermal model of the electric motor can be developed based on assumption that the machine is homogenous body (but actually the machine is made up of different materials with different thermal conductivities and complex geometrical shapes). This model is good enough for selecting the motor so that the motor temperature does not exceed the safe limit.

Let P_1 → Heat developed, joule / sec or watts

P_2 → Heat dissipated to the cooling medium, joule / sec or watt

W → Weight of the active parts of the machine, Kg

h → Specific heat, joule / kg / ^{0}C

A → cooling surface, m^2

d → Coefficient of heat transfer or specific heat dissipation, joule / sec / m^2 / ^{0}C

θ → Mean temperature rise, ^{0}C

During a time increment dt, let the machine temperature rise be $d\theta$,

Since, heat absorbed by the machine = (Heat developed inside the machine) – (Heat dissipated to surrounding cooling medium)

$$Wh\frac{d\theta}{dt}=P_1-P_2$$

Since $P_2=\theta dA=D\theta$ & let $C=Wh$, the above equation can be written as

$$C\frac{d\theta}{dt}=P_1-D\theta$$

Where C is called thermal capacity of the machine, joule/^{0}C and D is heat dissipation constant, watt/^{0}C. heat dissipation mainly occurs through convection.

The first order differential equation solution consists of two components, steady state component (particular integral or forced response) and transient component (complimentary function or force free responce).

The steady state component from the above equation is $\theta_{ss}=\frac{P_1}{D}$ = steady state temperature of the machine

And the transient component can be obtained from force free equation, given by

$$C\frac{d\theta}{dt}+D\theta=0$$

$$\theta_t=K e^{\frac{-t}{\tau}}$$

Its solution gives, $\theta(t)=\theta_{ss}+K e^{\frac{-t}{\tau}}$

Where $\tau=\frac{C}{D}$ = thermal time constant of the machine

the constant of integration can be obtained by substituting the initial condition at t = 0. Let the temperature at t = 0 is θ_1, then the solution becomes

$\theta_1 = \theta_{ss} + K$ → K = $\theta_1 - \theta_{ss}$, substituting in the $\theta(t)$ expression above,

$$\theta(t) = \theta_{ss}(1 - e^{\frac{-t}{\tau}}) + \theta_1 e^{\frac{-t}{\tau}}$$

θ_{ss} is the steady state temperature at which all the heat produced is dissipated in to the surrounding medium.

Let the load on machine be thrown off after its temperature rise reaches a value θ_2. Heat loss will reduce to a small value $P_1^{'}$ and the cooling operation of the motor will begin. Let the new value of the heat dissipation constant be *D'* . If the time is measured from the instant the load is thrown off, then

$$C\frac{d\theta}{dt} = P_1^{'} - D^{'}\theta$$

Solving the above the equation same as above, the solution becomes

$$\theta(t) = \theta_{ss}^{'}(1 - e^{\frac{-t}{\tau^{'}}}) + \theta_2 e^{\frac{-t}{\tau^{'}}}$$

Where $\theta_{ss}^{'} = \frac{P_1^{'}}{D^{'}}$ = steady state temperature fall for new conditions of operation

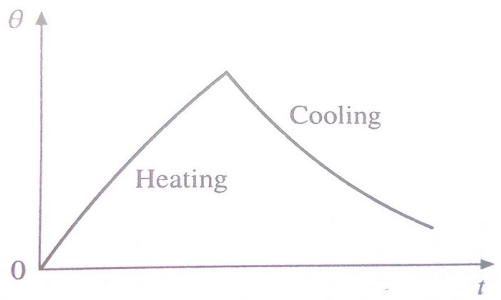
and $\tau^{'} = \frac{C}{D^{'}}$ = Cooling (or thermal) time constant of the machine.

If motor is disconnected from the supply during cooling then, $P_1^{'} = \theta_{ss}^{'} = 0$, then the final temperature becomes,

$$\theta = \theta_2 e^{\frac{-t}{\tau^{'}}}$$

In self cooled motors, where cooling fan is mounted on motor shaft, the velocity of cooling air varies with motor speed, thus varying cooling time constant $\tau^{'}$. In such cases the cooling time constant at standstill is much larger than when running. Therefore in high power applications, motor is provided separate forced cooling. So that motor cooling be independent of speed.

Figure shows the variation of motor temperature rise with time during heating and cooling. Thermal time constants of motor are far larger than electrical (1 to 100ms) and mechanical (10ms to 10 s) time constants. Thermal time constants varies from 10min to hours based type of cooling system, rating of the machine, ambient temperature, etc..



Heating and cooling curves

Classes of motor Duty:

Based on load time variations in practice, there are eight classes of duty

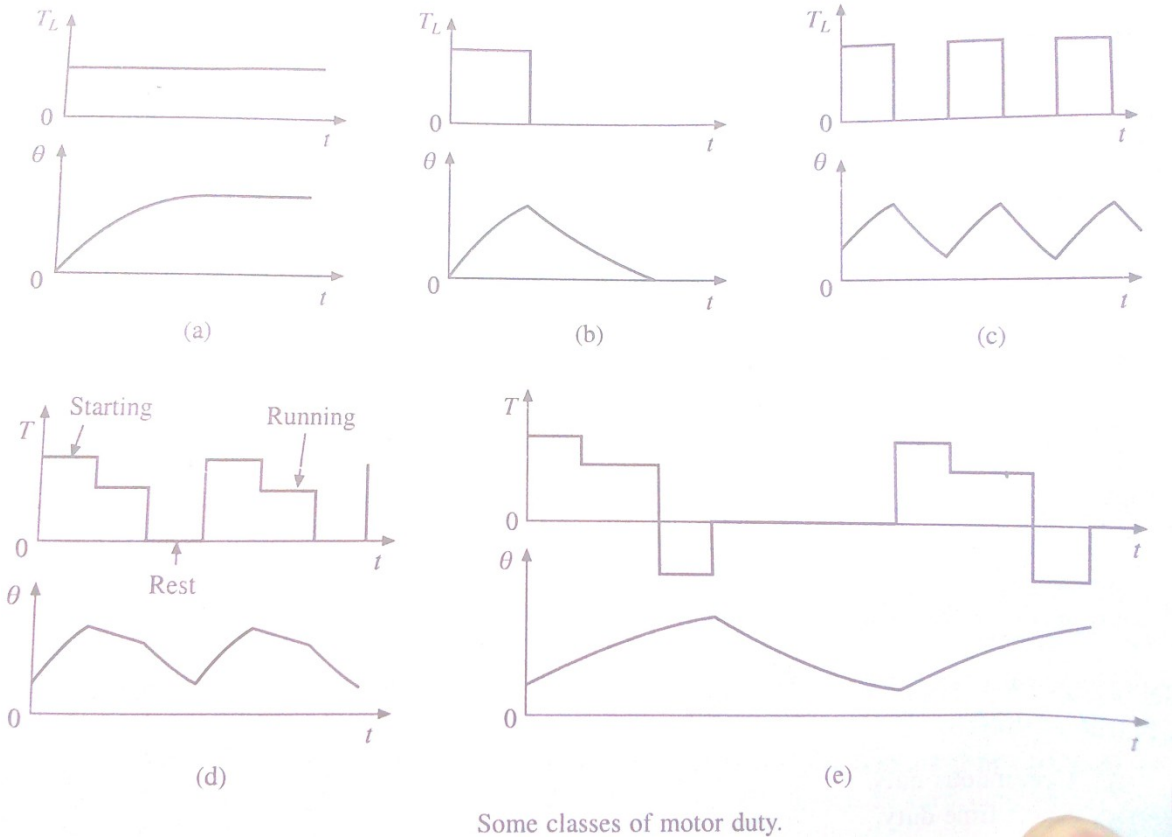
i) Continuous duty
ii) Short time duty
iii) Intermittent periodic duty
iv) Intermittent periodic duty with starting
v) Intermittent periodic duty with starting and braking
vi) Continuous duty with intermittent periodic loading
vii) Continuous duty with starting and braking
viii) Continuous duty with periodic speed changes

Continuous duty (fig. a): It denotes the motor operation at a constant load torque for duration long enough for the motor temperature to reach steady – state value. This duty is characterized by a constant motor loss. Ex:- paper mill drives, compressors, conveyors, centrifugal pumps, fans, etc..

Short time duty (fig. b): In this, the time of operation is less than heating time constant of the machine, the machine is allowed to cool before it start again. As the operation is for short time, the machine can be over loaded before the temperature exceeds the maximum temperature. Ex:- cranes, lifts, mixers, drilling machines, etc..

Intermittent Periodic Duty (fig. c): It consists of periodic duty cycles, each consists of periodic running at constant load and a rest period. The temperature may or may not reach to steady state value during heating. And temperature may reach or may not reach the ambient temperature during cooling. In this duty, heating of machine during starting and braking are negligible.

Ex:- pressing, cutting and drilling machine drives



Some classes of motor duty.

Intermittent period duty with starting (fig. d): This is intermittent periodic duty, where heat losses during starting cannot be ignored. In this duty, heating of machine during braking is negligible because the braking is smooth, or mechanical brakes are applied or machine stop because of its own friction. Ex:- metal cutting drive, drill tool drives, drives for fork lift trucks and mine hoists.

Intermittent periodic duty with starting and braking (fig. e): This is intermittent periodic duty, where heat losses during starting and braking cannot be ignored. Ex:- Billet mill drive, manipulator drive, ingot buggy drive, locomotives and mine hoist.

Continuous duty with intermittent periodic loading: It consists of periodic duty cycles, each consisting of a period of running at a constant load and a period of running at no load, with normal voltages across the excitation winding. Again the load period and no load period are too short for the respective temperatures to be attained. This duty has difference from the *Intermittent periodic duty,* that it consists of constant load followed by no load period instead of rest period. Ex:- pressing, shearing and drilling machine drives.

Continuous duty with starting and braking: this consists of periodic duty cycle, each having a period of starting, a period of running at constant load and a period of electrical braking. There is no rest period. Ex: blooming mill drive.

Continuous duty with periodic speed changes: Consists of periodic duty cycle, each having a period of running at one load and speed, and another period of running at different speed and load. Again both periods are too short to attain respective steady state temperature. Further there is no rest period.

Determination of motor rating

Form the point of view of calculation of motor rating for various duty cycles, the duty cycles are broadly classified as

(i) Continuous duty
(ii) Fluctuating loads
(iii) Short time and intermittent duty.

Continuous duty:- To select the motor rating in this case, power demand is calculated. A motor with next higher power rating commercially available is selected. Obviously at the same time, the speed should match the load requirements, starting torque must be enough to drive the load and time response must be as per the load requirement.

Equivalent current, torque and power methods for fluctuating and intermittent loads: this method can be employed for class of duties from (iii) – (viii). In this the equivalent motor rated current (I_{eq}) is calculated, which produces same motor losses machine as actual current. Any machine consists of variable losses(winding losses or copper losses) and constant losses(iron, friction and windage losses). Let P_c is constant losses which are independent of load. Let the fluctuating load drawing a current of I_1, I_2, . . . I_n for durations t_1,t_2, . . . t_n respectively. The equivalent current can be calculated as follows.

$$P_c + I_{eq}^2 R = \frac{\left(P_c + I_1^2 R\right)t_1 + \left(P_c + I_2^2 R\right)t_2 + \ldots + \left(P_c + I_n^2 R\right)t_n}{t_1 + t_2 + \ldots + t_n}$$

$$P_c + I_{eq}^2 R = \frac{P_c(t_1 + t_2 + \ldots + t_n)}{t_1 + t_2 + \ldots + t_n} + \frac{\left(I_1^2 t_1 + I_2^2 t_2 + \ldots + I_n^2 t_n\right)R}{t_1 + t_2 + \ldots + t_n}$$

$$I_{eq}=\sqrt{\frac{\left(I_1^2t_1+I_2^2t_2+\ldots+I_n^2t_n\right)}{t_1+t_2+\ldots+t_n}}$$

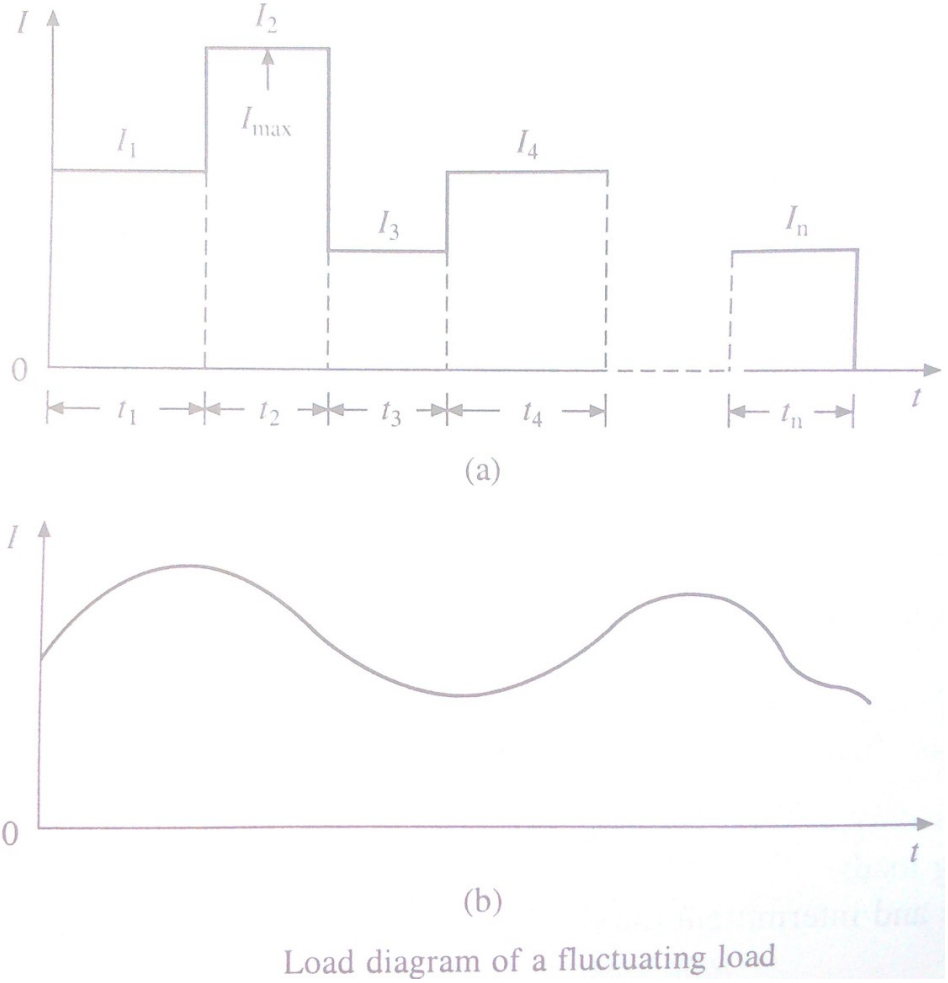
If the current varies smoothly over a period Tas shown in figure, the equivalent current can be calculated as

$$I_{eq}=\sqrt{\frac{1}{T}\int_0^T i^2dt}$$

Integral $\int_0^T i^2\,dt$ represents the area under curve of i^2 vs t curve and the time axis for duration 0 to T.

In the above analysis, the assumption is that heating and cooling conditions are same. If the motor runs at constant speed the heating and cooling conditions are same. If speed varies, the constant losses will change. If cooling is forced cooling, the heating and cooling will remain the same. In self ventilating machines, the cooling will change with respect to speed.

Once I_{eq} is determined, the commercially available next higher current rating (I_{rated}) machine is purchased.



Load diagram of a fluctuating load

The chosen current rating can be checked for its practical feasibility as follows.

DC motor: A DC motor usually allowed to carry 2 to 4 times the rated current for short time. Let the short time overload capacity is λ, it should see that $\lambda > (I_{max}/I_{rated})$ else I_{rated} is selected such that $I_{rated} > (I_{max} / \lambda)$.

Induction and synchronous motor: in case of induction and synchronous motor, for stable operation, maximum load torque should be well within the breakdown torque of the motor. If the selected motor current rating violates this constraint, the motor rating is selected to satisfy breakdown torque constraint. The breakdown torque in case of induction motor varies from 1.65 to 3 times the rated current and it is 2 to 2.25 in case of synchronous motor. If the ratio of breakdown to rated torque is denoted by λ' , then the rated torque is chosen based on

$T_{rated} > (T_{max} / \lambda')$.

When torque is directly proportional to current, the equivalent torque can be cal calculated as follows

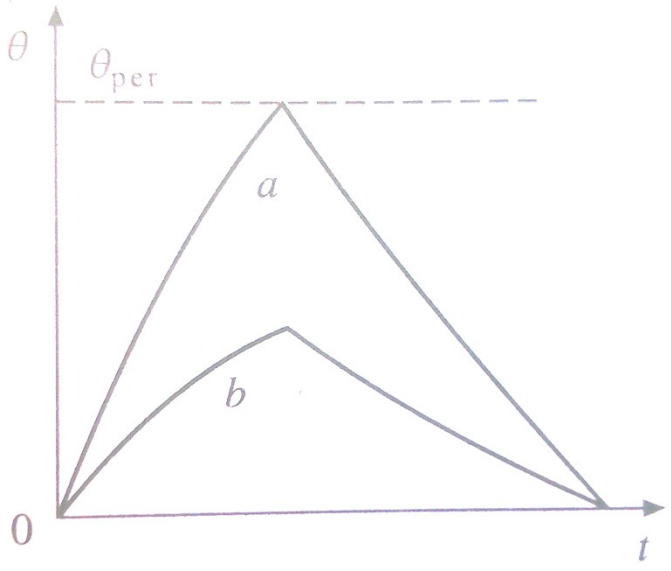
$$T_{eq}=\sqrt{\frac{T_1^2 t_1+T_2^2 t_2+\ldots+T_n^2 t_n}{t_1+t_2+\ldots+t_n}}$$

When the motor operates nearly fixed speed, its power will be directly proportional to torque. Then equivalent power can be calculated as follows

$$P_{eq}=\sqrt{\frac{P_1^2 t_1+P_2^2 t_2+\ldots+P_n^2 t_n}{t_1+t_2+\ldots+t_n}}$$

Short time duty:-

In short time duty, time of motor operation is considerably less than the heating time constant and motor is allowed to cool down to the ambient temperature before it is required to operate again. If a motor with continuous duty power rating of P_r is subjected to a short time duty load of magnitude P_r' then the motor temperature rise will be far below the maximum permissible value θ_{per} and the motor will be highly underutilized. Therefore the motor can be overloaded by a factor K (K>1) such that maximum temperature rise just reaches the maximum permissible value θ_{per} as shown in figure.



θ vs t curves for short time duty loads:
a—with power KP_r; b—with power P_r

The overloading factor K can be calculated as follows

$$\theta_{per}=\theta_{ss}\left(1-e^{\frac{-t_r}{\tau}}\right)$$

(It is written from $\theta(t)=\theta_{ss}(1-e^{\frac{-t}{\tau}})+\theta_1 e^{\frac{-t}{\tau}}$, neglecting initial temperature rise)

$$\frac{\theta_{ss}}{\theta_{per}}=\frac{1}{1-e^{\frac{-t_r}{\tau}}}$$

In the above formula, θ_{ss} is the steady state temperature rise which will be attained if motor delivers a power (KP_r) on continuous basis. Where as θ_{per}also steady state temperature rise if the motor operates with a power P_r. if the motor power losses are P_{lr} and P_{ls} for powers P_r and KP_r respectively.

$$\frac{\theta_{ss}}{\theta_{per}}=\frac{P_{ls}}{P_{lr}}=\frac{1}{1-e^{\frac{-t_r}{\tau}}}$$

(From the formula $\theta_{ss}=\frac{P_1}{D}$ = steady state temperature of the machine)

Let $P_{lr}=P_c+P_{cu}=P_{cu}(\alpha+1)$ where $\alpha=\frac{P_c}{P_{cu}}$, $P_c=constant\,losses \wedge ¿\ P_{cu}=coppere\,losses$

Similarly $P_{ls}=P_c+P_{cu}\left(\frac{KP_r}{P_r}\right)^2=P_c+K^2P_{cu}=P_{cu}¿\ K^2¿$

$$now=\frac{P_{ls}}{P_{lr}}=\frac{\alpha+K^2}{\alpha+1}=\frac{1}{1-e^{\frac{-t_r}{\tau}}}$$

From the above $K=\sqrt{\frac{\alpha+1}{1-e^{\frac{-t_r}{\tau}}}-\alpha}$

The above equation allows the calculation of overloading factor K which can be calculated when constant losses and copper losses are known separately.

Intermittent period duty:-

Let us consider a simple intermittent load, where the motor is alternatively subjected to a fixed magnitude load P_r' for a duration of t_r and stand still condition of t_s. in steady state the temperature will fluctuate between a maximum value θ_{max} and θ_{min} as show in figure. The motor rating should be selected such that θ_{max}<¿ θ_{per}.

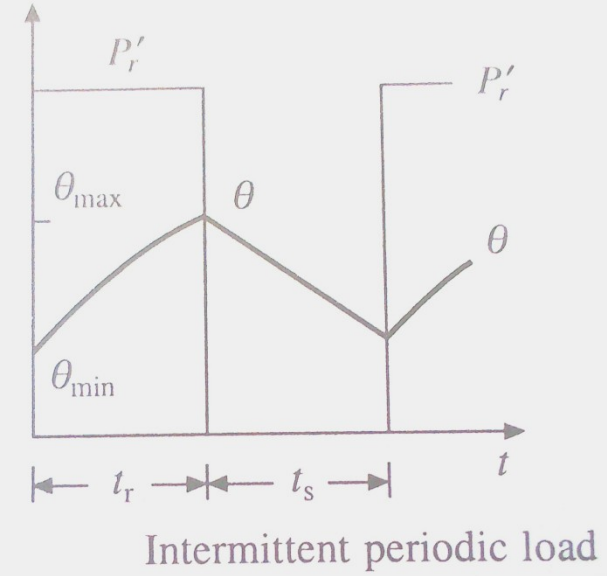
The temperature at the end of working interval is given by

$$\theta_{max}=\theta_{ss}\left(1-e^{\frac{-t_r}{\tau_r}}\right)+\theta_{min}e^{\frac{-t_r}{\tau_r}}$$

And the fall in temperature in standstill is given by

$$\theta_{min}=\theta_{max}e^{\frac{-t_r}{\tau_s}}$$

θ'_{ss}= 0 as motor is in stand stiil



Where $\tau_r$and $\tau_s$are thermal constants of the motor for working and standstill conditions.

Combining the above two equations

$$\frac{\theta_{ss}}{\theta_{max}}=1-e^{-\{¿¿¿}$$

As θ_{per} is the maximum permissible temperature rise of the motor, for full utilization of motor, $\theta_{max}=¿\ \theta_{per}$. From the discussion of short time duty

$$\frac{\theta_{per}}{\theta_{ss}}=\frac{P_{ls}}{P_{lr}}$$

$$P_{lr}=P_{cu}(\alpha+1)$$

$P_{ls}=P_{cu}¿\ K^2¿$

The overloading factor K (P_r'/P_r) is given by

$$K=\sqrt{(\alpha+1)1-e^{-¿¿¿¿}}$$

Example 3.1

A rolling mill driven by thyristor converter-fed dc motor operates on a speed reversing duty cycle. Motor field current is maintained constant at the rated value. Moment of inertia referred to the motor shaft is 10,000 kg-m^2. Duty cycle consists of the following intervals.

i) Rolling at full speed (200 RPM) and a constant torque of 25,000 N-m for 10 sec

ii) No load operation for 1 sec at full speed.
iii) Speed reversal from 200 to – 200 RPM in 5 sec
iv) No load operation for 1 sec at full speed.
v) Rolling at full speed and at a torque of 20,000 N-m for 15 sec.
vi) No load operation at full speed for 1 sec
vii) Speed reversal from – 200 to 200 RPM in 5 sec.
viii) No load operation at full speed for 1 sec.

Determine torque and power ratings of the motor.

Solution: Since the motor filed current is constant, torque is proportional to current. Then the equivalent torque can be finding in a same manner of finding equivalent current.

During reversal, load torque $T_l = 0$, the speed changing from 200 to – 200 RPM in 5 sec.

The torque during reversing is, $T = J\frac{dw}{dt} = 10000$ ¿¿= 83776 N-m

T_{rated} or T_{rms} or T_{eq} is given by

$$T_{rms} = \sqrt{\frac{25000^2 * 10 + (83776^2 * 5)2 + 20000^2 * 15}{39}} = 47,686 N - m$$

The toque during reversal is 83776 N-m, which is only 1.76 time than rated torque, so rated torque of 47,686 N-m can be accepted.

Power rating of the motor = $\frac{47686 * 200 * 2\pi}{60} = 998.7 Kw$

Example: 3.2

A constant speed drive has following duty cycle:
i) Load rising from 0 to 400 KW in 5 min.
ii) Uniform load of 500 KW for min.
iii) Regenerative power of 400 KW returned to the supply for 4 min.
iv) Remains idle for 2 min.
Estimate power rating of the motor. Assume losses to be proportional to (power)

Solution:
Rated power = rms value of power P_{rms}
RMS value of the power in interval i) is

$$P_1 = \sqrt{\frac{1}{5}\int_0^5 \left(\frac{400 * x}{5}\right)^2 dx} = \frac{400}{\sqrt{3}} KW$$

$$P_{rms} = \sqrt{\frac{\left(\frac{400}{\sqrt{3}}\right)^2 * 5 + 500^2 * 5 + 400^2 * 4}{16}} = 367 KW$$

Since the P_{max} less than two times of P_{rms}, the motor power rating can be taken as 376 KW

Example 3.3

A motor has a heating time constant f 60 min and cooling time constant of 90 min. When run continuously on full load of 20 KW, the final temperature rise is 40^0C.

(i) What load the motor can deliver for 10 min if this is followed by a shut down period long enough for it to cool

(ii) If it is on an intermittent load of 10 min followed by 10 min shut down, what is the maximum value of load it can supply during the on load period.

Solution:

As the constant and copper losses are not given, they are assumed to be proportional to square of the power and $\alpha$is assumed to be zero.

(i) The over loading factor for short time duty is given by $K=\sqrt{\frac{\alpha+1}{1-e^{\frac{-t_r}{\tau}}}-\alpha}$, taking $\alpha=0$

$K=\sqrt{\frac{1}{1-e^{\frac{-t_r}{\tau}}}}$ = $\sqrt{\frac{1}{1-e^{\frac{-10}{60}}}}$ = 2.55

Permitted load = 2.55 * 20 = 51 KW.

(ii) The over loading factor for intermittent load is given by

$$K=\sqrt{(\alpha+1)1-e^{-¿¿}¿¿}$$

Taking $\alpha=0$

$$K=\sqrt{1-e^{-¿¿}¿¿} = 1.257$$

Permitted load = 1.257 * 25.14 KW

Example 3.4:

Half an hour rating of a motor is 100 KW. Heating time constant is 80 min and the maximum efficiency occurs at 70% full load. Determine the continuous rating of the motor.

Solution : at maximum efficiency, copper losses is equal to the constant losses

P_{cu} be copper losses at full load and P_c be the constant losses, at 70 % loading

$P_{cu} * 0.7^2 = P_c \rightarrow P_c / P_{cu} = 0.49$

That is $\alpha=\frac{p_c}{P_{cu}}=0.49$

The over loading factor is given by

$$K=\sqrt{\frac{\alpha+1}{1-e^{\frac{-t_r}{\tau}}}-\alpha}$$

$$K=\sqrt{\frac{0.49+1}{1-e^{\frac{-30}{80}}}-0.49}=2.0676$$

$$therefore\,the\,continuous\,rating=\frac{100}{2.0676}=48.37\,KW$$

Exercise Problems:

1. A drive consisting of semiconductor converter fed DC motor, runs according to the following periodic cycle:

i) Acceleration from standstill to 1000 RPM in 10 sec at uniform acceleration
ii) Running at 1000 RPM and 800 N-m torque for 8 sec
iii) Braking from 1000 RPM to standstill in 10 sec at uniform deceleration
iv) Remain idle for 20 sec

Determine torque and power ratings of the machine. Assume forced cooling and constant field current. J = 100 kg-m^2

(Ans: 750.73N-m, 78.616 KW)

2. A constant speed motor has the following duty cycle:

Load rising linearly from 200 to 500 KW: 4min
Uniform load of 400 KW: 2min
Regenerative power returned to the supply reducing linearly from 400 KW to 0: 3min
Remains idle: 4 min
Determine power rating of the motor assuming loss to be proportional to $(power)^2$

(Ans: 277.35 KW)

3. A motor has heating constant of 70 min and a cooling constant of 90 min. When running continuously on full load of 400 KW, final temperature rise is 50^0C.

i) What load can be delivered by the motor for 10 min if the initial temperature rise is zero
ii) When used in short time periodic duty cycle consisting of load period of 10min followed by no load period long enough for the motor to cool down, what will be the maximum load that motor can carry
iii) Determine the maximum load the motor can deliver when subjected to intermittent periodic load cycle consisting of a load period of 10 min followed by a no load period of 15 min.

Assume losses to be proportional to $(power)^2$

(Ans: (a) 1096.3 KW (b)1096.3 KW (c) 565.64 KW)

4. The 10 min motor rating of motor used in a domestic mixer is 200 watt. The heating time constant is 40 min and the maximum efficiency occurs at full load (continuous). Determine continuous rating

(Ans: 70.53 KW)

5. A motor has a continuous rating of 100 KW. The heating and cooling time constants are 50 and 70 min respectively. The motor has a maximum efficiency at 80% full load and is employed in an intermittent periodic load cycle consisting of a load period of 10 min followed by a no load period of 10 min. calculate the value of the load in KW during the load period.

(Ans: 140.93 KW)