Electrical Drives

5. Selection of motor power rating

- The power rating of a motor for a specific application must be carefully chosen to achieve economy with reliability.
  - use of a motor having insufficient rating
    - it fails to drive the load;
    - lowers the productivity and reliability through frequent damages and shut-downs due to overloading of the motor and power modulator;
  - use of motor having extra power than needed
    - extra initial cost
    - extra loss of energy
    - operate below rated power factor

(extra initial cost, extra loss of energy } uneconomical)

(operate below rated power factor } Especially, IMs & Synch. motors)

- **It is clear that, heat is produced due to losses in copper, iron and friction during motor operation.**

- **As the temperature of the motor increases beyond ambient value part of the heat flows to the surrounding medium.**

- **As outflow of heat increases, equilibrium sets when the heat generated becomes equal to heat dissipated.**

- **The motor temperature reaches steady state and it depends on power loss, which intern depends on the output power of the machine; and this dependence of temperature rise on output power which is taken as thermal loading on the machine.**

- Steady state temperature is not the same at various parts of the machine. It is usually highest in the winding because loss density in conductors is high and dissipation rate is low. (since windings are embedded in slots)
- Among the various materials used in machines, insulation has the lowest temperature limit.
- Depending on the temperature limits, insulating materials are divided into classes.

Insulation temperature limits

Insulation class	temperature limit
γ	90ºC
A	105oC
E	120ºC
B	130ºC
F	155ºC
H	180ºC
C	Above 180ºC

- **For a specific operation, motor rating should be chosen such that the insulation temperature never exceeds the prescribed limit. Otherwise, it will lead to its immediate thermal break down causing short circuit and damage of the winding.**

- **For loads which operate at a constant power and speed, determination of motor power rating is simple.**

- **Usually, most loads operate at variable power and speed, and the patterns of these variations are different for different applications**

5.1. Thermal model of motor for heating and cooling

- An accurate prediction of heat flow and temperature rise inside an electrical motor is very difficult owing to complex geometrical shapes and use of heterogeneous materials.

- A drive engineer's duty is to select a motor rating for a given application ensuring that temperature in various parts of motor body do not exceed the safe limit.

- Thus, assuming that heat conductivities of various materials do not differ by large amount and thus by assuming the motor to be homogeneous, a simple thermal model of the machine can be obtained. Although inaccurate, such a model is good enough to determine rating of a motor.

- Let the motor as assumed, be a homogeneous body, and the cooling medium has the following parameters at time" t".

  P1 = Heat developed; joules/sec or watts

  P2 = Heat dissipated to the cooling medium; joules/sec or watts

  W = weight of the active parts of the motor; kg

  h = Specific heat; joules/kg/^{0}C

  A = cooling surface area; m^2

  d = Coefficient of heat transfer; joules/sec/m^2/^{o}C

  θ = mean temperature rise; ^{o}C

- During a time increment dt, let the machine temperature rise be dθ,

- **Since ,**

Heat absorbed (stored) in the motor = { Heat developed inside the motor – Heat dissipated to the surrounding }

OR $$Whd\theta = P_1 dt - P_2 dt \qquad \text{..................} \qquad 5.1$$

Since $$P_2 = \theta dA \qquad \text{..................................} \qquad 5.2$$

substituting 5.2 in 5.1, we get;

$$C\frac{d\theta}{dt} = P_1 - D\theta$$ **First order diff. equation** **5.3**

Where, C = Wh, thermal capacity of the motor; watt/°C
D = dA, heat dissipation constant; watt/°C

- **Heat dissipation mainly occurs through convection. Typical values of "d" are in the range of 40 of 600 w/m²/ºC.**
- **The 1st order differential equation 5.3. has a solution;**

$$\theta = \theta_{ss} + Ke^{-\frac{t}{\tau}} \qquad \text{.....................} \qquad \textbf{5.4}$$

Constant of integration K is obtained by Substituting the temperature rise at t = 0.

where,

$$\theta_{ss} = \frac{P_1}{D}$$

$$\tau = \frac{C}{D}$$

Heating or thermal time constant of the motor

- **when the initial temperature rise is θ_1, the solution of the above equation is;**

$$\theta = \theta_{ss}(1 - e^{-\frac{t}{\tau}}) + \theta_1 e^{-\frac{t}{\tau}} \qquad \text{.........} \qquad \textbf{5.5}$$

- As $t = \infty$, $\theta = \theta_{ss}$; thus, θ_{ss} is the steady state temperature of the motor when it is continuously heated by power P_1. At this temp., all the heat produced in the motor is dissipated to the surrounding medium.

- Let the load on the motor be thrown off after its temperature rise reaches a value θ_2. Heat loss will reduce to a small value P'_1. and cooling operation of the motor will begin.
- Let the new value of heat dissipation constant be D'. If time is measured from the instant the load is thrown off, then;

$$C\frac{d\theta}{dt} = P_1^{'} - D^{'}\theta \quad \text{....................} \quad 5.6$$

- Solving this equation subjected to the initial condition $\theta = \theta_2$ at $t = 0$ gives;

$$\theta = \theta^{'}_{ss}(1 - e^{-\frac{t}{\tau}}) + \theta_2 e^{-\frac{t}{\tau}} \quad \text{.........} \quad 5.7$$

Where,

$$\theta'_{ss} = \frac{P'_1}{D'}$$

Θ'_{ss} - is again steady state temperature rise for new conditions of operation and;

$$\tau' = \frac{C}{D'}$$

τ' - is known as the cooling (thermal) time constant of the motor.

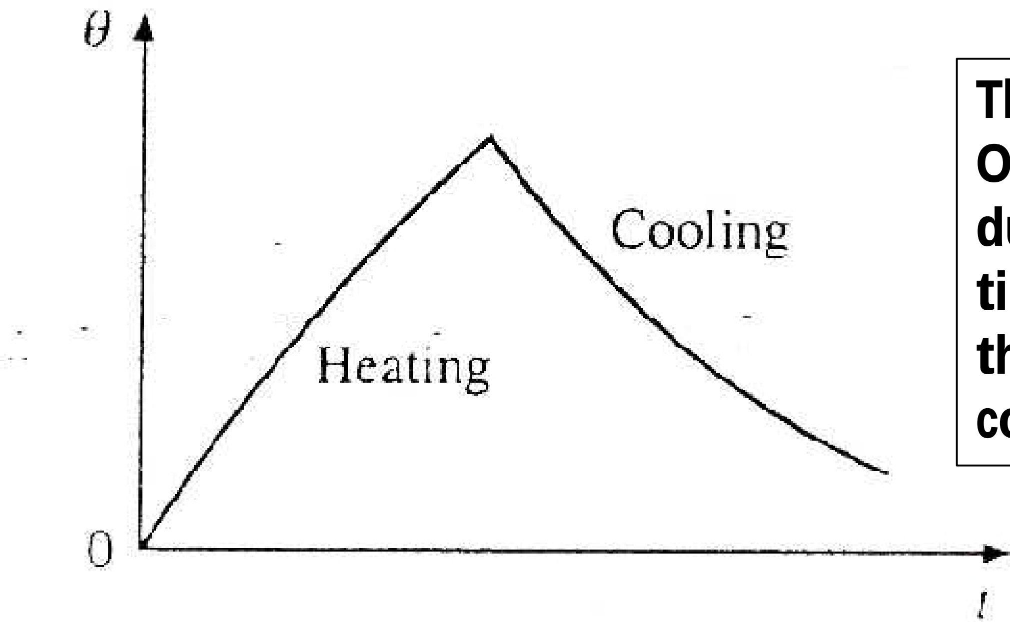
If the motor were disconnected from the supply during cooling then $P'_1 = \theta'_{ss}$ This explains that the final temperature attained by the motor will be ambient temperature.

If substituted in equation 5.7, then

$$\theta = \theta_2 e^{-\frac{t}{\tau}} \quad \text{.........} \quad 5.8$$

This shows that both heating time constant τ and cooling time constant τ' depend on the respective heat dissipation constants D and D', which in turn depend on the velocity of cooling air.

- In self cooled motors where cooling fan is mounted on the motor shaft, the velocity of cooling air varies with motor speed, thus varying cooling time constant τ'.
- In high performance , medium and high power variable speed drives, motor is always provided with separate forced cooling, so that motor cooling be independent of speed.



This figure shows the variation Of motor temperature rise with time during heating and cooling. Thermal time constants of a motor are far larger than electrical and mechanical time constants.

Fig. 5.1. Heating and cooling curves

5.2. Classes of motor duty

- **The three basic classes of motor duty are: -**

a) Continuous duty

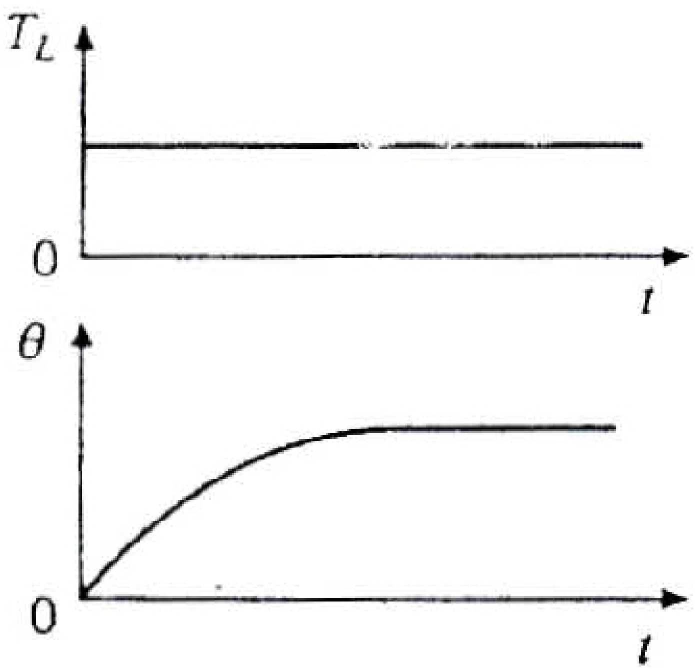


Fig. 5.2. motor load diagram

It denotes the motor operation at a constant load torque for s duration long enough for the motor temperature To reach steady state value. This duty is characterized by a constant motor loss.

Paper mill drives, compressors, fans etc

b) Short time duty

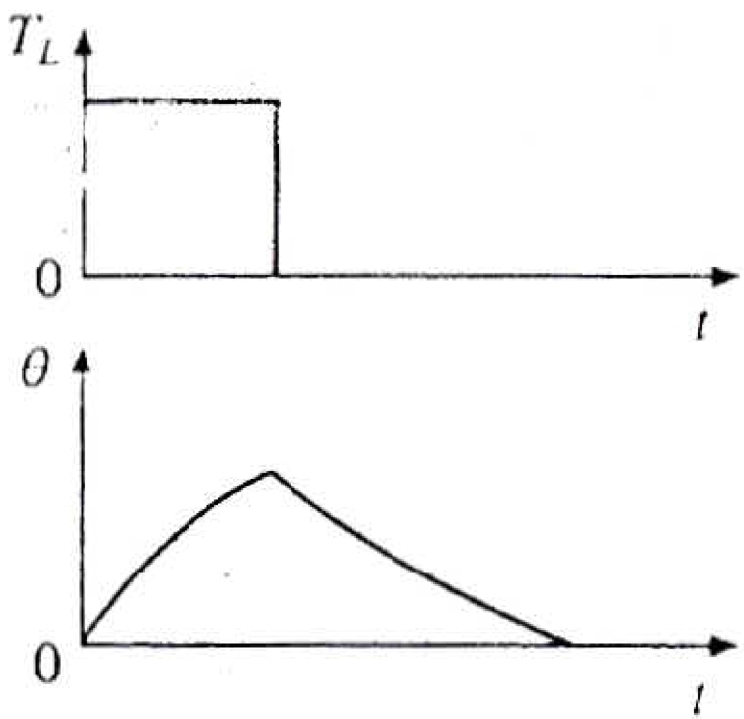


Fig. 5.3. Motor load diagram

Time of drive operation is considerably less than the heating time constant and motor is allowed to cool off to ambient temperature before the motor is required to operate again.
In this operation, the machine can be overloaded until temperature at the end of loading time reaches the permissible limit.

e.g. Cranes, valve drives, drives for position control, etc

c) Intermittent periodic duty

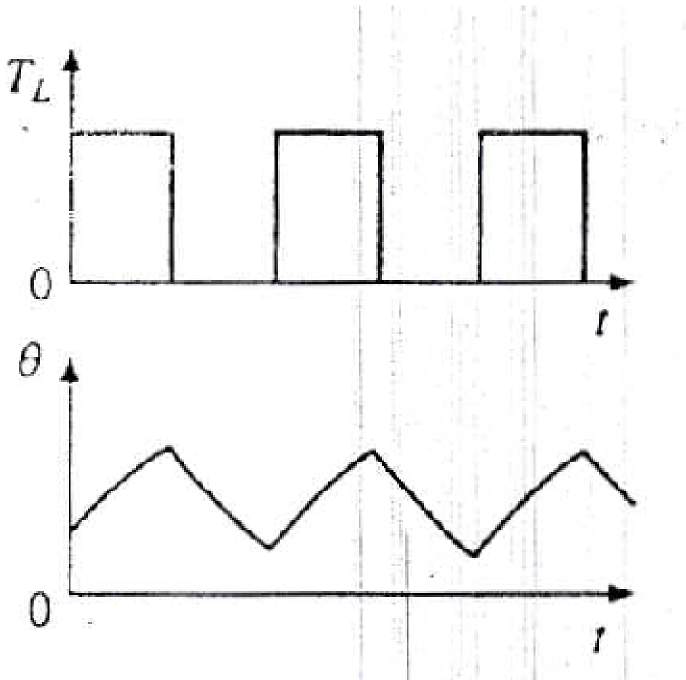


fig. 5.4. motor load diagram

**It consists of periodic duty cycles,
each consisting of a period of running
At a constant load and a rest period.
Neither the duration of running period
is sufficient to rise the temperature to a
Steady value nor the rest period is long
enough for the machine to cool to ambient
temperature.
e.g. metal cutting and drilling tool drives,
fork lift drives etc**

5.3. Determination of Motor rating

- To determine motor rating, duty cycles discussed previously can be broadly classified as: -

    i) Continuous duty

    ii) Fluctuating loads

    iii) Short-time and intermittent duty

i) Continuous duty: -

- The selection of the motor capacity for such a drive is simple if we know approximately the constant power input required by the machine.
- In order to select a motor for a rating equal to the known power input requirement , one may be sure that this rating is the maximum permissible with respect to heating because the manufacturer designs and rates it so as to attain maximum utilization of the material used at rated output.

- **For continuous duty at constant or slightly varying load, a motor is selected from the relevant catalogue for a capacity corresponding to the power required.**
- **Although losses during starting are greater than those under rated load, they may be neglected because starting under continuous duty is very infrequent and practically no influence on motor heating.**

ii) Fluctuating and intermittent duty

- **Equivalent current, torque and power methods**

- **This method is based on approximation that the actual variable motor current can be replaced by an equivalent I_{eq}, which produces same losses in the motor as actual current. The equivalent current is determined as follows;**

- As we know, motor loss (P_l) consists of two components.
    - P_c - Constant loss which is independent of load
        - Core loss and friction loss
    - P_{cu} - Variable loss () dependant on load
        - copper loss

Thus for a fluctuating load consisting of n values of motor currents $I_1, I_2, I_3, \ldots, I_n$ for duration $t_1, t_2, t_3, \ldots, t_n$ respectively, the equivalent current I_{eq} is: -

$$P_c + I^2{}_{eq}R = \frac{\left(P_c + I^2{}_{eq}R\right)t_1 + \left(P_c + I^2{}_{eq}R\right)t_2 + \ldots + \left(P_c + I^2{}_nR\right)t_n}{t_1 + t_2 + \ldots + t_n}$$

$$P_c + I^2{}_{eq}R = \frac{P_c\left(t_1 + t_2 + \ldots + t_n\right)}{t_1 + t_2 + \ldots + t_n} + \frac{\left(I^2{}_1t_1 + I^2{}_2t_2 + \ldots + I^2{}_nt_n\right)R}{t_1 + t_2 + \ldots + t_n}$$

$$I_{eq} = \sqrt{\frac{I^2{}_1 t_1 + I^2{}_2 t_2 + \ldots + I^2{}_n t_n}{t_1 + t_2 + \ldots + t_n}} \qquad \text{.........} \quad 5.9$$

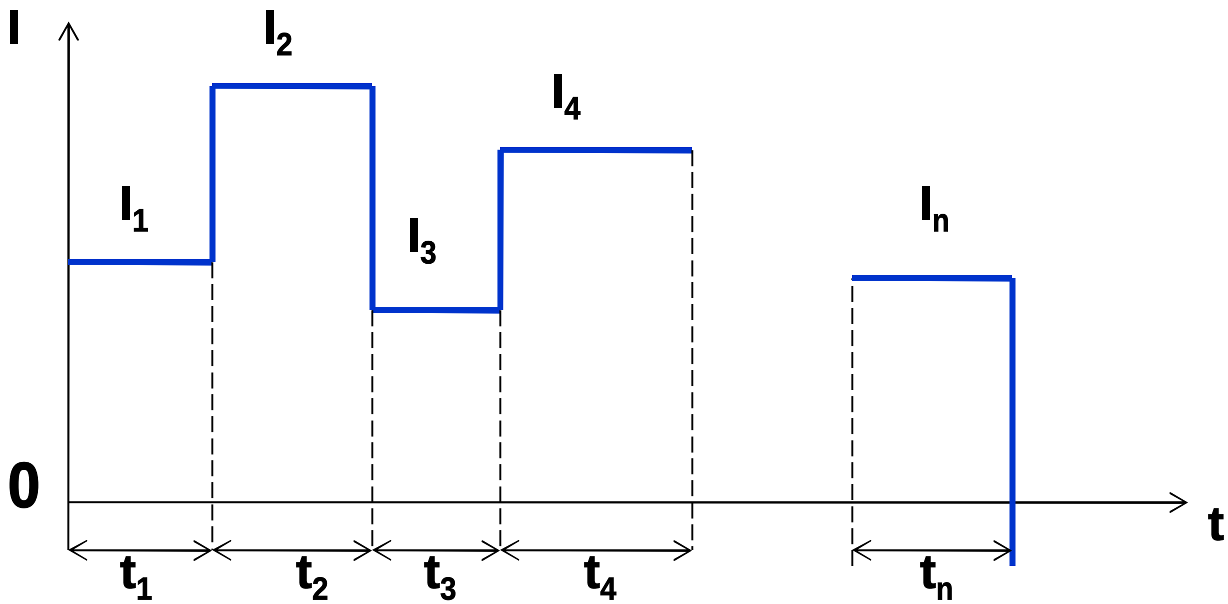


Fig. 5.5. (a) Load diagram of Fluctuating load

- If the current varies smoothly over a period T, I_{eq} is: -

$$I_{eq} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} \qquad \text{.................................} \qquad 5.10$$

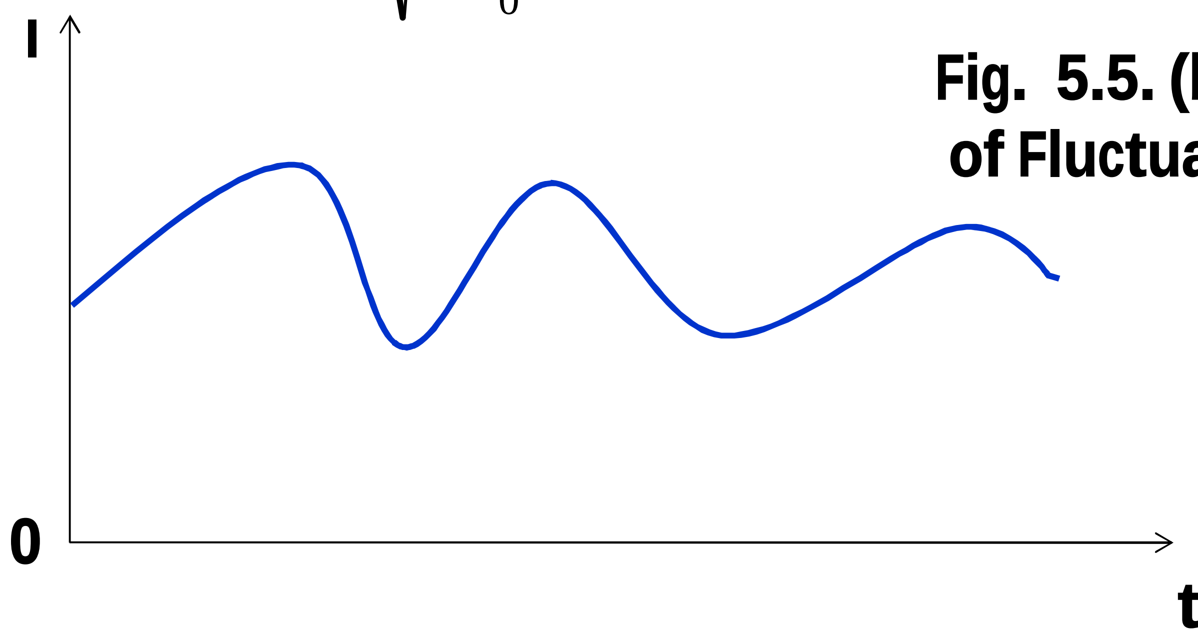


Fig. 5.5. (b) Load diagram of Fluctuating load

- After I_{eq} is determined, a motor with next higher current rating from commercially available rating is selected. Then this rating is checked for its practical feasibility . i.e. ,

DC motor

- This motor can be allowed to carry larger than the rated current for a short duration. (Short time overload capacity of the motor)
- A normally designed DC machine is allowed to carry up to 2 times the rated current. (for special designs, 3 – 5.3)
- Let the ratio of maximum allowable current (short time overload current capacity) to rated current be λ.

$$\lambda \geq \frac{I_{\max}}{I_{rated}}$$

Where, I_{max} is the maximum value of current (fig 5.5.) and I_{rated} is the motor rated current

If the above condition is not satisfied, the motor rating is calculated from: -

$$I_{rated} \geq \frac{I_{\max}}{\lambda} \qquad \text{..} \qquad 5.11$$

Induction and Synchronous motors

- In case of induction and synchronous motors, for stable operation, maximum load torque should be well within the breakdown torque of the motor.

- The ratio of breakdown to rated torque for induction motors with normal design varies from 1.65 to 3 and for synchronous motors it varies from 2 to 2.25. (for special SM types up to 3.5)

- If the ratio of breakdown to rated torque is λ', then the motor torque rating is chosen based on;

$$T_{rated} \geq \frac{T_{\max}}{\lambda'} \qquad \text{..............................} \qquad 5.12$$

- The equivalent current method assumes "constant losses" to remain constant for all operating points. Therefore, this method should be carefully employed when these losses vary.
- It is also not applicable to motors with frequency (or speed) dependent parameters of the equivalent circuit;

  e.g. in deep bar and double squirrel cage rotor motors where the rotor winding resistance and reactance vary widely during starting and braking.

-When torque is directly proportional to current;

  e.g. dc separately excited motor,

$$T_{eq} = \sqrt{\frac{T^2{}_1 t_1 + T^2{}_2 t_2 + \ldots + T^2{}_n t_n}{t_1 + t_2 + \ldots + t_n}} \quad \ldots\ldots \quad 5.13$$

- **When a motor operates at nearly fixed speed, its power will be directly proportional to torque. Hence, for nearly constant speed operation, power rating of the motor can be obtained directly from;**

$$P_{eq} = \sqrt{\frac{p^2{}_1 t_1 + p^2{}_2 t_2 + \ldots + p^2{}_n t_n}{t_1 + t_2 + \ldots + t_n}} \qquad \ldots\ldots\ldots \qquad \mathbf{5.14}$$

<u>Example</u>

A constant speed drive has the following duty cycle.

i) Load rising from 0 to 400 KW ; 5 min

ii) Uniform load of 500 KW; 5 min

iii) Regenerative power of 400 KW returned to the supply; 4 min

iv) Remains idle for ; 2 min

Estimate power rating of the motor. Assume losses to be proportional to (power)^2

Sol.

Rated power = rms value power. = P_{rms} ;

Now the rms value of the power in interval (i) is;

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

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

Since P_{max} = 500 KW is less than two times P_{rms}, motor rating = 367 KW

Work out

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-m2. Duty cycle consists of the following intervals: -

   i) Rolling at full speed(200 rpm) and at a constant torque of 25,000N-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 the torque and power of the motor.

Solution.

iii) 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.
- A motor with continuous duty power rating P_r can be overloaded by a factor K (K>1) such that the power rating becomes KP_r and the maximum temperature rise reaches the permissible value (θ_{per}).

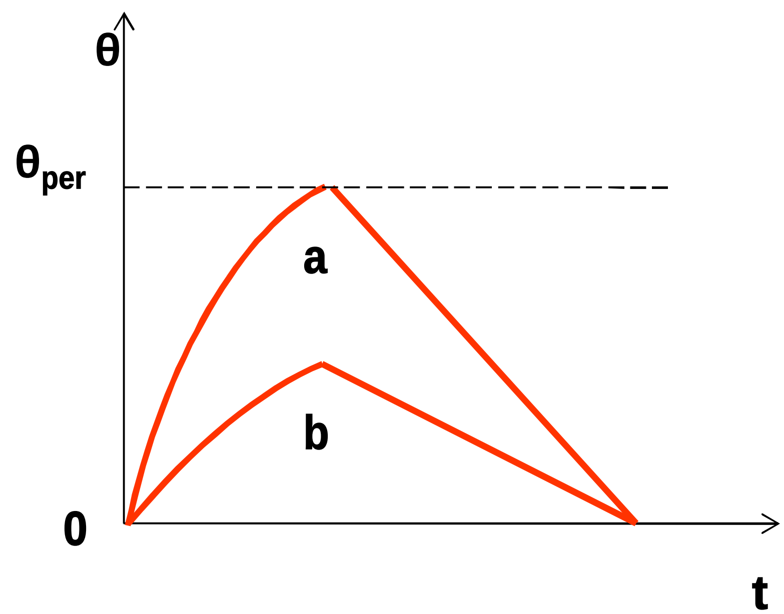


Fig. 5.6. θ vs t curves for short time duty loads
(a) - with power KP_r
(b) - with power p_r

- **When the duration of running period in a duty cycle with power KP_r is t_r, then from equation 5.5;**

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

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{1}{1 - e^{\frac{-t_r}{\tau}}} \qquad \text{............... .....} \qquad 5.15$$

Note that θ_{ss} is the steady state temperature rise which will be attained if the motor delivers a power (K_{Pr}) on continuous bases, whereas the permissible temperature rise θ_{per} is also the steady state temperature rise attained when the motor operates with a Power P_r on continuous bases.

- **If the motor losses for powers P_r and KP_r be P_{1r} and P_{1s}, respectively, then**

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{P_{1s}}{P_{1r}} = \frac{1}{1-e^{-\frac{t_r}{\tau}}} \quad \text{..................... ....} \quad 5.16$$

$$P_{1r} = P_c + P_{cu} = P_{cu}(\alpha + 1) \quad \text{...................} \quad 5.17$$

Where,

$$\alpha = \frac{P_c}{P_{cu}} \quad \text{...} \quad 5.18$$

and P_c is the load independent (constant) loss and P_{cu} the load dependent loss. Then;

$$P_{1s} = P_c + P_{cu}\left(\frac{KP_r}{P_r}\right)^2 = P_c + K^2 P_{cu} \quad \text{..................} \quad 5.19$$

-Making substitutions results;

$$P_{1s} = P_{cu}(\alpha + K^2) \quad \text{.......................................} \quad \mathbf{5.20}$$

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

$$K = \sqrt{\frac{1+\alpha}{1 - e^{-t/\tau}} - a} \quad \text{.....................................} \quad \mathbf{5.21}$$

Equation 5.21 allows the calculation of overloading factor K which can be calculated when constant and variable losses are known separately. If not Known separately, total loss is assumed to be only proportional to (Power)^2; i.e. alpha (α) is assumed to be 0.

- **As already mentioned, K is subjected to the constraints imposed by maximum allowable current in case of dc motors and breakdown torque limitations in case of IM and SM.**

Intermittent periodic duty

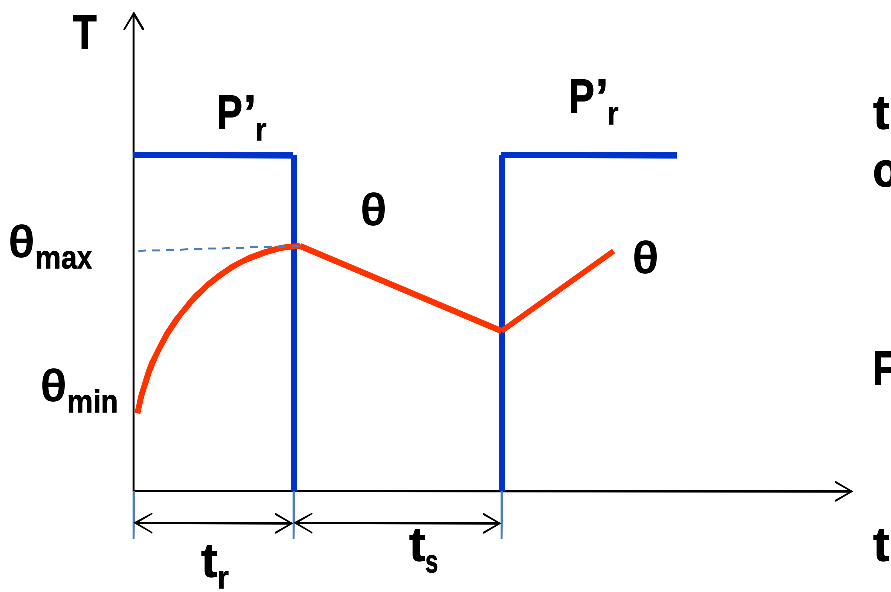
- During a period of operation, if the speed changes in wide limits, leading to changes in heating and cooling conditions, methods of equivalent current, torque or power described previously can not be employed.
- Let us consider an intermittent load where the motor is alternatively subjected a fixed load P_r' of duration t_r and stand still condition of t_s.
- As the motor is subjected to a periodic load, after the thermal steady state is reached the temperature rise will fluctuate between a max. value θ_{max} and a minimum value θ_{min}.
- For this load, the motor rating should be selected such that, $\theta_{max} \leq \theta_{per}$ where θ_{per} is the max. permissible temperature rise of the motor.

- **At the end of working (running) max. temperature will be;**

$$\theta_{\max} = \theta_{ss}\left(1 - e^{\frac{-t_r}{\tau_r}}\right) + \theta_{\min} e^{\frac{-t_r}{\tau_r}} \quad \text{..................} \quad 5.22$$

And fall in temperature rise at the end of standstill interval t_s will be

$$\theta_{\min} = \theta_{\max} e^{\frac{-t_s}{\tau_s}} \quad \text{..............................} \quad 5.23$$



t_r and t_s are thermal time constants of motor for working and standstill

Fig.5.7. intermittent periodic load

Combining 5.22 and 5.23, we can get;

$$\frac{\theta_{ss}}{\theta_{\max}} = \frac{1 - e^{\{(t_r/\tau_r)+(t_s/\tau_s)\}}}{1 - e^{-t_r/\tau_r}} \quad \text{..........................} \quad 5.24$$

For full utilization of the motor, $\theta_{max} = \theta_{per}$. Further θ_{per} will be the motor temperature rise when it is subjected to its continuous rated power P_r.

$$\frac{\theta_{ss}}{\theta_{\max}} = \frac{P_{1s}}{P_{1r}} \quad \text{.............................} \quad 5.25$$

Overload factor K is given by

$$K = \sqrt{(\alpha+1)\frac{1 - e^{-\{(t_r/\tau_r)+(t_s/\tau_s)\}}}{1 - e^{-t_r/\tau_r}} - \alpha} \quad \text{............} \quad 2.26$$

Example

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

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.

Sol.

Alpha(α) is assumed to be zero, since constant and copper losses are not available separately.

i) When **α = 0, the overloading factor is;**

$$K = \sqrt{\frac{1}{1-e^{-t_r/\tau}}} = \sqrt{\frac{1}{1-e^{-10/60}}} = 2.25$$

Permitted load = 2.25x20 = 51 KW

ii) From equation 5.26 for α = 0,

$$K = \sqrt{\frac{1-e^{-\{(t_r/\tau_r)+(t_s/\tau_s)\}}}{1-e^{-t_r/\tau_r}}} = \sqrt{\frac{1-e^{-\left\{\frac{10}{60}+\frac{10}{90}\right\}}}{1-e^{-10/60}}} = \sqrt{\frac{0.2425}{0.1535}} = 1.257$$

Permitted load = 1.257x20 = 25.14 KW

Work out

2. **Half 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.**

3. **A motor operates on a periodic duty cycle in which it is clutched to its load for 10 min and declutched to run on no load for 20 min. Minimum temperature rise is 40^{o}C. Heating and cooling time constants are equal and have a value of 60 min. When load is declutched continuously, the temperature rise is 15^{o}C. Determine,**

    i) Maximum temperature during the duty cycle.

    ii) Temperature when the load is clutched continuously.