Sizing of Electric Motors for Variable Speed Drive Applications

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Learning Objectives and Outcomes

- Learning Objectives:
  - Understand how to choose power rating of an electric motor optimally.
  - Understand different types of losses in electrical machines: constant losses and variable losses.
  - Understand what is meant by thermal loading of an electrical machine.
  - Understand loading capacity of an electrical machine.
  - Understand different types of time constants in an electric drive system.
- Learning outcome
  - You should be able to specify the right sizing (power rating) of an electrical machine for a given application and the type of the electrical machine to be used.

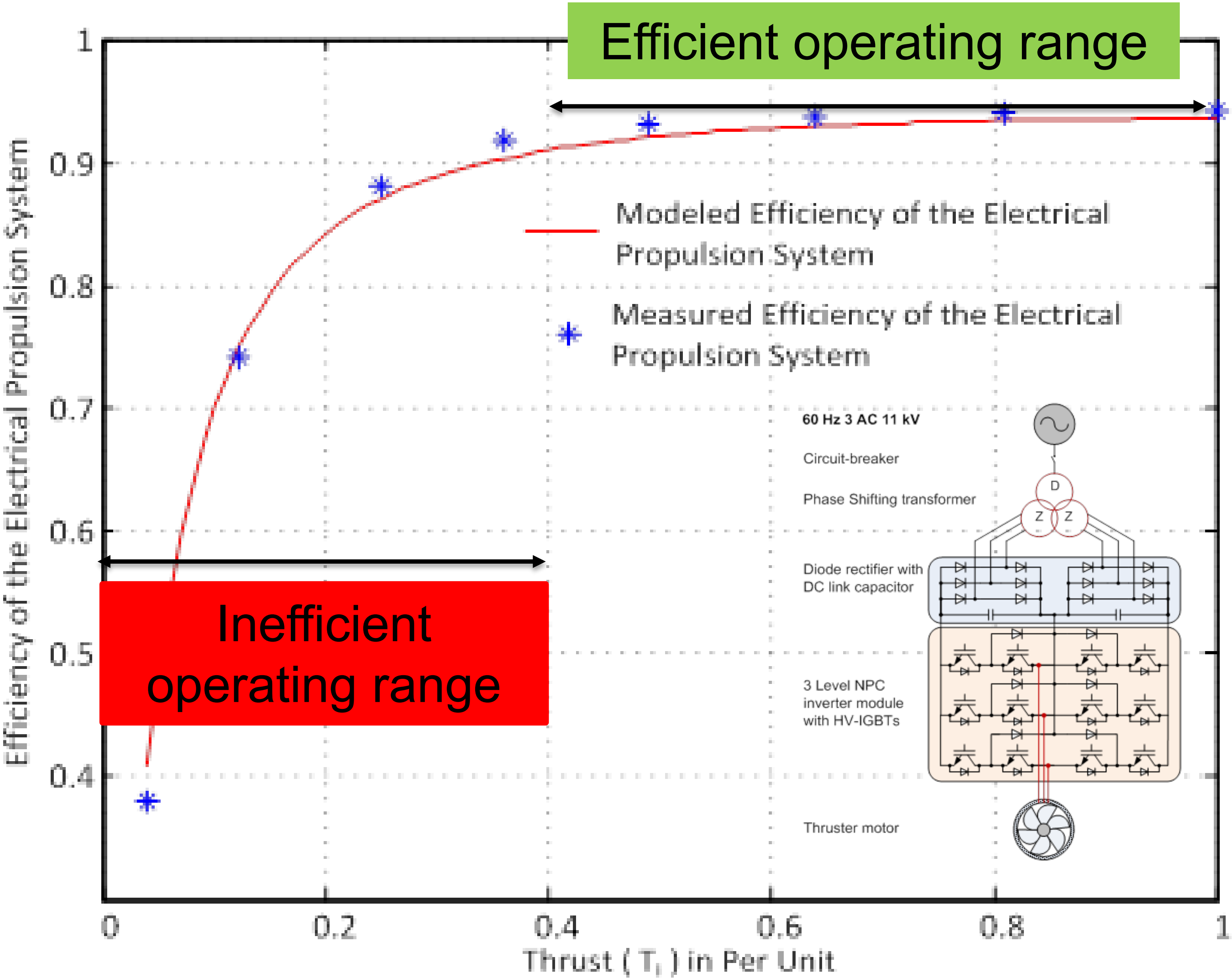
Selection of Motor Power Rating

- Power rating of an electric motor must be chosen carefully to make a balance between cost and reliability.

- Motors must satisfy requirements such as:
  - provide suitable torque-speed characteristics to match that of the load,
  - provide adequate output power on a sustained basis,
  - under full-load condition steady-state temperature rise of the motor windings and core must be within acceptable limit, and

  - must be capable of withstanding short-term overload and have enough torque to start and accelerate the drive system from rest.

- What happens if the motor chosen is under-rated ?
  - it fails to drive the load at nominal power or
  - lowers the productivity and reliability of the drive system.
- Alternatively, if the motor chosen is over-rated ?
  - it is expensive and
  - it runs inefficiently due to operation at reduced loading.



Efficient operating range

Inefficient operating range

Power Losses and Heating of Electric Motors

- During motoring operation, losses are produced which cause winding temperature to rise and subsequently heat is dissipated to the surrounding medium.
- Losses : **constant** and **variable** (copper) losses.

$$p = p_c + x^2 p_v \quad (2.1)$$

where p - total loss, p_c - constant loss, p_v - variable loss at rated load and x - percentage of motor load in terms of rated load.

- Losses ⇒ temperature rise ⇒ heat outflows ⇒ thermal equilibrium is reached (heat produced = heat dissipated, i.e. absolute temperature remains constant).

- At thermal equilibrium, temperature-rise reaches a steady-state value and is dependent on the total power loss, p which in turn is a function of the output power, P_{out} of the machine.

- The temperature rise of the machine has a direct relationship with the output power, P_{out} and is referred to as **thermal loading** of the machine.

- Steady-state temperature rise must always be maintained within acceptable limit of the winding insulating materials.

- Depending on the temperature rise limit, insulating materials used for windings are:
  - Class A: 105° *C* – cotton, synthetic, paper;
  - Class B: 130° *C* – resin;
  - Class H: 180° *C* – glass fibre, silicone rubber etc.

- Electrical machines have sufficient overload capability but thermal restriction does not allow continuous overloading - because losses ($p_{loss} \alpha i^2$) rise more steeply than output power ($P_{out} \alpha i$).

- Time lag due to thermal time constant between losses taking place and the resulting temperature rise - allows overloading of motors for short periods (of the order of few minutes) only.
- For loads operating at constant torque and speed it is easy to calculate rated output power rating of the motor ($P_{rated,\ output} = T_{em,rated} \times \omega_{m,rated}$).
- However, most of the motors operate with variable load (torque) and speed - it becomes difficult to calculate the power rating of the motor for such applications.

- The main objectives of our study in this chapter are:
  - to obtain a suitable thermal model of the electrical machine;
  - to categorize various types of loading into some standard form, and
  - to present methods for calculating motor power rating for various classes of duty (loading of the motor).

Thermal Model of Motor for Heating and Cooling

- Accurate prediction of heat flow and temperature distribution within the machine is very complex and extremely difficult to represent analytically.
- A simple thermal model may be obtained by assuming the machine as a homogeneous body having a uniform temperature gradient.
- Heat dissipation is assumed to be proportional to the temperature difference between the machine and the surrounding medium.

Heating Curve

- Let the electrical machine be considered as a homogeneous body and the cooling medium have the following parameters at any time t :

p_1 = heat developed, joule/s or watts,

p_2 = heat dissipated to the cooling medium,joule/s (W)

W = weight of the active part of the machine, kg,

h = specific heat, joule/kg/ºC,

A = area of the cooling surface, m²,

d = coefficient of heat transfer, joule/s/m² ºC,

θ = mean temperature rise, ºC, (above ambient)

$C = W \times h$ = thermal capacity of the machine, joule /ºC,

$D = d \times A$ = heat dissipation constant, watts /ºC

- During a time increment dt, let the machine temperature rise (above ambient) be $d\theta$.
- The heat balance equation is given by:

$$\begin{bmatrix} Heat \\ developed \\ in the \\ machine \end{bmatrix} = \left[\begin{pmatrix} Heat \\ dissipated \\ to the \\ surrounding \\ cooling medium \end{pmatrix} + \begin{pmatrix} Heat \\ absorbed \\ or stored \\ in the \\ machine \end{pmatrix}\right] \quad (2.2)$$

$$p_1 dt = p_2 dt + C d\theta$$

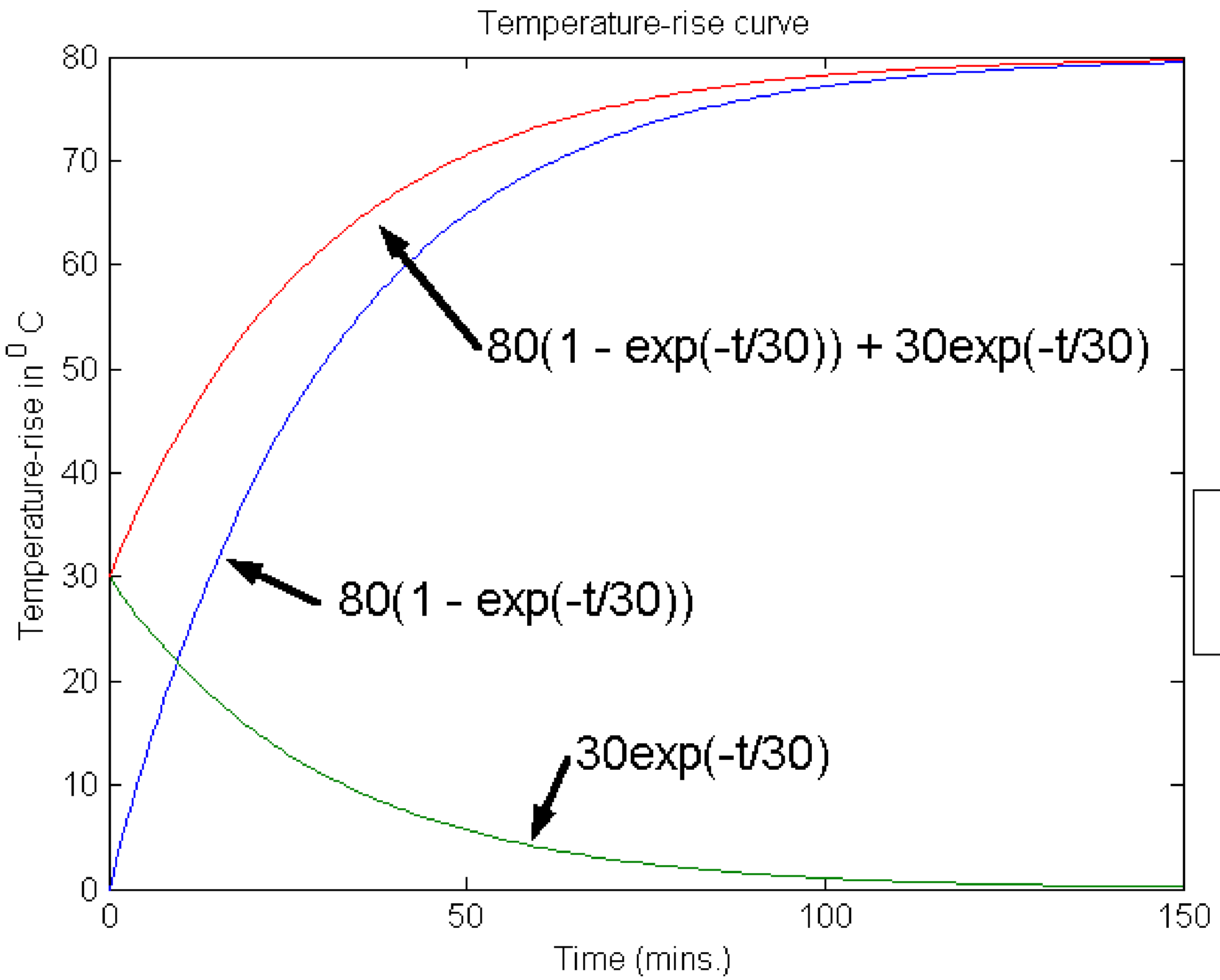
$$\frac{d\theta}{dt} + \frac{p_2}{C} = \frac{p_1}{C} [p_2 = (d \times A) \times \theta = D \times \theta]$$

$$\frac{d\theta}{dt} + \frac{D}{C}\theta = \frac{p_1}{C} \Rightarrow \frac{C}{D}\frac{d\theta}{dt} + \theta = \frac{p_1}{D}$$

$$\tau \frac{d\theta}{dt} + \theta = \theta ss \quad (2.3)$$

$$\Rightarrow \theta(t) = \theta_{ss}\left(1 - e^{-t/\tau}\right) + \theta_1 e^{-t/\tau} \quad (2.4)$$

- where τ = *C/D*, heating time constant,
- θ_1 - initial temperature rise and
- θ_{SS} (= p_1/D) - steady-state temperature rise.



$$\tau \frac{d\theta}{dt} + \theta = \theta ss$$

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

$\theta_1 = 30^0C$ &

$\theta_{ss} = 80^0C$

Figure 2.1: Heating temperature-rise curve of an electric motor.

Cooling Curve

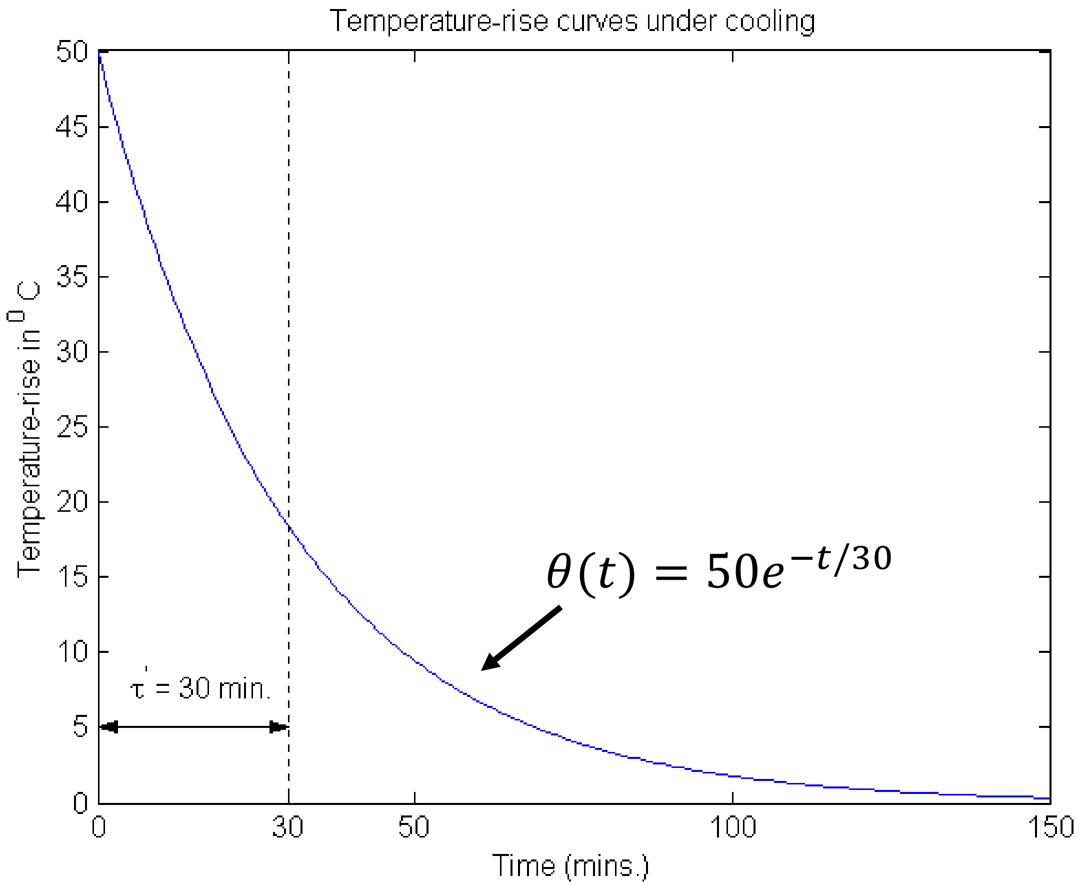
- When the machine is switched off, no heat is generated (p_1 = 0) - machine cools down and the temperature rise reduces to the ambient temperature.

- Heat balance equation 2.2:

$$0 = p_2 dt + C d\theta \rightarrow \frac{d\theta}{dt} + \frac{D'}{C}\theta = 0 \rightarrow \frac{C}{D'}\frac{d\theta}{dt} + \theta = 0 \quad (2.5)$$

$$\Rightarrow \theta(t) = \theta_2 e^{-t/\tau'} \; (2.6)$$

where $\tau' = C/D'$ time constant during cooling and $\theta_2 -$ initial temperature rise, $\mathrm{D}' = d' \times A -$ heat dissipation constant being different during cooling.



$$\theta_2 = 50^0 \text{ C}$$

Figure 2.2: Cooling curve of an electric motor switched off from the mains.

- Assume that load on the electrical machine is reduced rather than switched off completely so that ($p_1 > p_1{}' \neq 0$).
- This causes cooling of the machine and let the new value of the heat dissipation constant be *D'*.

$$\frac{d\theta}{dt} + \frac{D'}{C}\theta = \frac{p_1{}'}{C} \rightarrow \frac{C}{D'}\frac{d\theta}{dt} + \theta = \frac{p_1{}'}{D'} \quad (2.7)$$

$$\Rightarrow \ \theta(t) = \theta'_{ss}\left(1 - e^{-\frac{t}{\tau'}}\right) + \theta_2 e^{-\frac{t}{\tau'}} \quad (2.8)$$

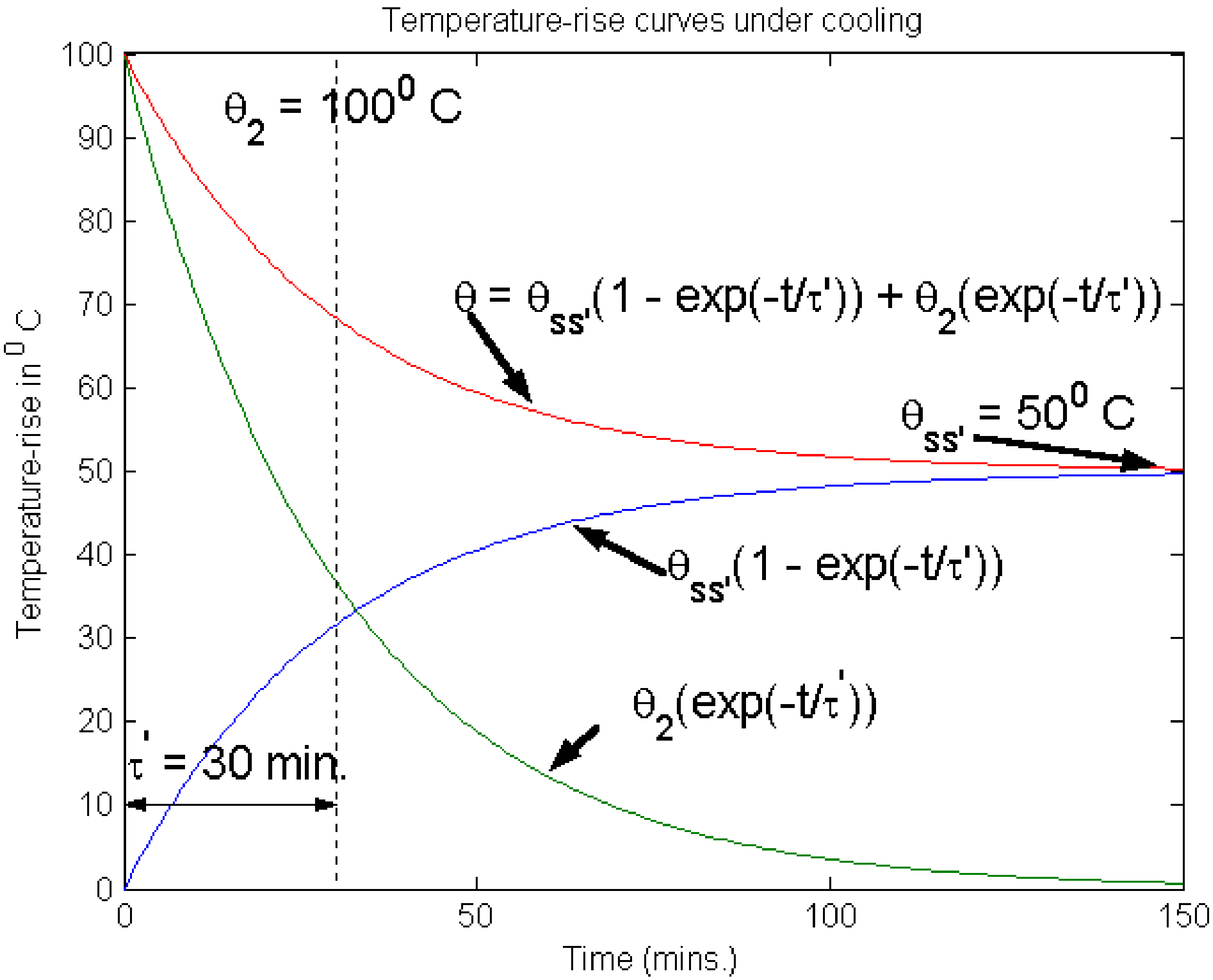


Figure 2.3: Cooling curve of an electric motor when the load is reduced but not equal to zero.

- If machine is switched-off from the mains supply completely then p'_1 = 0 and eqn. 2.8 reduces to:

$$\theta(t) = \theta_2 e^{-t/\tau'} \ (2.9)$$

- Cooling curve shown in Fig. 2.3 can be considered as the sum of two curves:
  - heating curve as if the machine is loaded to give a maximum temperature rise of θ'_{SS} (first term of the RHS of eqn. 2.8) and
  - cooling curve as if the machine is disconnected from the mains supply when the temperature rise is θ_2 (second term of the RHS of eqn. 2.8).

- In self-cooled machines heating time constant τ and cooling time constant τ' are different and it depends on the respective heat dissipation constant, *D*.

- Thermal time constant (of the order of mins.) is much higher usually order of magnitude larger than the mechanical time constant (sec), which is again order of magnitude higher than the electrical time constant (ms).

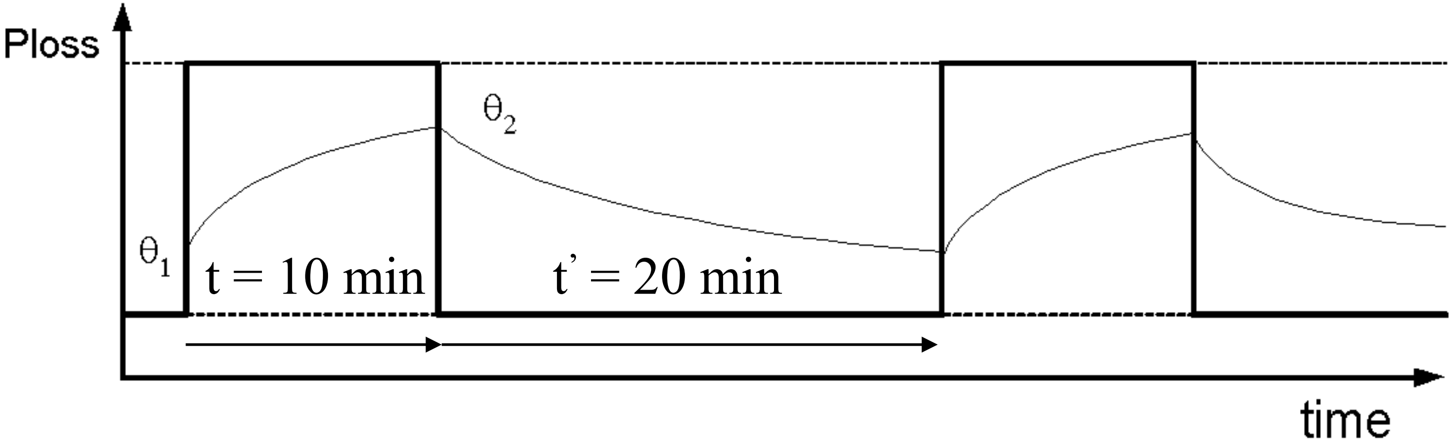
Electrical time constant	Mechanical time constant	Thermal time constant
0.1 – 100 ms	10 ms – 10 s	10 min – 60 min.

Example 2.1: A motor operates in a periodic duty cycle in which it is clutched (connected) to its load for 10 min. and de-clutched to run on no-load for 20 min. Minimum temperature rise is 40°C. Assume that heating and cooling time constants are equal and have value of 60 min. When load is de-clutched continuously the temperature rise is 15°C.

Determine:

(a) maximum temperature during the duty cycle, and

(b) temperature when the load is clutched continuously.



Solution: We have $\tau = \tau' = 60\ min$, $\theta_1 = 40°C$, $\theta'_{ss} = 15°C$.

We have $\theta_2 = 49.9°C$, $\theta_{SS} = 104.5°C$.

Classes of Motor Duty

- Various categories of load-time variations can be grouped into the following classes:
  - Continuous running duty
  - Short-time duty
  - Intermittent periodic duty
  - Intermittent periodic duty with high start-up torque
  - Intermittent periodic duty with high start-up torque and electrical braking

Continuous Duty

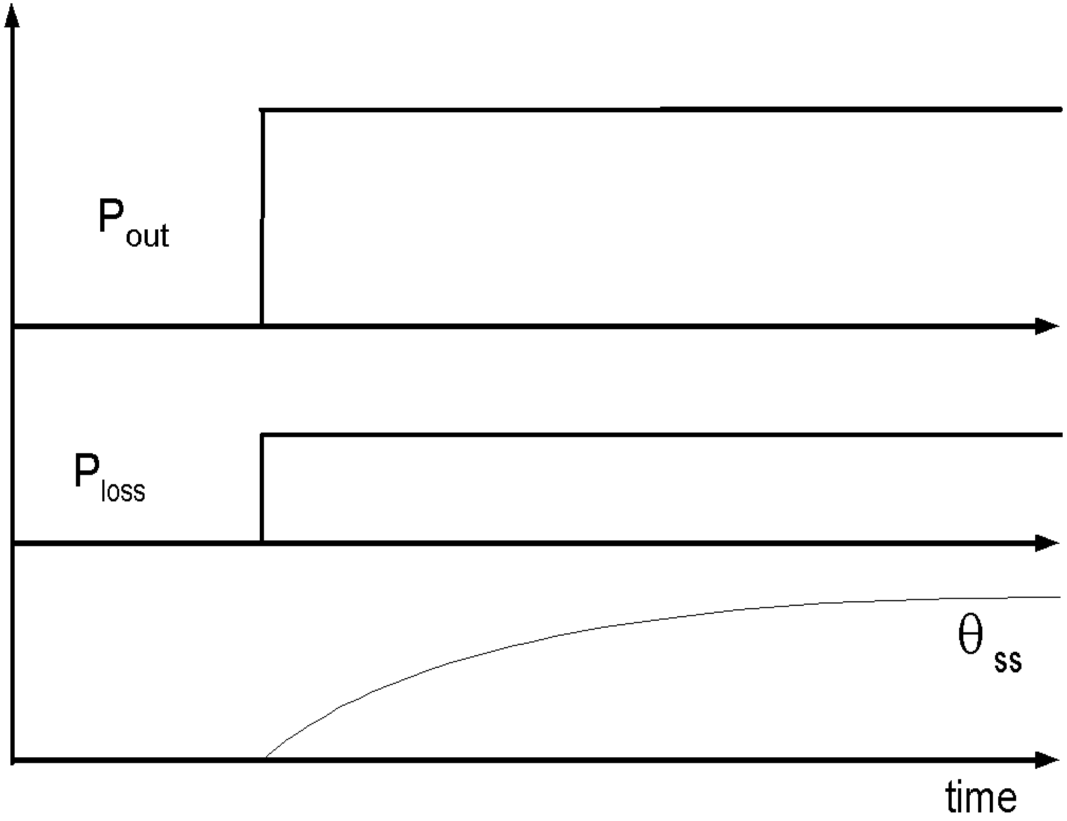


Figure 2.4: Continuous duty of a motor delivering the rated (constant) load.

- Examples - centrifugal pumps, fans and conveyors.

Short Time Duty

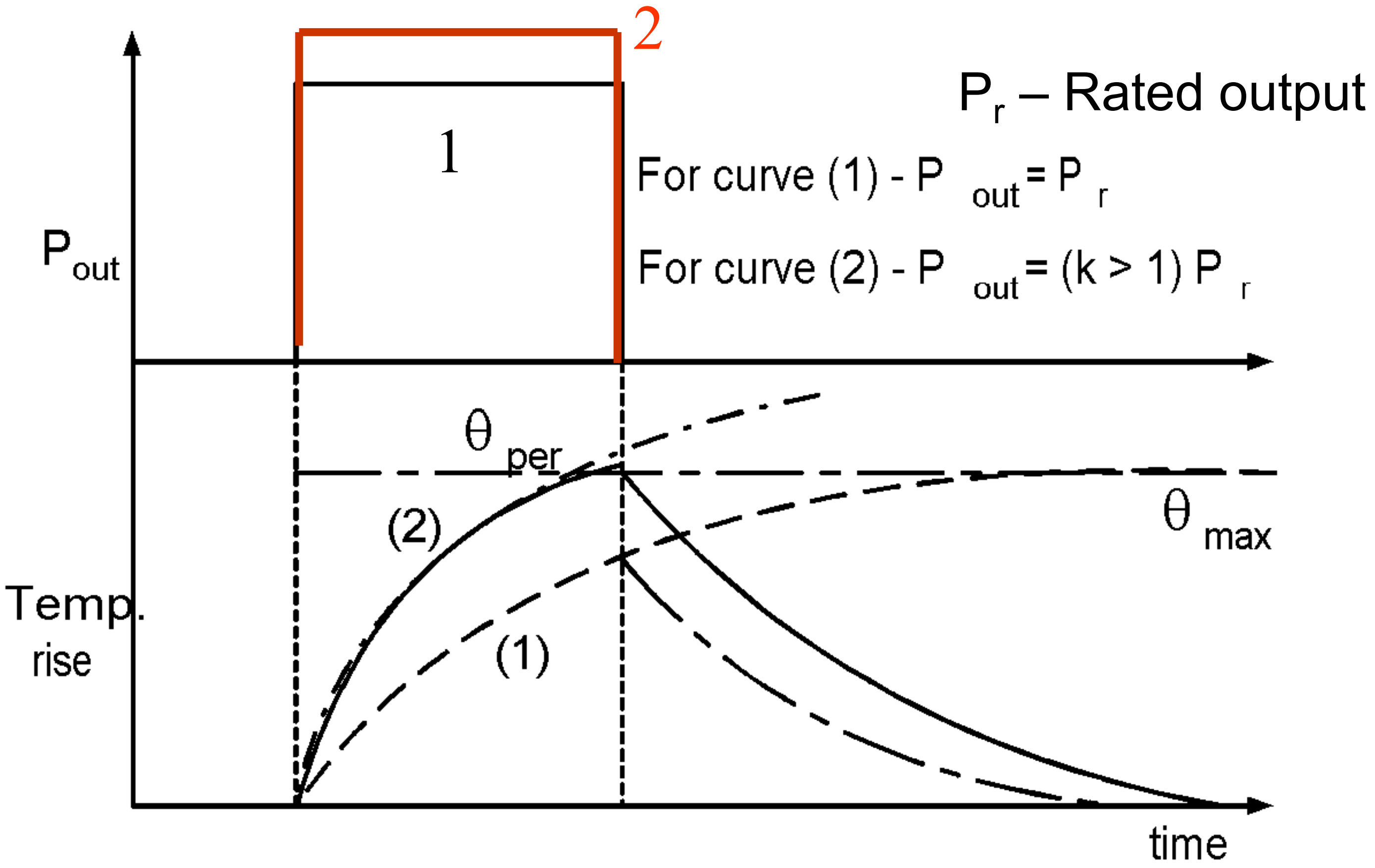


Figure 2.6: Short time duty of a motor (a) load diagram and (b) temperature rise curve.

- Examples - crane drives, household appliances, opening and closing of lock-gates and bridges etc.

Intermittent Periodic Duty

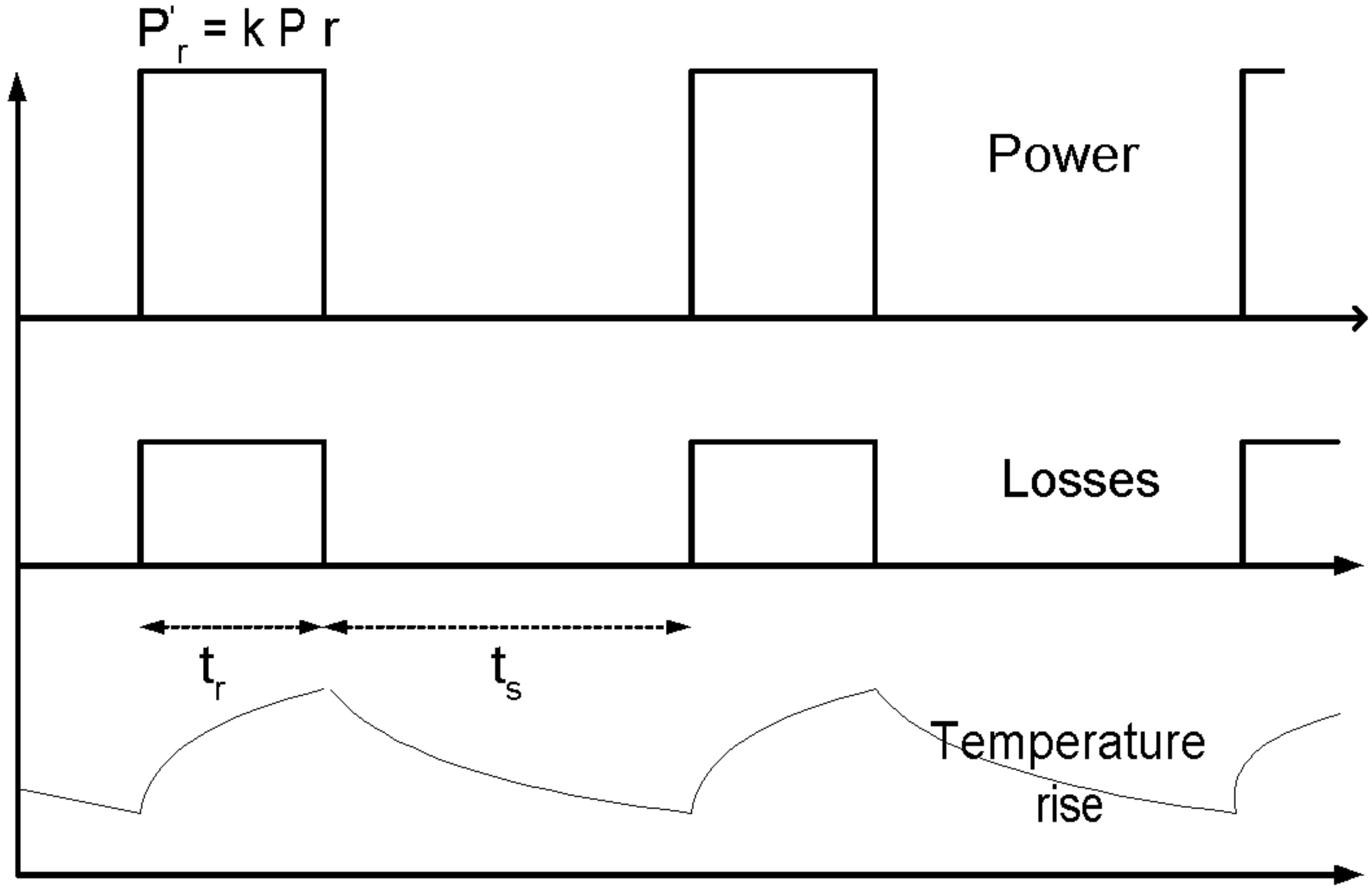


Figure 2.7: Periodic intermittent duty of a motor.

Intermittent Periodic Duty with High Start-up Torque

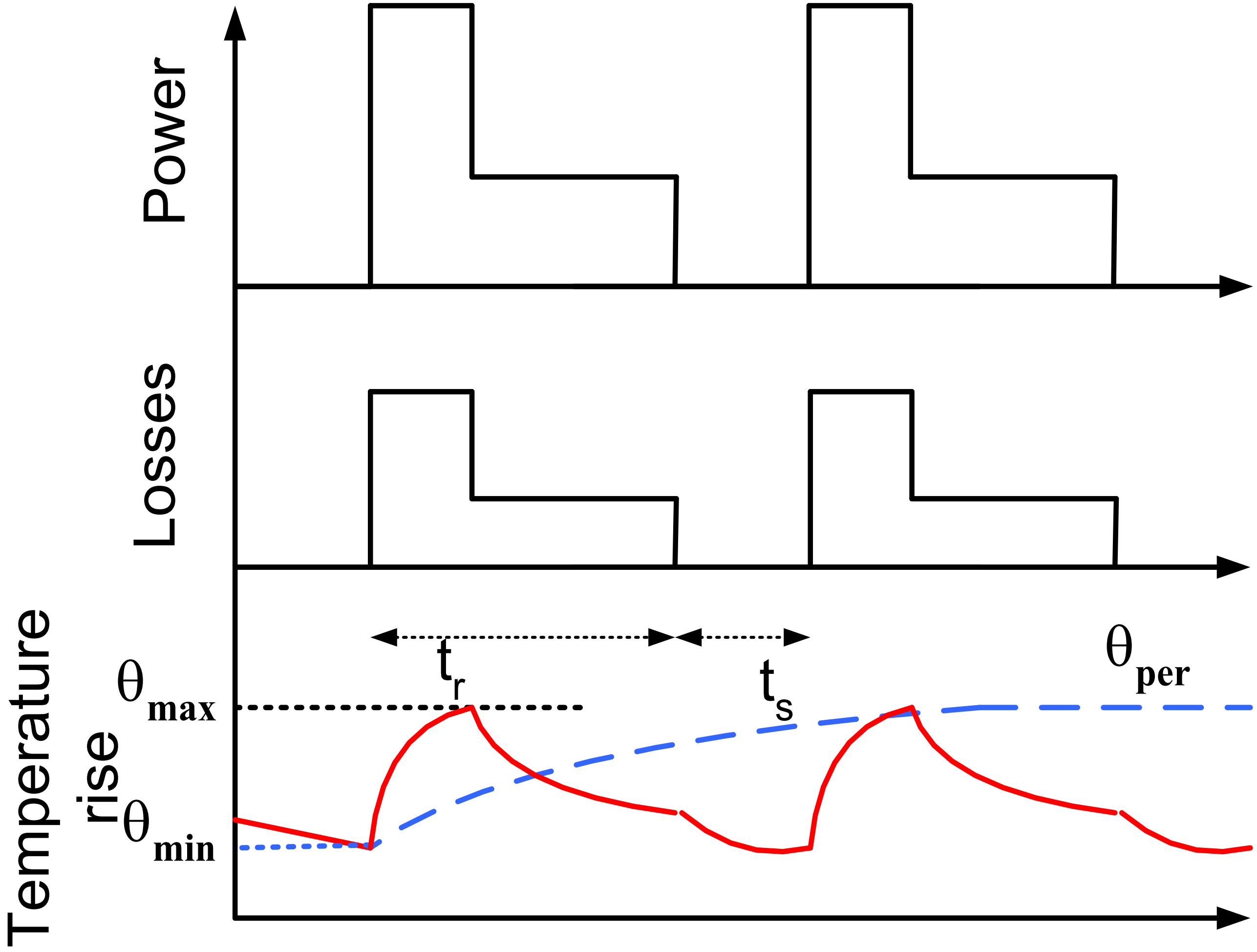


Figure 2.8: Periodic intermittent duty with starting.

Intermittent Periodic Duty with High Start-up Torque and Braking

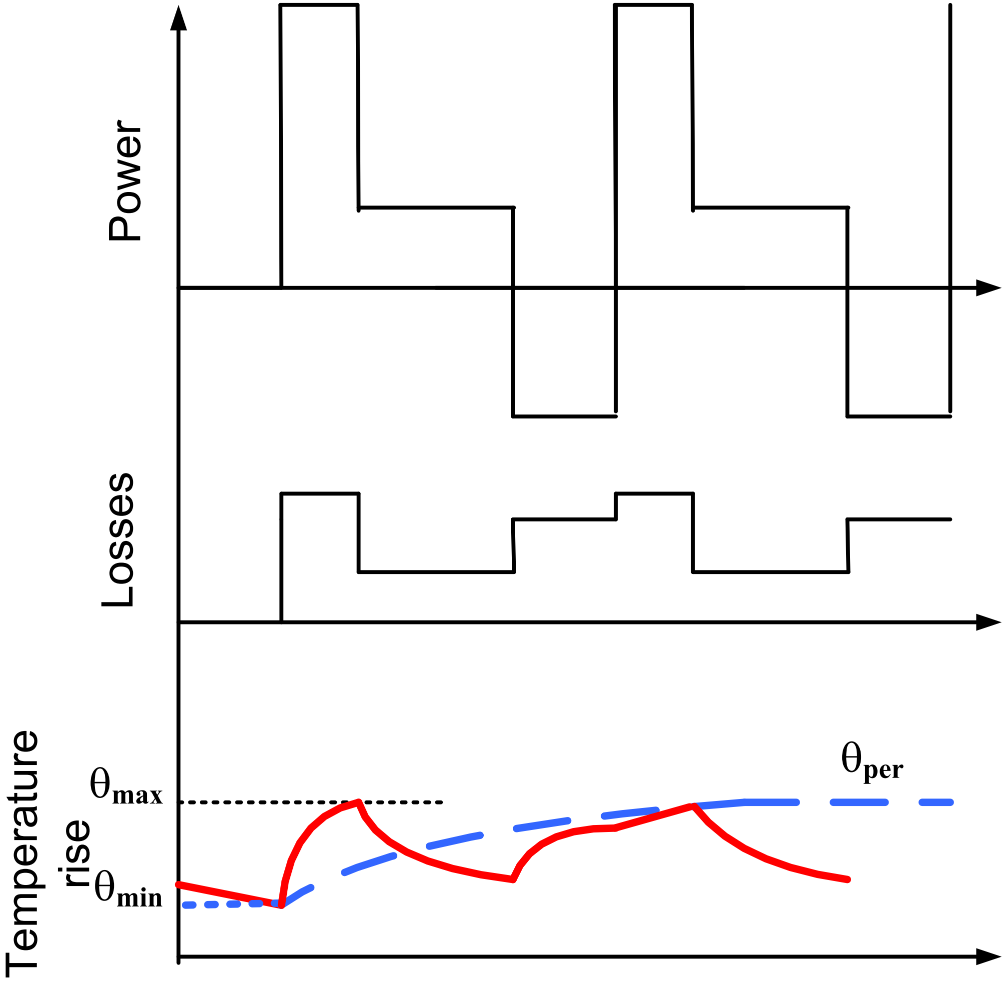


Figure 2.9: Periodic intermittent duty with starting and stopping.

Determination of Motor Power Rating

- **Continuous Duty**
    - continuous duty with **constant load**
    - continuous duty with **variable load** cycles
- **Continuous Duty with Constant Load Cycle**
    - – Selection of the motor rating for this type of load is straight forward.
    - – The maximum load (power) requirement is found and then a motor with power rating slightly higher than that of the load is chosen.

Continuous Duty – Variable Load Cycle

- The method of equivalent current criterion for selecting a motor rating for variable load is based on the principle that the actual variable i.e. motor current is replaced by an equivalent (rms) current i_{eq}, which when flows through the motor winding would produce the same amount of motor losses as would be the case with actual motor current.
- The objective is to find i_{eq} for a given variable load (torque or current).

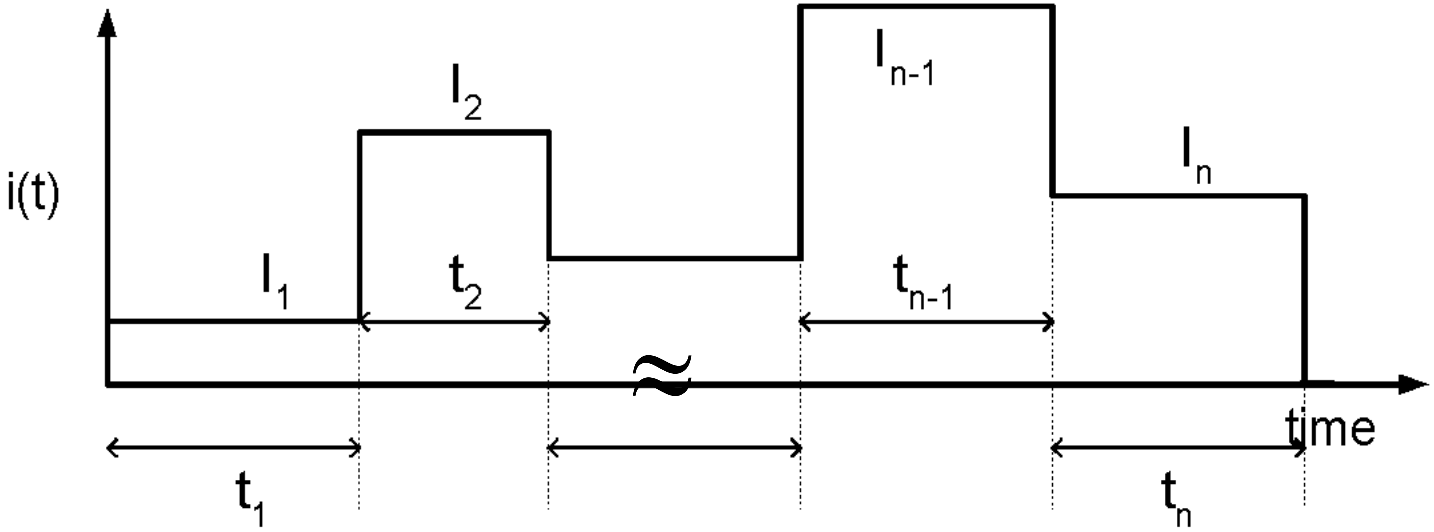


Figure 2.10: Equivalent current criterion for selecting a motor rating for variable load.

- The equivalent (rms) current i_{eq} can be calculated as

$$i_{eq} = \sqrt{\frac{I1,rms^2 \times t1 + I2,rms^2 \times t2 + I3,rms^2 \times t3+\ldots+In,rms^2 \times tn}{t1 + t2 + t3+\ldots+tn}} (2.9)$$

- If the motor torque is directly proportional to the current (DC Motor) we have

$$Teq = \sqrt{\frac{T1^2 \times t1 + T2^2 \times t2 + T3^2 \times t3+\ldots+Tn^2 \times tn}{t1 + t2 + t3+\ldots+tn}} [T = k\varphi IA](2.10)$$

- For constant speed operation we have

$$Peq = \sqrt{\frac{P1^2 \times t1 + P2^2 \times t2 + P3^2 \times t3+\ldots+Pn^2 \times tn}{t1 + t2 + t3+\ldots+tn}} [P = T \times \omega](2.11)$$

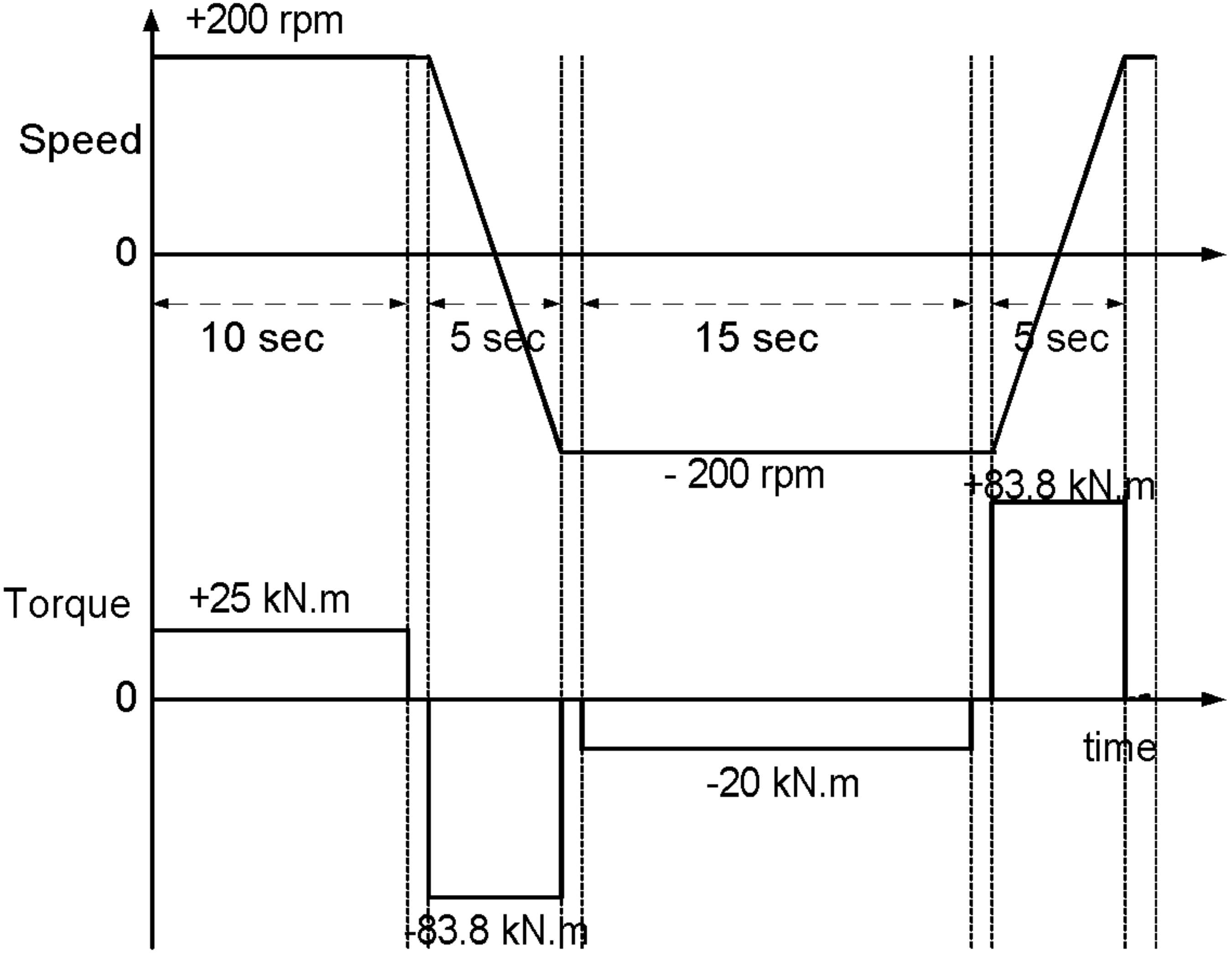
Example 2.2: A rolling mill driven by a thyristor based power converter-fed dc motor operates on a speed reversing duty cycle. Motor field current is maintained constant at the rated value. Moment of inertia referred to the rotor shaft is 10,000 kg.m². Duty cycle consists of the following intervals:

i. Rolling at full speed of 200 rpm and at a constant torque of 25,000 N.m for 10 s.
ii. No-load operation for 1 s at full speed.
iii. Speed reversal from 200 rpm to -200 rpm in 5 s.
iv. No-load operation for 1 s at full speed.
v. Rolling at full speed and at a torque of 20,000 N.m for 15 s.
vi. No-load operation at full speed for 1 s.
vii. Speed reversal from -200 rpm to +200 rpm in 5 s.
viii. No-load operation at full speed for 1 s.

Determine the torque and power ratings of the motor.

Solution: The duty cycle can be represented as follows:

Speed in RPM	Load torque in N.m	Time in sec.
N_1 = 200	T_{l1} = 25,000	t_1 = 10
N_2 = 200	T_{l2} = 0	t_2 = 1
N_3 = +200 to -200	T_{l3} = 0	t_3 = 5
N_4 = -200	T_{l4} = 0	t_4 = 1
N_5 = -200	T_{l5} = - 20,000	t_5 = 15
N_6 = -200	T_{l6} = 0	t_6 = 1
N_7 = -200 to +200	T_{l7} = 0	t_7 = 5
N_8 = +200	T_{l8} = 0	t_8 = 1


+200 rpm
Speed
0
10 sec
5 sec
15 sec
5 sec
- 200 rpm
+83.8 kN.m
Torque
+25 kN.m
0
time
-20 kN.m
-83.8 kN.m

$$Teq = \sqrt{\frac{(25\ kN.m)^2 \times 10\ sec + (-83.5kN.m)^2 \times 5\ sec + (-20kN.m)^2 \times 15\ sec + (+83.8\ kN.m^2) \times 5\ sec}{10+1+5+1+15+1+5+1}} = 49.975kN.m$$

$$T_{eq} = 45{,}975N.m$$

$$P = T_{rms} \times \omega_m = 45{,}975 \times \left(\frac{2\pi}{60} \times 200\right) = 963kW$$

If we compare it with the peak motor power required we have,

$$P_{peak} = 83{,}776 \times \left(\frac{2\pi}{60} \times 200\right) = 1755.1kW$$

Actual motor rating is almost half of that of peak power requirement.

Motor Rating under Short Time Duty

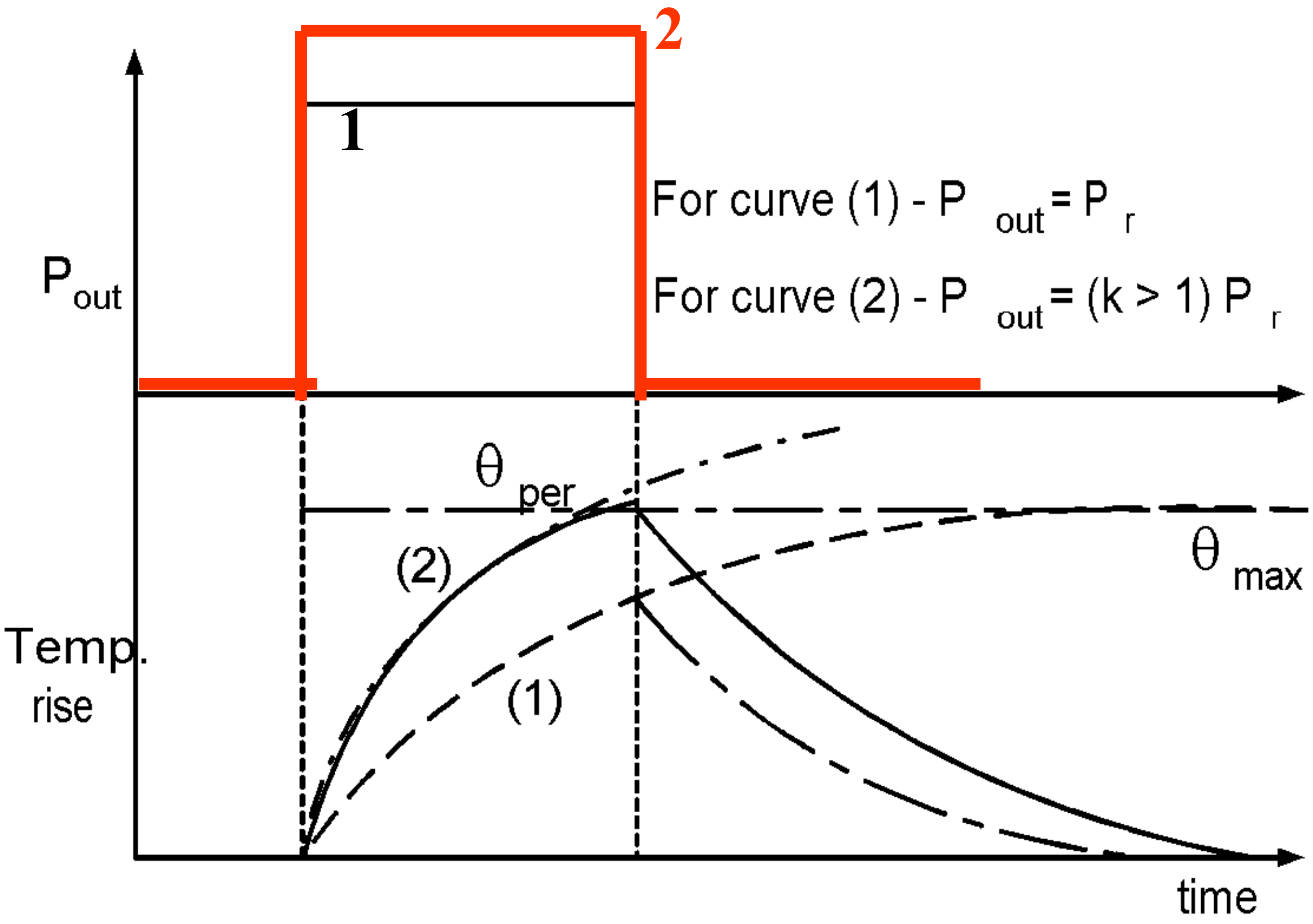


Figure 2.11: Short time duty of a motor (a) load diagram and (b) temperature rise.

- If the motor rating is chosen based on short-term load then the motor would be highly under-utilised with regard to its thermal capability (curve 1).
- Alternatively, a smaller motor is chosen and is used to supply the same load i.e. the motor is overloaded and the temperature rise curve would follow curve 2.
- The machine is effectively utilised from thermal capability point of view (curve 2).
- The motor can be overloaded by a factor of ***k (*** > 1) such that $\theta_{max} = \theta_{per}$ at the end of the duty cycle.

- How to calculate the overloading factor, ***k*** ?
- Assume that motor is operating with a load of ***k* x *P*** $_r$ (***P*** $_r$ - rated output power) for a duration t_r with initial temperature(θ_1 = 0) then we have,

$$\theta_{per} = \theta_{ss}(1 - e^{-t_r/\tau}) \rightarrow \frac{\theta_{ss}}{\theta_{per}} = \frac{1}{(1 - e^{-t_r/\tau})} (2.12)$$

- θ_{SS} is the steady-state temperature rise if the motor delivers output power, (***k* x *P*** $_r$)continuously.
- θ_{per} is the steady-state temperature rise if the motor delivers output power of ***P*** $_r$ continuously.

- Let power losses be p_{1r} and p_{1s} respectively when the motor delivers power $\boldsymbol{P_r}$ and $\boldsymbol{kP_r}$ continuously.

$$\theta_{per} = \frac{p_{1r}}{D} and \theta_{ss} = \frac{p_{1s}}{D}$$

$$\text{whichgives} \frac{\theta_{ss}}{\theta_{per}} = \frac{p_{1s}}{p_{1r}} = \frac{1}{(1 - e^{-t_r/\tau})} \quad (2.13)$$

$$p_{1r} = p_c + p_{cu,r} = p_{cu,r}\left(1 + \frac{p_c}{p_{cu,r}}\right)$$

$$= p_{cu,r}(1 + \alpha)$$

where $\alpha = p_c / p_{cu,r}$, p_c – constant loss and $p_{cu,r}$ – variable loss at rated condition.

$$p_{1s} = p_c + k^2 p_{cu,r} = \left(\frac{p_c}{p_{cu,r}} + k^2\right) p_{cu,r} = p_{cu,r}(\alpha + k^2)(2.14)$$

$$\frac{p_{1s}}{p_{1r}} = \frac{p_{cu,r}(k^2 + \alpha)}{p_{cu,r}(1 + \alpha)} = \frac{1}{(1 - e^{-t_r/\tau})} \rightarrow k = \sqrt{\frac{1 + \alpha}{1 - e^{-t_r/\tau}} - \alpha}\ (2.15)$$

where $\alpha = p_c/p_{cu,r},\ t_r$ - time at which the temperature rise is θ_{per} and τ - heating time constant of the machine.

- Eqn. 2.15 tells us how to calculate the overloading factor, k when the constant, p_c and variables losses, p_{cu} of the motor are known separately. If unknown then assume $\alpha = p_c/p_{cu,r} = 0$.

- **Example 2.3:** An electric motor has a heating time constant of 60 min. and a cooling time constant of 90 min. When run continuously on a full load of 20 kW, the final temperature rise is 40°C.
  - What load the motor can deliver for 10 min. if this followed by a shutdown period long enough for the motor to cool down?

Solution: The following parameters are given:

$$\tau_r = 60 \text{ min}, \ \tau_s = 90 \text{ min}, \ P_r = 20 \ kW \text{ and } \theta_{per} = 40°C$$

$$k = 2.55$$

The permitted load is $\boldsymbol{k} \times \boldsymbol{P}_r = 2.55 \times 20\ kW = 51\ kW$.

Example 2.4: Assume that half-hour rating of a motor is 100 kW, heating time constant is 80 min. and the maximum efficiency occurs at 70% of full load. Determine the continuous rating of the motor.

Solution: The parameters given are:

- $K \times P_r = 100\ kW$, $\tau = 80\ min$, η_{max} at 70% of full-load
- Let $P_r\ kW$ be the continuous rating of the motor and p_c be the constant loss.
- Necessary condition for maximum efficiency is $p_c = p_{cu}$.
- At 70% of full-load when maximum efficiency occurs we have $p_c = p_{cu@70\%}$.

$$p_{cu\,@\,100\%rated} = \frac{p_c}{0.49}$$

$$\alpha = \frac{p_c}{p_{cu\,@\,100\%rated}} = \frac{p_c}{\frac{p_c}{0.49}}$$

$$= 0.49$$

$$k = \sqrt{\frac{1+\alpha}{1-e^{-t_r/\tau}} - \alpha} = 2.0676$$

- Thus, the continuous rating of the motor is

$$\text{Pr} = \frac{\text{Pr}'}{k} = \frac{100kW}{2.0676} = 48.37kW$$

Motor rating under Intermittent Periodic Duty

- $P_r' = kP_r$ during the period, t_r and followed by a **standstill** period of t_s.

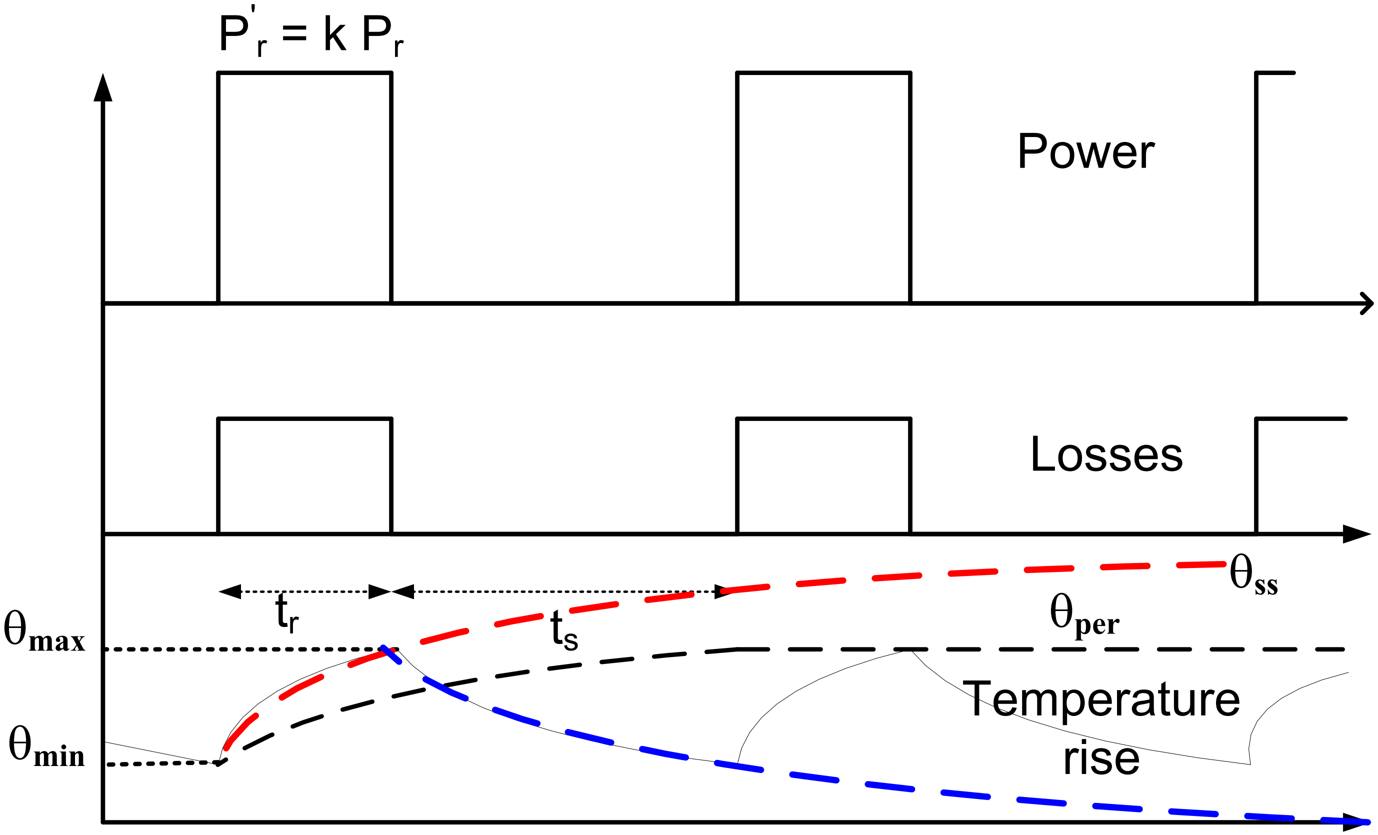


Figure 2.12: Intermittent periodic load.

- The motor rating should be chosen such that $\theta_{max} \leq \theta_{per}$ where θ_{per} is the maximum temperature rise allowed when the motor is continuously operated at **rated** power P_{r}..

- During interval t_r temperature rise is given by

$$\theta(t) = \theta_{SS}\left(1 - e^{-t/\tau r}\right) + \theta_{\min} \quad e^{-t/\tau r} \ (2.16)$$

- During interval t_s the temperature rise would drop and is given by

$$\theta(t) = \theta_{\max} \quad e^{-t/\tau s} \left[\mathrm{as} p_1 = 0, \theta_{SS\prime} = \frac{p_1}{D} = 0\right] (2.17)$$

- From eqns. 2.16 and 2.17 we have,

$$\frac{\theta ss}{\theta \max} = \frac{1 - e^{-(tr/\tau r + ts/\tau s)}}{1 - e^{-(tr/\tau r)}} \ (2.18)$$

- For proper utilisation of the motor it is necessary that $\theta_{max} = \theta_{per}$.
- θ_{per} is the steady-state temperature rise when the machine is delivering a continuous load of rated power, P_r.
- If we assume that the power losses p_{1s} and p_{1r} be losses in the machine for power output of $P'_r = kP_r$ and P_r respectively then we have for ($\theta_{max} = \theta_{per}$).

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{p_{1s}}{p_{1r}} = \frac{k^2 + \alpha}{1 + \alpha} = \frac{1 - e^{-(t_r/\tau_r + t_s/\tau_s)}}{1 - e^{-(t_r/\tau_r)}}$$

$$\rightarrow k = \sqrt{(\alpha + 1)\frac{1 - e^{-(t_r/\tau_r + t_s/\tau_s)}}{1 - e^{-(t_r/\tau_r)}} - \alpha} \ (2.19)$$

Example 2.5: For the motor is Example 2.3 if we assume that the motor is on an intermittent load of 10 min followed by a 10 min. shutdown, what is the maximum value of load it can supply during the on load period?

Solution: We have t_r = 10 min. and t_s = 10 min. From Example 2.3: $\alpha = 0$, τ_r = 90 min. and τ_s = 60 min. Substituting in eqn. 2.19, we have

$$k = \sqrt{(\alpha + 1)\frac{1 - e^{-(t_r/\tau_r + t_s/\tau_s)}}{1 - e^{-(t_r/\tau_r)}} - \alpha} = 1.257$$

Thus, the permitted motor load is $P_r' = kP_r = 1.257 \times 20\ kW = 25.14\ kW$.

Frequency of Operation of Motors Subjected to Intermittent Loads

- In some applications, the intermittent load is applied with starting (t_{st}), braking (t_{br}), occurring quite frequently and running period, t_r and standstill period, t_s are comparable to t_{st} and t_{br} and much smaller as compared to τ_r and $\tau_{s.}$
- As $t_r \ll \tau_r$ and $t_s \ll \tau_{s\,,}$ we can have $e^{-x} \approx 1 - x$.

$$\frac{p_{1s}}{p_{1r}} = \frac{\theta_{ss}}{\theta_{per}} = \frac{\frac{t_r}{\tau_r}+\frac{t_s}{\tau_s}}{\frac{t_r}{\tau_r}}$$

$$p_{1s} \times t_r = p_{1r} \times t_r + p_{1r}\left\{\left(\frac{\tau_r}{\tau_s}\right) \times \ t_s\right\} = p_{1r} \times \left(t_r + \left(\frac{\tau_r}{\tau_s}\right) \times \ t_s\right)$$

- Applying the same relationship to starting, braking and short running interval we have

$$E_{st} + p_{1s} \times \ t_r + E_b = p_{1r} \times (\gamma t_{st} \ + t_r + \gamma t_b + \beta \ t_s)$$

  where, γ and β are some constants based on measurements.

- β varies in the range 0.3 – 0.7 and $\gamma = (1 + \beta) / 2$.
- All parameters are known except t_s that can be computed and the permissible frequency of switching per hour would be

$$f_{max} = \frac{1}{t_{st} + t_r + t_b + t_s}$$

Example 2.6: A thyristor converter-fed DC motor drive has the following specifications: rated armature current = 500 A, armature resistance = 0.01 ohm.

The drive operates in the following duty-cycles:

1. Acceleration at twice the rated armature current for 10 sec.
2. Running at full-load for 10 sec.
3. Deceleration at twice the rated armature current for 10 sec.
4. Idling interval.

The core loss is constant at 1 kW. If β has a value of 0.5, determine the maximum frequency of drive operation.

$$E_{st} = p_{1s} \times t_s = \left[\left(\left((500 \times 2)\right)^2 \times 0.01\right) + 1000\right] \times 10\, sec = 110\, kW$$

$$E_{br} = p_b \times t_b = \left[\left(\left((500 \times 2)\right)^2 \times 0.01\right) + 1000\right] \times 10\, sec = 110\, kW$$

$$p_{1s} = \left[\left(\left((500)\right)^2 \times 0.01\right) + 1000\right] = 3.5\, kw$$

$$\gamma = \frac{1+\beta}{2} = \frac{1+0.5}{2} = 0.75$$

$$E_{st} + p_{1s} \times t_r + E_{br} = (110 + 3.5\, kw \times 10\, sec + 110)$$
$$= 3.5\, kW(0.75\, x\, 10 + 10 + 0.75\, x\, 10 + 0.5 t_s) \Rightarrow t_s = 95.7\, sec$$

$$f_{max} = \frac{3600}{t_{st}+t_r+t_b+t_s} = \frac{3600}{10+10+10+95.7} = 28.64\, per\ hour$$

Summary

- Power rating of an electric motor must be chosen carefully: cost & reliability.
- Losses in electrical machines: constant losses and variable losses.
- Temperature-rise is directly related to thermal loading of the machine.
- Electrical machines have sufficient overloading capability but thermal restrictions does not allow continuous overloading.
- Electrical time constant (ms) << Mechanical time constant (sec) << Thermal time constant (mins.).

- Classes of motor duty: - (a) continuous, (b) short-term and (c) intermittent.
- Equivalent criterion method for selection of motor power rating for variable load.
- Calculation of motor overloading factor under: (a) Short Term Duty and (b) Periodic Intermittent Duty.

References

1. Fundamentals of Electric Drives – G K Dubey – Chapter 4.
2. Control of Electric Drives – Leonhard – Chapter 4.