Efficiency Improvement by Thermo-Mechanical Coupling

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Abstract:

Electric motor or generator when running on load becomes hot due to the heat produced by the energy that is lost in the process of the electromechanical conversion of energy. There are suitable cooling and ventilation system to dissipate the heat, thereby putting a limit to the rise of temperature of the machine. Additional cooling measure by way of using thermo-mechanical coupling in torque transmission between the driving-shaft and the driven-shaft may facilitate faster dissipation of heat from the machine, thereby reducing somewhat the maximum temperature rise of the machine bringing in improvements in many aspects of performance of electrical machine.

Keywords. Performance, efficiency, temperature, coupling, cooling

1. INTRODUCTION

Electric motor upon running on load for some length of time appears hot, temperature being considerably higher than the ambient temperature. There are various cooling methods for purpose of cooling and ventilation of the machine. The source of heat and the necessity and the way of cooling thus appear important features in matters of electric dynamo, more particularly of performance, analysis, design and construction aspects.

The electric dynamo operates on the principle of electromagnetic energy conversion which is necessarily accompanied by a certain amount of irreversible conversion of energy to heat in the conversion device e.g., electric motor or generator. In each time of energy conversion process, say electrical to mechanical or mechanical to electrical, some of the energy is used up to meet the losses in the conversion process. These losses are converted into heat and are lost from the system for ever. Thus, electromechanical energy conversion is a reliable process except for the losses in the system.

It becomes a necessity to arrange to dissipate the heat produced in the machine. There are developed cooling and ventilation system of various types. Heat is dissipated by way of radiation from the surface of the machine and by way of convection by circulation of air by fan which itself consumes some power. There are too many applications of electric motor to act as prime mover to drive some mechanical equipment viz. pump, gearbox. In many a situations mechanical coupling e.g., flange coupling, gear coupling are used to connect driving shaft with driven shaft for torque transmission. Some modified coupling, say thermo-mechanical coupling may provide additional scope of dissipating heat by conduction which may help reducing the maximum temperature rise of the electric machine. Thus, lesser rise of temperature of the machine in steady-load service remain beneficial for the electrical machine.

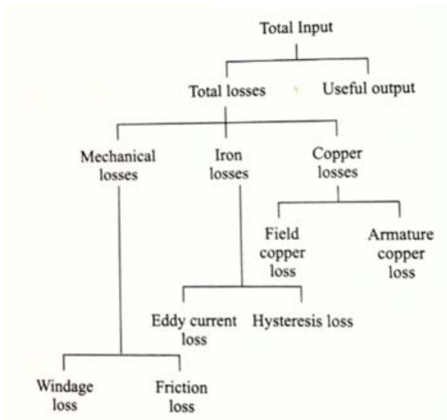

Figure 1: Different types of losses in motor

A. Energy losses and efficiency

The energy losses arise in electromechanical conversion process because of several reasons, e.g., circuit resistance (copper or electrical losses), existence of alteration of fluctuating magnetic fields (core or iron losses) and mechanical losses (friction and windage). Although they play essentially no basic role in the energy conversion process, these are nevertheless important factors in practical application of machines.

These machine losses are important for basically three reasons.

- i) Power losses determine the efficiency of the machine and appreciably influence its operating cost.
- ii) Power losses determine the heating of the machine and hence fix the rating of power output that can be obtained without deterioration of the insulation because of overheating.
- iii) The losses associate with voltage drops or current component used to be accounted for in a machine representation for desired analysis of electrical machines.

B. Efficiency

The efficiency (η) of an electrical machine, like that of any other apparatus, is defined as the ratio of useful power output to the input power.
Machine efficiency, η = output/input
or, η = output / (output + losses)
or, η = (input – losses) / input
or, η = 1 - losses/input ………………………………………………………..……………... (1)
Considering various power stages in dc generator represented as in figure 2

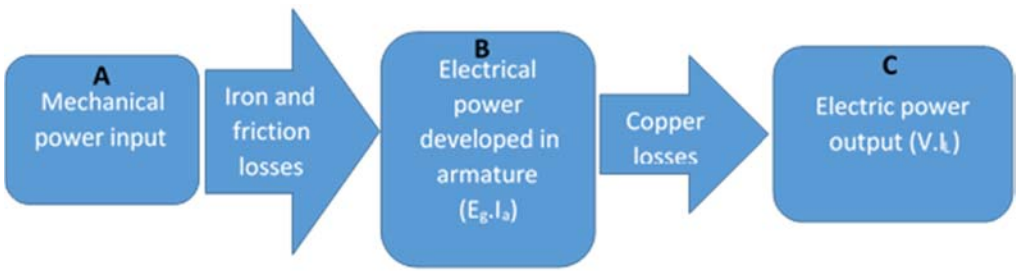

Figure 2: Schematic power stages in a dc generator.

a) Mechanical efficiency, $\eta_m = \frac{B}{A} = \frac{E_g.I_a}{mechanical\ power\ input}$ ………….……….…..…….... (2)
b) Electrical power efficiency, $\eta_e = \frac{C}{B} = \frac{V.I_L}{E_g.I_a}$ ………………………….......................... (3)
c) Commercial efficiency, $\eta_c = \frac{C}{A} = \eta_m * \eta_e = \frac{V.I_L}{mechanical\ power\ input}$ .... (4)

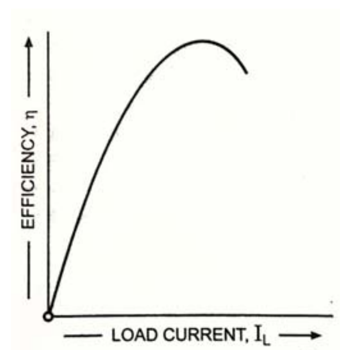

Figure 3: Load current vs efficiency curve

Rotating electrical machines in general operate efficiently at light loads. The full load efficiency of average motors, for example, is about 74% for 0.75kW size, 89% for 37kW, 93% for 375 kW and 97% for 3750kW. The efficiency of slow speed motors is usually lower than that of high-speed motors, the total spread being 3-4%. Load current vs efficiency curve appears as in figure 3.

For electrical machines, efficiency is most commonly determined by measurement of losses instead of directly measuring the output and input under load. Loss measurement have the advantage of conversion and economy and of yielding more accurate and precise values of efficiency because a given percentage error in the measuring of losses cause only about one-tenth ($\frac{1}{10}th$) of their percentage error in the efficiency. Efficiency determined by the measurement of losses can be used in comparing machines if exactly the same methods of measurement and computation are used in each case.

C. Constant and Variable losses

The losses in electromagnetic conversion process, say for a dc generator or motor can be subdivided into i) constant losses ii) variable losses.
i) Constant losses: - Those losses in an electrical machine which remain constant at all loads are known as constant losses. e.g. - a) Iron losses b) mechanical losses c) shunt field losses.
ii) Variable losses: - Those losses in a dc generator/electrical machine which vary with load are called variable losses. e.g. - a) Copper losses in armature winding ($I_a^2R_a$) b) copper losses in series winding ($I_{se}^2R_{se}$)
Total losses = Constant losses + Variable losses.
$P = P_c + P_v$ ……………………………………..…... (5)
The point at which the variable losses are equal to the constant losses determine the maximum efficiency. The value of load current (I_L) corresponding to maximum efficiency can be determined as,
$I_L = \sqrt{\frac{Pc}{R_a}}$
The efficiency of an electrical machine, say of a dc generator, will be maximum when the load current is such that Variable losses = Constant losses.

D. Temperature rise in electrical machines

For the losses in various parts, heat is developed causing the temperature of that part to rise. This temperature rise continues until all the heat generated is dissipated to the surroundings by one or more of the natural modes of heat transfer like conduction, convection and radiation.
Ultimately then, under steady load, each part achieves final temperature, the magnitude of which depends on balances between the rate at which heat is developed in that part (or received by conduction from a hotter part) and the rate at which heat can be dissipated which is determined by effectiveness of the cooling method.
The temperature rise depends on

i) The amount of heat produced
ii) The amount of heat dissipated per ℃ rise of temperature from the surface of the machine.

According to Newton’s law of cooling the rate of loss of energy of a hot body is proportionate to the difference in temperature between the body and the surroundings. This law is approximately true for moderate temperature difference (up to 100°C) and for the bodies dissipating heat by radiation and natural convection. It means that the amount of heat dissipated per 1°C rise of the surface of a machine depends on the surface area of cooling.

E. Size of motor

The size of motor for any service is governed by the maximum temperature rise when operating under the given load condition and the maximum torque required. The form is more important because if the motor operates satisfactorily at maximum temperature rise it will usually provide the required maximum torque except in special cases where the load consist of heavy peaks followed by relatively long intervals of no load. Electric machines are therefore designed for a limiting temperature rise.

F. Insulation

In fact, continuous rating of a machines is the rating for which the final temperature rise is equal to or just below the permissible value of temperature rise for insulating material used in protection of motor windings. In any situation if the temperature rise of 50°C can be brought down to a limit of 40°C, then insulation A can be utilized for 40°C temperature rise instead of utilizing insulation B which is applicable for 50°C temperature rise. When the machine is overloaded for such a long time that its final temperature rise exceeds the permissible limit, it is likely to be damaged. In worst cases, it will result to an immediate thermal breakdown of the insulating material which will cause a short circuit in the motor thus putting a stop in its functioning. The short circuit may also eventually lead to a fire.

In less severe cases, immediate thermal breakdown of insulating material may not occur, but the quality of insulation will deteriorate such that the thermal breakdown with future overloads or even natural loads might soon occur, thus shortening the useful life of the machines. The temperature rise to which a motor be allowed to rise is limited by the insulation employed.

2. HEATING TIME CURVE

The maximum temperature rise which should not be exceeded by different types of motors are fully set out in the relevant IS. Since temperature rise is one of the chief features in fixing the size of a motor, its calculation become a matter of importance.
For determination of an expression for the temperature rise of an electric machine after time t seconds from the instant of switching it on, let
Power converts into heat = P joules/s or watts
Mass of active part of machines = m kg
Specific heat of material = C_p joules/kg/°C
Surface area of cooling = S metre^2
Coefficient of cooling = α in watts per metre^2 of surface per °C of difference between machine surface and ambient temperature.

Assumptions made

i) Losses and heat produced remain constant during the temperature rise.
ii) Temperature of cooling medium remain unchanged.
iii) Heat dissipated is directly proportional to the difference in temperature of the machine and cooling medium.

Suppose a machine attains a temperature rise of θ℃ above ambient temperature after t seconds of switching on the machine and further rise of temperature by dθ in very small time dt.
Energy converts into heat = Pdt joules
Heat absorbed = $mC_p d\theta$ joules
Heat dissipate = $S\theta\alpha dt$ joules
Since, energy converted to heat = Heat absorbed + Heat dissipated
Therefore, $Pdt = mC_p d\theta + S\theta\alpha dt$
or, $(P-S\theta\alpha)dt = mC_p d\theta$
or, $\frac{dt}{\text{m Cp}/_{S\alpha}} = \frac{d\theta}{P/_{S\alpha} - \theta}$ …………………………………………………………………………… (6)
When final temperature (θ_F) is reached, there is no absorption of heat, whatever heat is generated has to be dissipated.
∴ $Pdt = S\theta_F\alpha dt$
or, Final temperature rise, $\theta_F = \frac{P}{S\alpha}$ ……………………………………………………………… (7)
Substituting $\theta_F = \frac{P}{S\alpha}$ in equation (6)
We get, $\frac{S\alpha dt}{mCp} = \frac{d\theta}{\theta_F - \theta}$
Integrating both sides, we get $\frac{S\alpha}{mCp} t = -\log_e(\theta_F - \theta) + K_1$……………………………………...(8)
K_1 = Constant of Integration
Substituting t = 0, $\theta = \theta_I$ in equation 8, initial temperature rise from initial condition, we have
$0 = -\log_e(\theta_F - \theta_I) + K_1$
or, $K_1 = \log_e(\theta_F - \theta_I)$
So equation (7) becomes
$\frac{S\alpha}{mCp} t = -\log_e(\theta_F - \theta) + \log_e(\theta_F - \theta_1)$
or, $\frac{S\alpha}{mCp} t = \log_e \frac{\theta_F - \theta}{\theta_F - \theta_1}$
or, $e^{-\frac{S\alpha}{mCp}t} = \frac{\theta_F - \theta}{\theta_F - \theta_1}$
or, $\theta_F - \theta = (\theta_F - \theta_I)\, e^{-\frac{S\alpha}{mCp}t}$
or, $\theta = \theta_F - (\theta_F - \theta_I)\, e^{-\frac{S\alpha}{mCp}t}$ …………………………………………………………………… (9)
or, $\theta = \theta_F - (\theta_F - \theta_I)\, e^{-\frac{t}{\tau_h}}$ ……………………………………………………………………………(10)
$\tau_h = \frac{m\,Cp}{S\alpha}$ is known as heating time constant.
If motor is at ambient temperature $\theta_1 = 0$
$\theta = \theta_F - \theta_F\, e^{-\frac{t}{\tau_h}}$

or, $\theta = \theta_F(1 - e^{-\frac{t}{\tau_h}})$ .... (11)

Heating time constant is defined as the time taken by the motor in attaining the final steady value. If the initial rate of rise of temperature were maintained throughout the operation.

Substituting t= τ_h in equation (11), we have $\theta = \theta_F\,(1\text{-}e^{-1}) = 0.632\ \theta_F$ .... (12)

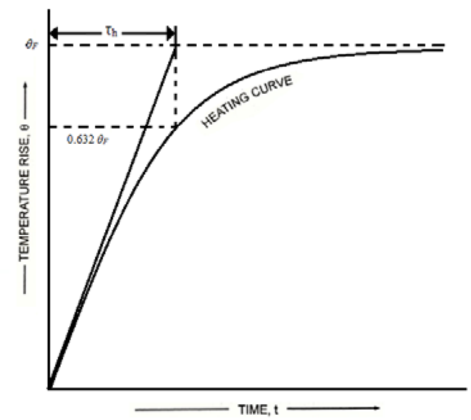

Figure 4: Heating time curve

So, heating time constant may also be defined as the time duration in which the machine will attain 63.2% of its final limit rise above the ambient temperature the corresponding heating curve has been shown in figure 4.

From equation 7, i.e., θ_F = P/Sα, it is obvious that θ_F is directly proportional to the power losses and inversely proportional to the surface area S and specific heat dissipation α. For poorly ventilate machines, it will attain a higher final temperature rise.

Heating time constant τ_h, being equal to mCp/Sα, has small value for well ventilated machines and large value for poorly ventilated machines.

Large size machine has large heating time constant because with the increase in size of machine, the volume hence the mass increases in proportion to third power of linear dimensions and surface area S is proportional to second power.

Typical values of heating time constant lie between about one and half hour for small motors (7.5 kW to 15kW) up to above five hours for motors of several hundred kW.

3. COOLING TIME CURVE

After reaching steady temperature rise θ_F and operation of the machine, during which period heat production due to losses get dissipated equally, when machine is switched off, no heat is produced.

So, Heat absorbed + Heat dissipated = 0 and τ_c = mCp/Sα' is cooling time constant.

$\theta = \theta_F\, e^{-1} = 0.368\, \theta_F$ ……………………………………………………………(13)

I.e. cooling time constant may also be defined as the time required for cooling machine down to 0.368 times the initial temperature rise above ambient temperature. It has been shown in figure 5.

The heating and cooling curves follow an exponential law. Heating time constant and cooling time constant may be different for the machines as the ventilation condition in the two cases may not be same.

The cooling time constant of a rotating machine is usually larger than its heating time constant owing to poor ventilation condition prevailing when the machine cools.

In self-cooled rotating machine, the cooling time constant is about 2-3 times greater than its heating time constant because cooling condition are worse as the machine stands still.

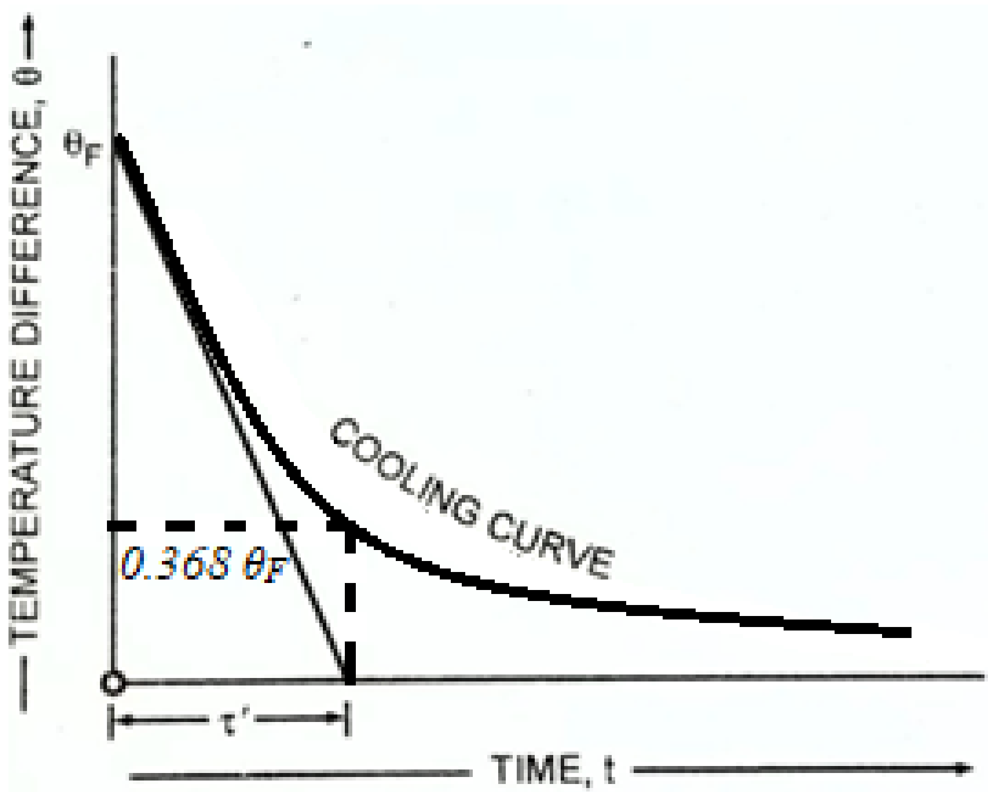

Figure 5: Temperature difference-time curve

4. COOLING AND VENTILATION OF ELECTROMECHANICAL MACHINES

It is necessary to provide suitable ventilation and cooling for the machines so that temperature rise at any part of the machine does not exceed the permissible limit governed by the types of insulation employed in the construction. The cooling of electrical machine by means of air stream is taken as ventilation.

There are various methods of such ventilation and cooling like natural cooling, self-cooling and separate cooling, open-circuit ventilation, surface ventilation and others. Alongwith also comes types of enclosure for protection of man and machines both and IS-4691 provides the IP codes. The types of enclosures corresponding to the service condition and vicinity of location of the machine include open type, protection type, screen-protected type, totally enclosed fan cooled type (TEFC), pipe ventilation type and other types.

5. ADDITIONAL COOLING

Important relations below indicate that increase in the heat dissipation brings down the value of parameters like temperature rise, heating time constant and influence the heating curve well.

θ_F = p/Sα, τ_h = mCp/Sα, $\theta = \theta_F\,(1 - e^{-\frac{t}{\tau_h}})$

In general, Sα represents heat dissipation from the surface area of the electrical machine that radiate heat to the atmosphere. In well ventilated fan cooled machine heat dissipation takes place also by convection by flow of air.

There are too many applications of the electrical machine in driving the mechanical equipment. Coupling is employed to connect the driving shaft of motor with the driven shaft of the mechanical equipment and torque is transmitted from motor shaft to the shaft of mechanical equipment e.g., gear box, pump.

Such mechanical coupling, say flange coupling of improved concept and design may give scope to dissipate heat by conduction from motor shaft to the driven shaft of mechanical equipment which apparently become heat sink and the temperature of such driven-equipment may not change appreciably and remain near ambient temperature. Heat dissipation from electrical machine by application of such coupling in transmission of heat from prime mover to utility equipment may facilitate reducing the temperature rise θ_F and the heating time constant τ_h and in turn, improve the relevant features like rating, life, insulating matters.

Considering additional heat dissipation by conduction by way of use of thermo-mechanical coupling of suitable design the heat balance equation develops to

$$Pdt = m\,C_p\,d\theta + S_1\,\theta\,\alpha_1\,dt + S_2\,\theta\,\alpha_2\,dt \quad \ldots\ldots (14)$$

Where $S_2 \theta \alpha_2$ dt is the equivalent of heat dissipation by conduction through thermo-mechanical coupling indicate here in afterwards.

The final temperature rise θ_F' at steady-state operation appears,

$\theta_F' = \frac{P}{S_1\alpha_1 + S_2\alpha_2}$

or, $\theta_F' = \frac{P}{S_1\alpha_1(1+\frac{S_2\alpha_2}{S_1\alpha_1})}$

or, $\theta_F' = \theta_F \cdot \frac{1}{h}$

where $h = (1 + \frac{S_2\alpha_2}{S_1\alpha_1}) > 1$ .... (15)

Also the heating time constant τ' in such case reduce to

$\tau' = \frac{mCp}{S_1\alpha_1 + S_2\alpha_2}$

or, $\tau' = \frac{mCp}{S_1\alpha_1(1+\frac{S_2\alpha_2}{S_1\alpha_1})}$

or, $\tau' = \tau_h \cdot \frac{1}{h}$ where h>1

The corresponding heating curve follows (in figure 5)

$\theta = \theta_F' - (\theta_F' - \theta_I)\, e^{-\frac{t}{\tau'}}$

When θ_1 being ambient temperature, $\theta_I = 0$

$\theta = \theta_F' (1 - e^{-\frac{t}{\tau'}})$ .... (16)

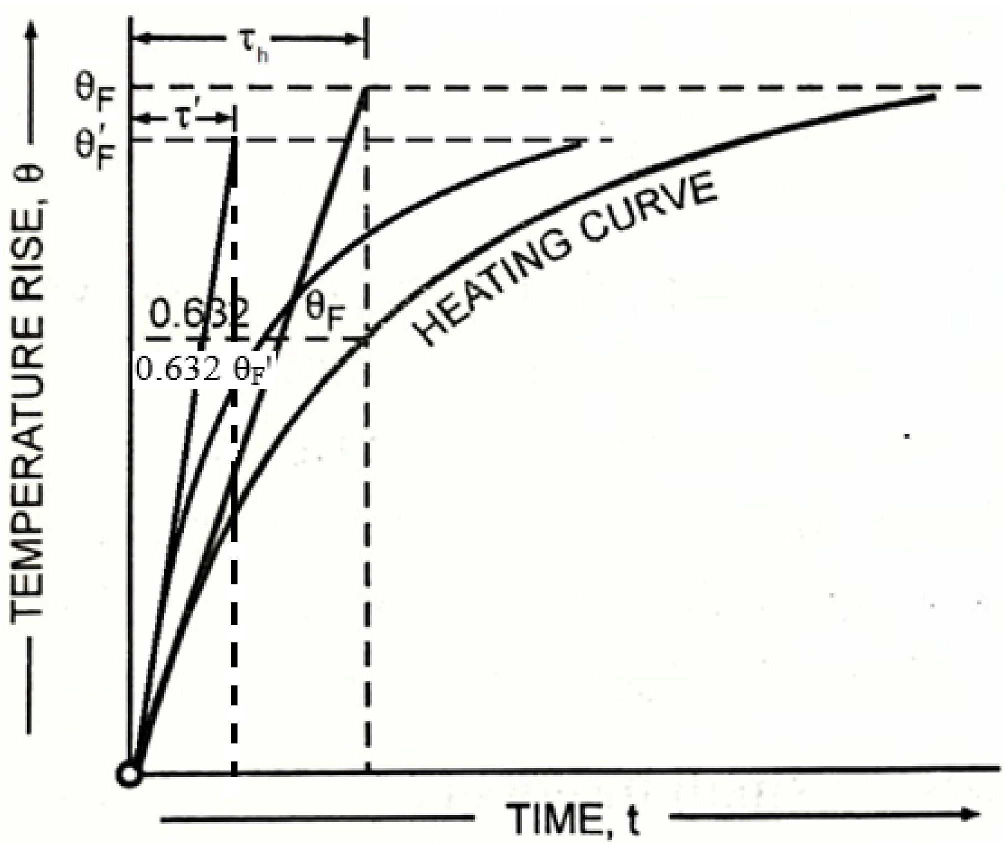

Figure 6: Temperature rise-time curve

6. THERMO-MECHANICAL COUPLING

Generally, a flange coupling of Cast Iron, used in connecting shafts manufactured separately for transmission of torque looks as in the figure 7.

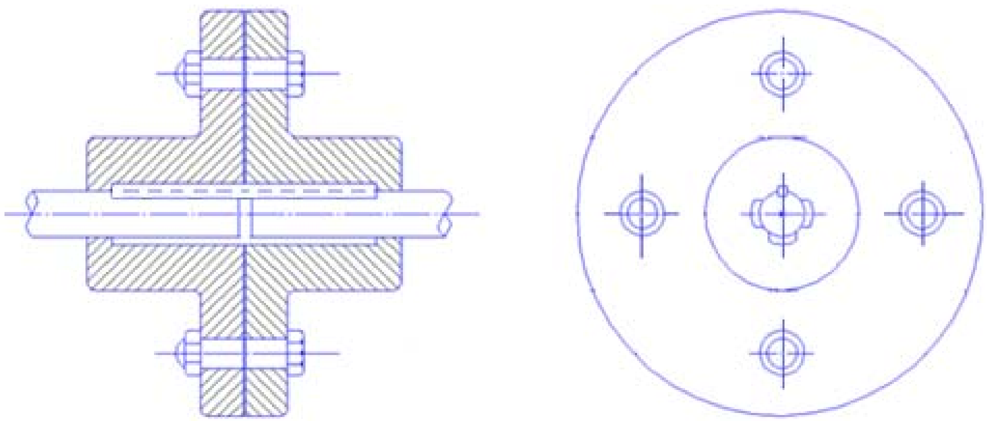

Figure 7: Flange coupling of Cast Iron

With such basic construction and design modification a thermo-mechanical coupling may be considered in figure 8.

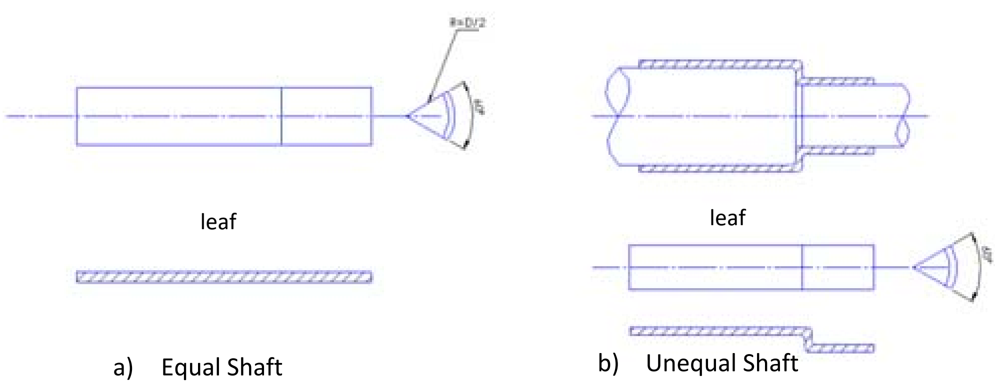

Figure 8: Thermo-mechanical coupling

The heat transmission leaf of suitable material like Cu, Al or Zn need be of required shape and dimension with due design and maintenance considerations, may be in multiple numbers. This leaf is accommodated into the suitable designed groove of the hub of the flange of the coupling.

The two shafts (driven and driver) are connected by such heat conducting leaves inserted into in the groves of the pair of flanges so as to have contact with the surface of both the shafts thereby can dissipate heat by conduction from hotter shaft to colder one. The leaf should not disturb the natural alignment of the shafts while the coupling transmits torque. This type of coupling continues to dissipate heat when the machine is switched off thus improves the cooling curve of the machine.

7. DUTY CYCLE

The nominal duty of the drive motor is the duty corresponding to the service condition and performance marked on its name plate. There are three types of duties viz

1) Continuous duty
2) Short time duty
3) Intermittent duty or intermittent provided duty

Continuous duty is that duty when the on-period is so much long that the motor attains a steady-state temperature rise. Figure 9(a)
The heating and cooling curves for short time duty motor are given in figure 9(b). The short time duty motors operate at a constant load for some specific period which is then followed by a period of rest. The period of run (or load) is so short that the machine cannot attain its steady temperature rise while period of test is too long.

The heating and cooling curves for intermittent periods, duty motors are illustrated in figure 9(c). On intermittent duty the periods of constant load and rest with machine de-energized alternate. The loading periods are too short to allow the motor to attain its final steady-state value while periods of rest are too small to allow the motor to cool down to ambient temperature.

Intermittent rating of a machine as the load which is applied during a certain fraction of time of a load cycle and the temperature rise limit is not exceeded.

The heating and cooling curve for maximum temperature rise of i) θ_F ii) θ_F', where $\theta_F > \theta_F'$ for various types of duties become modified as given in schematically figure 5.

The duty cycles for various motor duties appear as in figure 10.

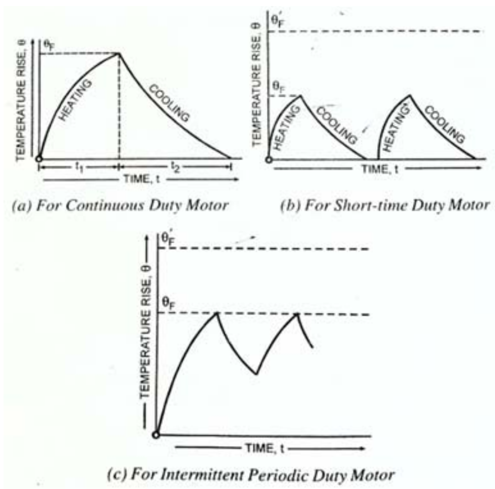

Figure 9: Temperature rise-time curve

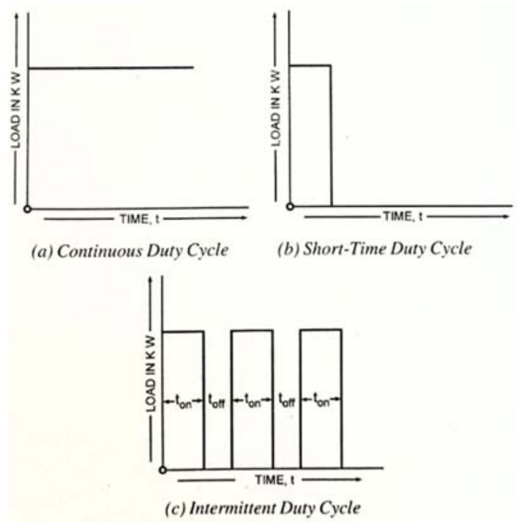

Figure 10: Temperature rise-time

8. RATINGS OF MACHINES

The rating of a machine must give the necessary information to safeguard the application of the machine from condition of operation which (i) would result in unsafe mechanical or electrical strains upon any part of its structure or (ii) would result in excessive deterioration of the mechanical or electrical characteristics of materials of construction. To give the information related to an electric machine should include the output voltage, speed and any other information that may be necessary for the proper operation of the machine.

Electric generators and motors are rated in terms of kVA or kW output at a given speed and voltage. The size and rating of an electric machine for some service is mainly governed by the factor ‘temperature rise’. The maximum temperature to which an electric machine is allowed to reach is limited by the type of insulation employed.

The maximum temperature rise permissible with insulation A and insulation B may be 40℃ and 50℃ respectively. Overloads are permissible generally for short period of time but when machines are required to carry greater loads than those specified, they must be kept under inspection to see that the temperature does not rise too much and that severe sparking at the commutater does not occur.

The type of service to which a machine is subjected to is of great importance. The machine operating continuously at rated (or near rated) load are physically larger than those working at intermittent loads. Also, electric machines that are not enclosed and are, in addition, well cooled by fans are likely to have higher ratings than covered up machines or those machines located where air does not circulate freely through or over them. High speed machines employing mica glass tapes and the new silicon insulation can generally be physically smaller, in given ratings than the low-speed machines employing standard insulation.

9. TESTING OF MOTORS

Electrical machines, particularly generators and motors are likely to undergo various tests for quality performance and life of the machine e.g., load, efficiency, insulation rating. There are various situation-specific testing methods like direct, indirect, regenerative method and others.

Heat run test or temperature rise test indicate the maximum temperature attainable by the machines while operating under certain load condition.

Heat Run test or Temperature Rise test

The life of insulation of electrical equipment depends upon the maximum temperature attained during operation. The objective of the test is to find out the actual maximum temperature attained while the machine is operating under certain load condition.

The back-to-back load is performed for the temperature run also. The normal duration of the hot run test for large machine is about 6 hours. In some cases, to avoid waste of energy during testing and to reduce testing duration (which is normally till the temperature rise attains a steady value), short time test is carried out and ultimate temperature rise of the machine is determined from the data obtained from these tests.

The equation for temperature rise is given by, $\theta = \theta_m (1- e^{-\frac{t}{\tau}})$

Where θ = the temperature rise at time t, θ_m = maximum temperature rise, τ = heating time constant depending upon the thermal capacity of the insulation and the rate of dissipation of heat.

The above equation being simplified by substituting $e^{-\frac{1}{\tau}}$ by k. we get $\theta = \theta_m (1\text{-}k^t)$.

When t = 1, $\theta_1 = \theta_m (1\text{-}k)$. t = 2, $\theta_2 = \theta_m (1\text{-}k^2)$. k^2

Then $\frac{\theta_2}{\theta_1} = \frac{1-k^2}{1-k}$ or, k = $\frac{\theta_2-\theta_1}{\theta_1}$

And the maximum temperature rise, $\theta_m = \frac{\theta 1}{1-k}$ ……...…………... (17)

It will thus be possible to determine the maximum temperature rise by taking two or more readings at regular intervals of time, i.e. k = $\frac{\theta_2-\theta_1}{\theta_1-\theta_0} = \frac{\theta_3-\theta_2}{\theta_2-\theta_1} = \frac{\theta_4-\theta_3}{\theta_3-\theta_2}$ and so on.

The interval of time during the test for measurement of temperature may be taken as 30 minutes or even smaller.

Example: in a heat run test on a dc machine, three consecutive readings taken at 30 mints time intervals were 35°C, 45°C and 50°C.

So, ratio of temperature rise during successive intervals of time,

k = $\frac{\theta_2-\theta_1}{\theta_1-\theta_0} = \frac{50-45}{45-35} = 0.5$

Maximum temperature likely to be attained, $\theta_m = \theta_0 + \frac{\theta_1-\theta_0}{1-k}$

When k = 0.5 we get $\theta_m = 35 + \frac{45-35}{1-0.5} = 55°C$

10. CLASSIFICATION OF INSULATING MATERIALS

The temperature rise which electric motor can safely withstand is determined by thermal stability (limiting temperature) of the insulating materials used in them. By using materials of higher thermal stability, motors of the same physical size may be rated for larger power output.

Different insulating materials have different limiting temperature. For example (ref. IS-1271), Class y (90℃), Class A (105℃), Class E (120℃), Class B (130℃), Class F (155℃), Class H (180℃)

11. CONCLUSION

Arrangement for additional heat dissipation from electrical machines by using thermo-mechanical coupling in torque transmission appear to be beneficial to various aspects of such machine e.g. improving the heating curve, cooling curve, lessening power consumption in cooling and ventilation by fan, increase in effective output power, reducing the heating time constant vis-a-vis maximum temperature rise, reducing cooling time constant, enduring insulation, improving the rating vis-a-vis reducing size or frame size of machine and reduces temperature dependent losses indicating more efficient performance of the machine. The machine may perform in relatively tougher service condition. In case effective output power increase even by 0.1%, in the power consumption order of 1 TW in the corresponding application, the saving of power ranges to 1000 MW which remains not negligible.

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Biographies

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