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# Dimensional and Constructional Details of Components, Fundamentals of TNM Method and Basics of SCIM Motor Heat Transfer

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**Abstract**
For the improvement in thermal design of squirrel cage induction (SCIM) motor, it is essential to know details of the methods for evaluation of thermal distribution in a SCIM motor. A presentation of various details of methods of basics of heat transfer that occur in a SCIM motor is done in this report. SCIM motors have wide applications and thus their construction is completely influenced by the starting characteristics specified by the operating loads. General constraints of a motor and specification of 30 KW motor are presented in this report as a case study of constraints. As the next step the Thermal Network Method (TNM) has been explained.

## I. INTRODUCTION

This paper presents all the basics that are required in establishing the methodology for grading of standard techniques and concepts used in reduction of losses, improve cooling methods and or reduction of thermal load. These techniques are used to reduce hot spot temperatures which are termed as techniques of thermal design improvement. Improvement of motors is to be achieved using standard dimensions of bearings and frames. It has been demonstrated that to achieve a 2.6 - 3% increase in efficiency for a 30 KW motor which corresponds to improvement of 2 classes of NEMA motor, whole of the information about motor, (name plate details) is required for the TNM model, the general format of which is provided. Generally stator end winding, rotor end ring or shaft is the hot spot. Large losses, poor cooling or large thermal loads are the causes. Many techniques are available which can bring improvement from this condition and it is necessary to evaluate to ensure the necessary improvements have been achieved. Before evaluating the thermal design improvement it is always a necessity to know the description of parts of squirrel cage induction motor, the flow of heat in it, general information of name plate details, basics of heat transfer and the basics steps that are used in the establishment of thermal resistances required for the TNM method. The general notations that are used in heat transfer method are also added in this report.

## II. DESCRIPTION OF SCIM MOTOR

Stator and Rotor are the main parts of an electric motor.

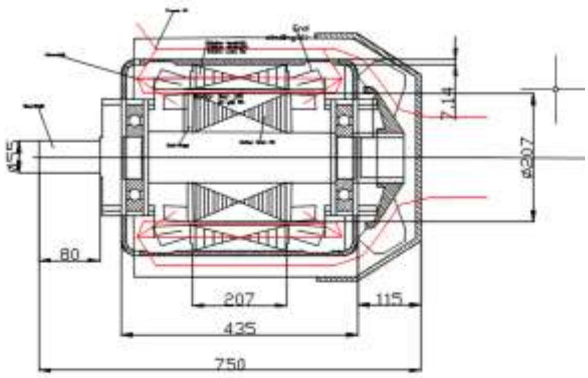


Fig. 1 General Assembly of SCIM Motor with path of heat flow added (red color)

The torque producing currents in the rotor of the induction motor are induced by electromagnetic action. The stator winding therefore not only produces the magnetic field or the excitation, but also supplies the energy that is converted to mechanical output. Stator magnetic field causes the rotor to rotate.

The most important features of squirrel cage induction motor that enhances its suitability in hostile environment are ruggedness and robustness.

## III. STATOR

Fig. 2 to Fig. 4 are made available by Brook Crompton company in the general public domain. Stator induces a magnetic field to penetrate the rotor. To optimize the distribution of the magnetic field, the windings are distributed in slots around the stator. Windings are made with copper or aluminum materials depending on specifications of motor like starting current requirement and minimization of losses.

Fig. 2 Stator of three-phase induction motor

***A. FRAME***

It is the outer most part of SCIM motor. Its main function is to support stator core and field winding. It acts as a covering and provides protection and mechanical strength to all the inner parts of motor. The frame is either made up of die cast Aluminum or fabricated steel. The frame of three phase induction motor should be very strong and rigid as the air gap length of three phase induction motor is very small, otherwise rotor will not remain concentric with stator, which will give rise to unbalanced magnetic pull.

If weight is a constraint, Al alloys are used for frame, otherwise Cast Iron (CI) frame is used. Al alloys are better conductors of heat in addition to being lighter where as CI frames offer greater strength and can absorb vibrations that might be present because of relaxations in fabrication, dynamic balancing or similar such specifications. Al alloys are ductile and may deform locally to the extent to fill the gaps between lamination stack (core) and the frame and may relax the stringent manufacturing tolerances that are specified otherwise. When accurate dimensional accuracies cannot be achieved bearings may need to be designed for heavier loads requiring bigger sizes and standard frame sizes available in the market to accommodate these higher size bearings may pose a difficulty. When provided with fins on the outer surface of the frame the heat transfer due to natural convection could increase almost by fifty (50) percent. The two ends of the motor are called drive end and fan end. The fan blows air axially and the speed variation along the axial length is generally ignored while estimating the average forced convective heat transfer coefficient. Radiation or natural convective heat transfer coefficients on the frame are considered only the fan does not work or works at very slow speeds.

***B. STATOR CORE***

The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current losses, stator core is laminated. The core is made up of stampings which are about 0.4 to 0.5 mm thick. The laminations are stamped together to form stator core, which is then housed in stator frame. The stamping is generally made up of silicon steel, which helps to reduce the hysteresis losses. For further lower thicknesses techniques involving state of art technology methods requiring laser cutting may need to be used for the reduction of losses. Also minimum mechanical strength due to lateral bending while stacking to get the required stacking factor is a specification driven constraint.

***C. STATOR WINDING***

The slots on the periphery of stator core of the three phase induction motor carries three phase windings. This three phase winding is supplied by three phase ac supply. The three phases of the winding are connected either in star or delta depending upon which type of starting method is used. The squirrel cage motor is mostly started by star – delta starter and hence the stator of squirrel cage motor is delta connected. When this winding is excited by three phase ac supply it produces a rotating magnetic field.

Dimensional specifications of c/s and length of embedded windings and end windings influence axial and radial distribution of heat in them.

## IV. ROTOR

It contains many longitudinal conductive bars forming a cage. The bars are usually made of aluminum. The core of the rotor is also built with stacks of Silicon Steel laminations. Rotor has different number of slots compared to the stator. This is done to prevent magnetic interlocking of rotor and stator teeth at the starting instant.

The iron core serves to carry the magnetic field through the rotor conductor. Because the magnetic field in the rotor is alternating with time, core energy loss is reduced. It is made of thin laminations, separated by varnish insulation, to reduce eddy currents in the core. Stator and rotor cores are made of low carbon but high silicon steel material without impurities.

Copper bars are better conductors of heat whereas Al bars can be easily formed and contact resistances can be minimized. Copper molding needs handling higher temperatures compared to Al material. Better thermal conductivity of copper permits use of lower cross section bars or end rings for the cause of decreasing the starting current requirements which otherwise will be higher.

Figure-3 Cage rotor for induction motor

For lower capacity motors the rotor conductor bars and end rings are cast in aluminum, and the blades attached to the end rings as shown in figure 4 serve as a fan for circulation of air.

### A. *END RINGS*

The rotor cage consists of end rings at both ends. Rotor bars are fitted to the end rings by welding or brazing. For higher efficiency motors end rings are made of copper material.

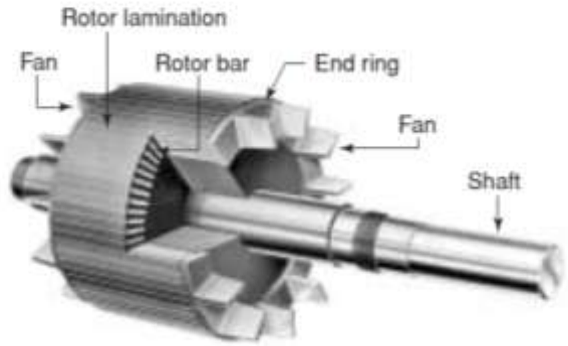


Fig. 4 Rotor with End rings

### *B. ROTOR BARS*

Rotor bars are made of aluminum or copper. They are set in to grooves and are connected at both ends by rings. The rotor bars are as shown in figure 4.

### *C.BEARINGS*

The sizes of the bearings used for the selected motors and their dimensional details are as given below.

Table I
Details of components affecting thermal design

| Stator Components | | | |
|---|---|---|---|
| | Construction | Heat dissipation features | Materials |
| Frame | Fins, Blowing air speed of fan, Radiation etc. More in Section III A | | |
| Fan | Blade outer dimension and peripheral speed of the rotor are to be limited. Un supported length of shaft on bearings should be limited to ensure critical speeds are not exceeded. | | |
| Core/Laminations | Section III B | | |
| Windings/End windings | Section III C | | |
| Rotor components | | | |
| Internal fan blades/Wafters | Heat generated in the rotor is dissipated by proper design of blades. Wafters are generally integral with end rings. | | |
| Windings/Rotor Bar | Copper losses are significant and require optimization. | | |
| Laminations | Core losses are insignificant and other criterions like mechanical strength and ease of fabrication, containing the bars and joints with end rings or rotor blades decide the material selection | | |
| End ring | Copper losses are significant. | | |
| Bearings | Selection of Standard sizes and easy mounting features ensure good design of motor | | |
| Shaft | Shaft is generally treated as made of 3 parts | Features are explained by equations (21) and (22) | |
| Air gap | Uniform air gap is achieved by good machining capabilities of rotor OD and stator id. Uniform and minimum air gap ensures lower loads for bearings and their lower sizes and easy containment of bearings in the enclosures. | | |
| Enclosure | Round enclosures can contain more air and cooling gets improved where as rectangular ones are easy to fabricate. Size is limited by frame dimensions. With higher capacity fans thicknesses can be reduced. | | |

Details of bearings that are generally use for a standard size motor of 30 KW motor are given in the following table.

TABLE II
DETAILS OF BEARINGS USED IN THE INDUCTION MOTORS OF 30 KW motor

| | Bearings | | Radial Ball Bearing details | | |
|---|---|---|---|---|---|
| Frame | Drive end | Non drive end | Bore | OD | Width |
| 200 L | 6312 | 6312 | 60 | 130 | 31 |

General name plate details of SCIM motor are given in the following table.

TABLE III
NAME PLATE DETAILS TEMPLATE (GENERAL FORMAT)

| | | |
|---|---|---|
| Manufacturer's name | | |
| Induction Motor | | |
| Made in India | | |
| Serial No. | Type | Insulation |
| HP | Frame | KVA |
| AMPS | Volts | Temp $^0$c |
| RPM | Hertz | Thermal protected sealed bearings |
| Duty | Phase | |

## V. DIMENSIONAL DETAILS OF FRAMES

B (ACRS) = distance between the centre lines of the fixing holes (side view)
ED = length of the shaft extension from the shoulder at the D-end
HD = distance from the top of the lifting eye, the terminal box or other most salient part mounted on the top of the motor to the bottom of the feet
L = overall length of the motor with a single shaft extension
AC = outside diameter of the flange, or in the case of a non-circular outline twice the maximum radial dimension

## VI. NAME PLATE DETAILS OF THE MOTOR

The name plate detail information is useful to maintenance personnel. The information is vital for the fast and proper replacement of the motor, if necessary.
For a better understanding of the motor, typical information found on motor nameplates is described as follows.

- Type identifies the type of the enclosure. This is the manufacturer's coded identification system.
- Frame size identifies the measurements of the motor.
- Service factor (or SF)—a service factor of 1.0 means the motor shouldn't be expected to deliver more than its rated horsepower. The motor will operate safely if it's run at the rated horsepower times the service factor, maximum. Common service- factors are 1.0 to 1.15. It is recommended that the motor not be run continuously in the service factor range. This may shorten the life expectancy of the insulation system.

Amperes means the current drawn from the line when the motor is operating at rated voltage and frequency at the fully rated nameplate horsepower.

- Volts should be the value measured at the motor terminals and should be the value for which the motor is designed. Voltage also decides the insulation class and thickness.
- Maximum limiting temperature decides the class of insulation which refers to the insulating material used in winding the motor stator. E.g., in a Class B system, the maximum operating temperature is 130°C; for Class F, it's 155°C; and for Class H, it's 180°C.
- RPM (or r/min) means the speed in revolutions per minute when all other nameplate conditions are met.
- Hertz is the frequency of the power system for which the motor is designed. Performance will be altered if it's operated at other frequencies.
- Duty is the cycle of operation that the motor can safely operate. "Continuous" means that the motor can operate fully loaded 24 hours a day. If "intermediate" is shown, a time interval will also appear. This means the motor can operate at full load for the specified period. The motor should then be stopped and allowed to cool before starting again. Considerations of steady state heat transfer are enough for continuous operating motors which are not overloaded.
- Ambient temperature specifies the maximum surrounding air temperature at which the motor can operate to deliver the rated horsepower.
- Phase entry indicates the number of voltage phases at which the motor is designed to operate.
- Efficiency is expressed in percent. This value is found on standard motors as well as "premium efficiency" motors. The value indicates effective conversion of electrical input into mechanical work and remaining gets generated as heat which needs to be dissipated.

| General dimensional details | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| B | ED | HD | L | AC | Lec | te | tsy | Ls |
| 304 | 80 | 399 | 750 | 422 | 750 | 20 | 193 | 207 |

TABLE IV
GENERAL DIMENSIONAL DETAILS OF FRAME

## VII. HEAT TRANSFER CONSIDERATIONS

Heat transfer in a squirrel cage induction motor occurs due to

a. Conduction
b. Convection and
c. Radiation

Various notations that are used in standard heat transfer text books for the heat transfer basics related to flow of heat only are mentioned in the following table.

TABLE V
NOMENCLATURE FOLLOWED IN THIS REPORT

| | | |
|---|---|---|
| h | W/(m$^2$. K) | Convective heat transfer coefficient, |
| g | m/s$^2$ | Acceleration due to gravity |
| x, l or L | M | Representative linear dimension or characteristic length |
| β | 1/K | Coefficient of expansion of the fluid, |
| Δt | K | temperature difference between the surface and the bulk of the fluid |
| θ | K | Temperature |
| ν | m$^2$/s | Kinematic viscosity of the fluid, |
| u | m/s | Velocity of flow |
| ρ | Kg/m$^3$ | Density of material |
| μ | N.m$^2$/s | Viscosity of fluid |
| α | m$^2$/s | Thermal diffusivity. |
| C | J/(Kg. K) | Specific heat |
| σ | | Stefen-Boltzmann's constant |
| ϵ | | Emissivity |
| A | m$^2$ | Area normal to the direction of flow of heat |
| *q* | W/m$^3$ | *is* the heat generated per unit volume |
| K | W/(m.K) | Thermal conductivity (suffix indicates the value in the specified direction (x,y,z) or (r, $\varphi, z$) |

In SCIM motors, heat transfer is a combination of all the three methods. For example, heat transfer between stator outer surface and ambient air it is transferred simultaneously by convection, conduction and radiation.

For example, heat transfer between stator outer surface and ambient air it is transferred simultaneously by convection, conduction and radiation. Usually in SCIM motor of TEFC design, the most significant method of heat removal is convection through the air.

## VIII CONDUCTION

In usual notation, the two dimensional equations of steady state heat conduction in Cartesian and polar coordinates are given in (1) and (2) respectively

$$0 = \frac{\delta}{\delta x}\left(K_x \frac{\delta\theta}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_y \frac{\delta\theta}{\delta y}\right) + q \quad ........... (1)$$

$$0 = \frac{1}{r}\frac{\delta}{\delta r}\left(K_r \frac{\delta\theta}{\delta r}\right) + \frac{1}{r^2}\frac{\delta}{\delta\varphi}\left(K_\varphi \frac{\delta\theta}{\delta\varphi}\right) + q \quad ......... (2)$$

The thermal resistance between two points at distances $x_1$and $x_2$ from origin of cylinder in axial direction is

$$R_{th} = \frac{x_2 - x_1}{K_x A} \quad ………………..(3)$$

Where, A is the area normal to the flow of heat

### B. *ONE DIMENSIONAL STEADY STATE HEAT FLOW (CARTESIAN COORDINATES)*

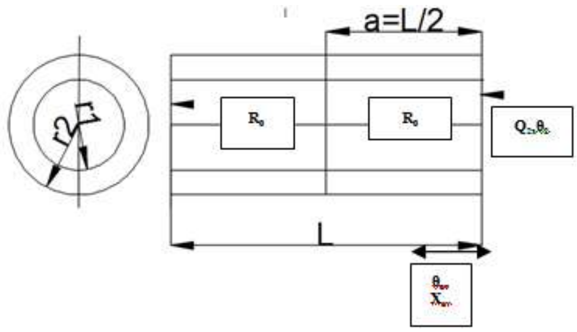


Fig. 6 Equivalent circuit for a cylindrical element in axial direction (only heat generation)

For an arbitrary cylinder, the steady state heat conduction in the axial direction is governed by Poisson's equation and is given by,

$$\frac{d_\theta^2}{dx^2} + \frac{q}{K_x} = 0.0 \quad ……………………………..(4)$$

$$Q_x = 0.0 = -k\,A\frac{d\theta}{dx} \quad \text{at } x = 0.0$$

The general solution to this equation, in the standard form, is given by

$$\theta(x) = \theta_4 + \frac{q}{2K_x}(a^2 - x^2) \quad \text{where } a = L/2 \quad …………..(5)$$

and the mean temperature is given by

$$\theta_{av} = \theta_4 + \frac{QR_0}{3} \quad \text{where} \quad \theta_{av} = \frac{1}{a}\int_0^a \theta(x)dx \quad (6)$$

$$Q = q\,a\,\pi\,(r_2^2 - r_1^2) \quad …………….(7)$$

$$R_0 = \frac{a}{\pi\,(r_2^2 - r_1^2)K_x} \quad ……………………..(8)$$

Comparison of equations above shows that the location of the mean temperature

$$X_{av} = \frac{a}{\sqrt{3}} = \frac{L}{2\sqrt{3}} \quad ……. .(9)$$

The 34behavior of the thermal circuit in the axial direction can thus be represented by the network shown in Fig. 8 with

$R_1 = \frac{a}{3\ \pi\ K_x\ (r_2^2 - r_1^2)} = \frac{R_0}{3}$ …………………. .(10)

This network, which is symmetrical, accurately represents the axial heat flow in the cylinder for the case of only internal heat generation, and has the representation for all the temperatures of interest; $\theta_3$ and $\theta_4$ of the surfaces and $\theta_{av}$, the mean temperature. It can be observed that thermal resistance from the mean temperature to the surface temperature is $\frac{R_0}{3}$ which is the thermal resistance of an equivalent cylinder of cross sectional area equal to $\pi(r_2^2 - r_1^2)$ and effective length a/3 subject to the radial boundary conditions

## C. *ONE DIMENSIONAL STEADY STATE HEAT FLOW (POLAR COORDINATES)*

Motor may be divided into number of thermal nodes depending on the requirement of accuracies that are expected in the solutions. And connecting the nodes by thermal resistances in a TNM model and applying heat at the locations are shown in the figures. Method of solutions for the locations where t internal heat is generated and internal heat is not generated are demonstrated in this report.

The governing one-dimensional Poisson's equation for radial conductive heat transfer is given by

$\frac{d_\theta^2}{dr^2} + \frac{q}{K_r} + \frac{1}{r}\frac{d\theta}{dr} = 0.0$ ……………. (11)

Subject to the radial boundary condition

$(\frac{d\theta}{dr})_{r=r1} = \frac{-Q1}{K_r\ A_1}$ and $\theta_{\ r = r2} = \theta_2$

The general solution, e in the standard form is as below:

$\Theta(r) = \theta_2 + C\left[\frac{r_2^2 - r_1^2}{2} - r_1^2 \ln\frac{r}{r_2}\right] - \frac{Q_1}{2\ a\pi\ K_r}\ln\frac{r}{r_2}$ …...(12)

Substituting $C = \frac{Q}{2\ a\ \pi K_r\ (r_2^2 - r_1^2)}$

from which (by substituting r=r$_1$), $\theta_{av} = \frac{1}{r}\int_0^a \theta(r)dr$

$\theta_1 = \theta_2 + C\left[\frac{r_2^2 - r_1^2}{2} - r_1^2 \ln\frac{r_1}{r_2}\right] - \frac{Q_1}{2\ a\ \pi K_r}\ln\frac{r_1}{r_2}$ .( 13)

and the mean temperature,

$\theta_{av} = \theta_2 + C\left[\frac{r_2^2 - r_1^2}{2} - r_1^2\ (1 - 2B)\right] + \frac{Q_1}{4\ a\ \pi K_r}(1\text{-}2B)$ ……………...( 14)

Where $B = \frac{r_1^2}{(r_2^2 - r_1^2)}\ \ln\frac{r_2}{r_1}$

For the particular case when Q=0, i.e. no internal heat generation, the temperature variation can be modeled by the two resistor network shown in fig. 7, where,

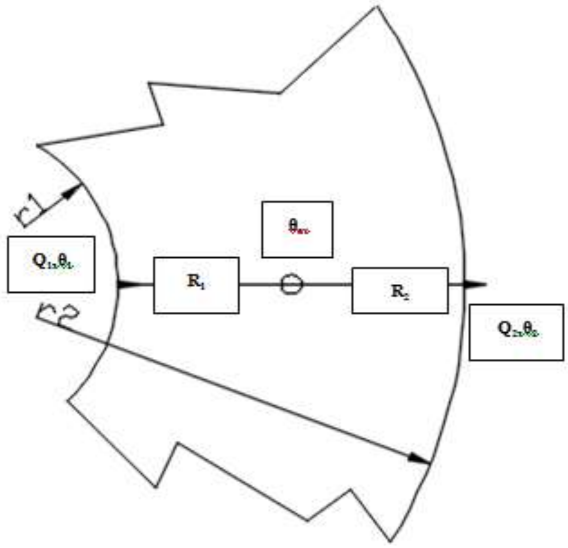


Fig. 7 Equivalent Circuit for Cylindrical Element in the Radial Direction (No internal heat generation)

$\frac{Q}{A} = - K\ \frac{dT}{dr}$ ……..(15)

$R_1 = \frac{\theta_1 - \theta_{av}}{Q_1} = \frac{1}{4\ a\ \pi K_r}\left[\frac{2\ r_2^2}{(r_2^2 - r_1^2)}\ln\frac{r_2}{r_1} - \right]$ (16)

$R_2 = \frac{\theta_{av} - \theta_1}{Q_1} = \frac{1}{4\ a\ \pi K_r}\left[1 - \frac{2\ r_1^2}{(r_2^2 - r_1^2)}\ln\frac{r_2}{r_1}\right]$ ……(17)

For the case when $Q \neq 0.0$, the 'T' equivalent circuit was the two resistor network shown in fig. 7, where,

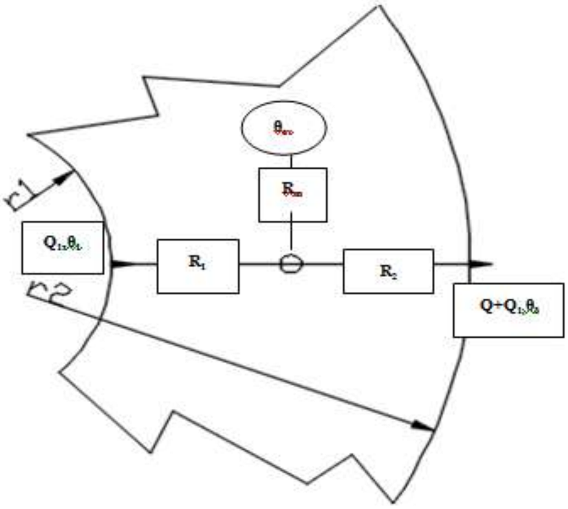


Fig. 8 Equivalent circuit for cylindrical element in the radial direction (With internal heat generation**)**

Where $R_m = \frac{\theta_{av} - \theta_2}{Q} - R_2(1 + \frac{Q_1}{Q})$

$= -QC\left[(r_2^2 + r_1^2) - \frac{4\ r_1^2\ r_2^2}{(r_2^2 - r_1^2)}\ln\frac{r_2}{r_1}\right]$ (18)

and R$_2$ as defined previously

By coupling the radial and axial equivalent circuits at the position of average temperature, a complete model of a hollow cylindrical section shown in Fig. 9 is obtained.

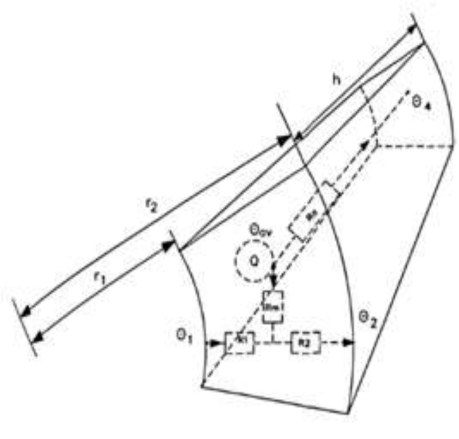

Fig. 9 Section of a cylinder showing the two dimensional thermal equivalent circuit

For particular solution of the radial flow equation for a solid cylinder, $r_1 \longrightarrow 0$, the temperature profile, Eq. (12) become

$$\theta (r) = \theta_2 + \frac{Q}{2\, a\, \pi K_r\, r_2^2}\left[\frac{r_2^2 - r^2}{2}\right] \quad \ldots(19)$$

And the mean temperature

$$\theta_{av} = \theta_2 + \frac{Q}{8\, a\, \pi K_r} \quad \ldots..(20)$$

Thus the resistance to heat flow from the component mean temperature to the radial boundary is given by

$$R_r = \frac{\theta_{av} - \theta_2}{Q} = \frac{1}{8\, a\, \pi K_r} \quad \ldots\ldots\ldots\ldots..(21)$$

and the thermal resistance in axial direction is given by setting $r_1 \longrightarrow 0$

$$R_a = \frac{h}{3\, a\, \pi K_a\, r_2^2} .. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(22)$$

The two previous equations can be used to model the shaft in the axial and radial directions as a cylindrical rod. The axial heat conduction of the shaft is modeled as three sections; one that lies under the rotor iron, a second that lies under the bearing, and a third that acts as a thermal link between mean temperatures of the first two. The mean temperature of the entire shaft is taken to be the temperature at centre of the third section. A good thermal contact is assumed to exist between the shaft and the frame across the bearings, and as there is only a small contact area with the end cap air, any heat transfer between these components was neglected.

Q is the dissipated heat (Power density in Watt).

The temperature dependence of the thermal conductivity of gases, including air is appreciable.

## IX. CONVECTION

Heat exchange due to convection is described by $Q = h\, A\, \Delta\theta$ and thermal resistance due to convection is

$R_{th} = \frac{1}{hA}$ Generally, h depends on many variables, such as shape and dimensions of the surface, flow characteristics, temperature and material characteristics of the fluid. Numerical values for h are in general determined from empirical relation involving dimensionless numbers.

In SCIM motors, the convective heat transfer can be divided into external and internal types. External type takes place between the outside of the machine and ambient. Internal convection heat transfer is across the air gap and from the end windings, tooth end caps and housing.

Film coefficients that describe the convective heat transfer from different surfaces of induction motor need to be considered. Two values of film coefficient are required for each surface. One coefficient describes stationary state of the machine, when the external and internal fans are ineffective. The second one is used for the case when machine is rotating.

These two cases are denoted by the subscripts s and r

- $h_1$ - heat transfer between frame and external air
- $h_{2s}$, $h_{2r}$ – heat transfer between stator or rotor via air gap
- $h_{3s}$, $h_{3r}$ – heat transfer between stator iron, rotor, end windings or end caps, end ring and end cap air.

The convection mechanism is due to transfer of energy between an object and its environment, due to fluid motion.

## X. TYPES OF CONVECTIVE HEAT TRANSFER

### *A. FREE OR NATURAL CONVECTION*

Fluid motion is caused by buoyancy forces that result from the density variations due to variation of temperature in fluid. In absence of an external source, the fluid is in contact with a hot surface, its molecules separate and scatter, causing the fluid to be less dense. As a consequence, the fluid is displaced while the cooler fluid gets denser and the fluid sinks. Thus, the hotter volume transfers heat to the cooler volume of the fluid.

### *B. FORCED CONVECTION*

When a fluid is forced to flow over the surface by external sources such as fan, stirrer or pumps, artificially induced convection is created.

## XI. MAIN DIMENSIONLESS NUMBERS IN CONVECTION

Many non dimensional numbers may be defined which makes the process of describing the convection phenomenon easier.

***A.GRASHOF NUMBER***

For free convection, the GRASHOF number is used. The significance of the GRASHOF number is that it represents the ratio of the buoyancy force due to spatial variation in fluid density (caused by temperature differences) and the restraining force due to the viscosity of the fluid.

$$G_r = \frac{g\, l^3}{\nu^2}\beta\Delta\theta \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(23)$$

***B. REYNOLDS NUMBER***

Another dimensionless number used is Reynolds number

$$R_e = \frac{u\, x}{\nu} \qquad \ldots\ldots\ldots(24)$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{C_p\,\mu}{K} \qquad \ldots\ldots...(25)$$

***C. PRANDTL NUMBER***

PRANDTL number, Pr, is a dimensionless parameter representing the ratio of diffusion of momentum to diffusion of heat in a fluid.

***D .NUSSELT NUMBER***

NUSSELT number, Nu, is the dimensionless parameter characterizing convective heat transfer. It is defined as

$$\mathrm{Nu} = \frac{h\, L}{K} \qquad \ldots\ldots\ldots..(26)$$

***E. TAYLOR NUMBER***

$$\mathrm{Ta} = \mathrm{Re}\sqrt{\frac{l_g}{R_r}} \qquad \ldots..(27)$$

Where $l_g$ is the air-gap radial thickness, $R_r$ is the rotor outer radius, and Re the Reynold number

## XII. RADIATION

Radiation depends on area, material characteristics, temperature and surroundings. Emissivity and absorptivity of a compact body are assumed to be equal and there is no transmission. Thus heat exchange depends on radiation angles, emissivity and temperatures of the interacting surfaces.

Thermal radiation is not of great significance in SCIM motor as much as thermal convection and conduction. Radiation heat transfer is of considerable significance in the total heat transfer of SCIM motors if there is only natural convection without any externally mounted fan on the motor. That is why in SCIM motor of TEFC design the heat transferred by radiation is often neglected. Radiation mode of heat transfer also occurs in inner parts of the SCIM motor, for instance, between stator end windings or rotor end rings and the end cap air or from the end cap air to the frame end caps.

The net amount of heat transferred by radiation depends on the temperature difference and the position between heat exchanging surfaces and can be calculated by

$$Q = \sigma\epsilon\,(\theta_b^4 - \theta_s^4) \qquad \ldots.(28)$$

Where $\theta_b$ == Temperature of body (in $K$)
$\theta_s$ = Temperature of Surrounding (in $K$)
Thermal resistance due to radiation is given by

$$R_{th,r} = \frac{1}{\sigma\epsilon A} \qquad \ldots\ldots\ldots\ldots\ldots..(29)$$

## XIII. THERMAL NET WORKS

For simplicity, SCIM motor can be considered as a coaxial system of concentric cylinders representing the shaft, rotor iron, motor frame, stator iron etc. based on principles described. Relevant empirical thermal models found in literature are applied for calculating thermal resistances. Thermal networks describe the main paths for heat flow, enabling temperatures of the main components within the motor to be predicted for given loss distribution.
Calculation of heat loss values has been done based on principles quoted in report 3 and 5.

***A. UNIFORMITY CONSIDERATIONS FOR NODES***

1. Uniformity of temperatures within the component and the surfaces
2. Uniformity of the heat generated for the active component
3. Uniformity of physical properties within each component
4. Uniformity of exchange conditions by convection for each of the surfaces

***B. FEATURES OF TNM MODELS***

1. Nodes are regions (components) of constant temperature connoting mean temperatures.
2 Heat generations at various positions in motor or motor losses are Iron losses, Joule losses, stray load losses and mechanical losses.
3. Thermal resistances are objects of heat resistances governed by heat conduction and convection while impact of heat radiation is given importance at only significant locations.

***C. HYPOTHESES FOR SIMPLIFYING TNM MODELS [4]***

1. A motor symmetry is assumed around the shaft and about the radial plane through the center of the motor. This leads to the result of using fig. 13 instead of fig.12.
2. The influence of the asymmetrical temperature distribution that exists in the motor with external fan mounted at one end is neglected. (Fan end and no fan end behave thermally in a similar manner)

3. Each cylinder is thermally symmetrical in the radial direction.
4. The inner heat sources are uniformly distributed.
5. The heat flux in the axial direction has been considered only in the shaft. It has been neglected in the rest of the motor. In this way, the thermal radial resistances can be computed using the equations of the hollow cylinder;

## XIV. Node Configuration

Generally, Thermal resistance $R_{th}$ describing the conductive heat transfer in one dimension is

$$R_{th} = \frac{L}{KA}$$

Where, L is length of the body, K is the thermal conductivity and A is the cross-section area.
It is well known that principle thermal networks of main parts of SCIM motor are built based on general cylindrical components as shown in fig. 10

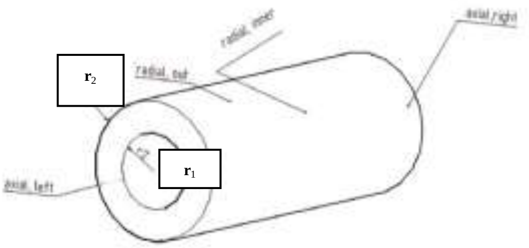


Fig.10 General cylindrical components with four unknown temperatures: two at the axial edges and two on the outer and inner surfaces

Thermal conduction resistance in the radial direction are represented in the figure.. Equation of resistance is derived from the Fourier law described below.

$$R_1 = \frac{\ln\left(\frac{r_m}{r_1}\right)}{2*\pi*K*L}$$
…....................(31)

$$R_2 = \frac{\ln\left(\frac{r_2}{r_m}\right)}{2*\pi*K*L} \quad \text{---------------------(32)}$$

Where, $r_m$= Average radius of $r_1$ and $r_2$ (in *m* )

L= Length of cylinder (in m)

$$r_m = \frac{r_1 + r_2}{2} \quad \text{……………………………..(33)}$$

A thermal model node configuration of one dimensional (either axial or radial direction) heat flow without internal heat generation.

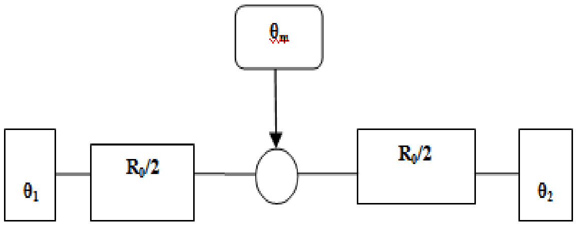


Fig. 11 Node configuration for one-dimensional heat flow without internal heat generation

The node configuration should be understood as the way a particular element is modeled by nodes and by thermal resistances to the surroundings. It is important that the node configuration is such that the average temperature of the element is obtained in one node. From this temperature the maximum temperature can generally be calculated. The simplest node configuration is of one dimensional heat flow with no internal sources. $R_0$ is total thermal resistance of the element in the direction of heat flow.
To describe the heat conduction across the cylindrical component, the following assumptions are made:

- Heat flows in the radial and axial direction are independent.
- A single mean temperature defines heat flow both in the radial and axial directions.
- There is no circumferential heat flow.
- Heat generation is uniformly distributed.

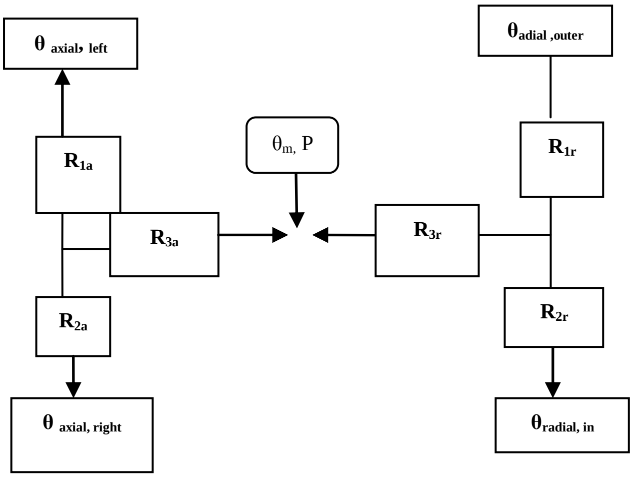


Fig. 12 Independent axial and radial thermal networks, θm is the average temperature, and the losses are denoted by P

On making these assumptions, two separate three terminal networks combined into one single network as shown in fig. 12 is obtained If there is uniform heat generation in the element, it could be quite easily shown that the two node configuration of fig. 12 could be modified as that in fig. 13 that can be used to obtain the average temperature in the element. The internal losses/heat generations of the elements are then injected to the node that obtains the average temperature $\theta_m$.

The node configuration is also suitable when heat is uniformly added or subtracted along the element, e.g. due to convection. In each network, two of the terminals represent the appropriate surface temperatures of the component, and the third represents the mean temperature $\theta_m$ of the component. The internal heat generation (P) is introduced in the mean temperature node. The central node of each network gives the mean temperature of the component if there is no internal heat generation. If there is heat generation the mean temperature will be obtained as a result of superposition of internal heat generation. This mean temperature is lower than the temperature given by the central node, which is reflected in the network by the negative values of the interconnecting resistances $R_{3a}$ and $R_{3r}$. The thermal resistances of each network are obtained from solutions of conduction equation in the radial and axial directions. The dimensions of the cylinder and the radial and axial conductivities $k_r$, $k_a$ are required for the calculation.

$$R_{1r} = \frac{1}{4*\pi*kr*L}\left[1-\frac{2r_1^2\ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2-r_1^2\right)}\right] \quad \text{.....(34)}$$

$$R_{2r} = \frac{1}{4*\pi*kr*L}\left[\frac{2r_2^2\ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2-r_1^2\right)}-1\right] \quad \text{...(35)}$$

$$R_{3r} = \frac{-1}{8*\pi*\left(r_2^2-r_1^2\right)*kr*L}\left[\left(r_1^2+r_2^2\right)-CC\right]$$

$$Where CC = \frac{4r_1^2r_2^2\ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2-r_1^2\right)} \text{................(36)}$$

$$R_{1a} = \frac{L}{2*\pi*ka}\left[\frac{1}{\left(r_2^2-r_1^2\right)}\right] \quad \text{......(37)}$$

$$R_{2a} = \frac{L}{2*\pi*ka}\left[\frac{1}{\left(r_2^2-r_1^2\right)}\right] \quad \text{.......(38)}$$

$$R_{3a} = \frac{-L}{6*\pi*ka}\left[\frac{1}{\left(r_2^2-r_1^2\right)}\right] \quad \text{........(39)}$$

## XV. HETEROGENOUS NATURE OF MATERIAL CONDUCTIVITY VALUES

When considering conductive heat transfer in SCIM's parts, one must keep in mind that heat conductivity can be in its maximum either in the radial or axial direction. For example, because of the presence of dielectric coating layers in laminated structures, the effective heat conductivity in the stack's axial direction is much lower than in the radial direction. And as a result the main heat transfer path is in the radial direction. On the other hand in stator windings the radial heat conductivity is low, because of the presence of different insulation layers, but the axial conductivity is almost the same as for copper, 400 W/m·K. The main heat transfer path is in the axial direction and the heat generated by the coil losses is removed towards the end windings, where it is removed by convection to the end cap air. Hence the maximum temperature in SCIM motor is often found in the end-winding areas.

It is assumed that the face temperatures $\theta_{axial,right}$ and $\theta_{axial,left}$ are equal, since the temperatures in the cylinder are symmetrical about a central radial plane. Reduced thermal network is presented in figure 13, where half of the cylinder is modeled with only a half of heat generation.

The network given below consists of two internal nodes and four thermal resistances $R_a$, $R_b$, $R_c$ and $R_m$.

$$R_a = R_{1a} + R_{3a} = \frac{L}{6*\pi*ka*\left(r_2^2-r_1^2\right)} \quad \text{(40)}$$

$$R_b = 2R_{1r} = \frac{1}{2*\pi*kr*L}\left[1-\frac{2r_1^2\ln\left(\frac{r_2}{r1}\right)}{\left(r_2^2-r_1^2\right)}\right] \quad \text{(41)}$$

$$R_c = 2R_{2r} = \frac{1}{2*\pi*kr*L}\left[\frac{2r_2^2\ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2-r_1^2\right)}-1\right] \quad \text{..........(42)}$$

$$R_m = 2R_{3r} = \frac{-1}{4*\pi*\left(r_2^2-r_1^2\right)*kr*L}\left[\left(r_1^2+r_2^2\right)-\frac{4r_1^2r_2^2\ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2-r_1^2\right)}\right] \quad \text{...(43)}$$

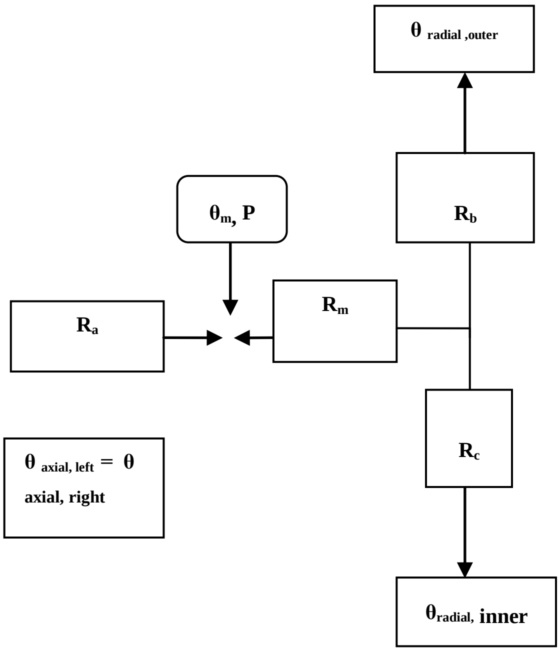


Fig. 13 Combined thermal network for symmetric component

This combined network allows different thermal conductivities in the radial and axial directions. Thus, the thermal effect of the stator and rotor laminations can be considered.

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