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Transient Analysis of Rotor Temperature of Single Cage and Double Cage Induction Motors

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Abstract**—***This paper is designed to carry out transient analysis of temperature of induction motor in both single cage and double cage configurations. The parameters of a 37.3 kW single-cage induction motor were obtained and then upgraded to a double-cage rotor via modelling and a thermal model was developed to evaluate the temperature of the rotor conductor. Simulations were conducted for varying operating load (0, 5, and 10 Nm). The results revealed that at no load, single cage rotor yielded a temperature of 27.4ºC, while cage 1 and cage 2 temperatures of the double cage were 17.0ºC and 15.8ºC respectively. With the motor running at half load, the single cage temperature was 33.4ºC, whereas cage 1 and cage 2 temperatures of the double cage were 19.8ºC and 18.3ºC respectively. At full load, the single cage temperature was 43.0ºC, while cage 1 and cage 2 temperatures of the double cage were 23.7ºC and 22.0ºC respectively. The effective thermal loss of the double cage rotor was higher than the thermal loss from single cage rotor. But, with respect to each of outer and inner cages, low temperature was observed in each conductor compared to single cage rotor when the machine was running.*

Keywords**—** *Double cage, Induction motor, Rotor temperature, Single cage, Transient analysis.*

I. INTRODUCTION

Induction motor encounters losses when it drives the load connected on its shaft. These losses serve as heat sources distributed throughout the entire induction motor and change at different operating conditions. Three main factors to power losses in induction motor are: stator copper losses, rotor bar losses, and iron losses [1]. Stator copper losses occur as a result of the heat generated when current flows through the stator windings, and thus making the machine's temperature to rise. These losses are function of stator current. The rotor bars losses are produced by the current flowing through rotor bars and are dependent of the square of the rotor current. Also, iron losses are produced in the conducting coil laminations of the machine and occurs because of hysteresis and eddy-current.

Several works have been carried out regarding analysis of thermal behaviour of induction motors. For instance, the temperature rise (or changes) of induction motor windings during start-up has been examined considering direct online start-up, soft starting, and use of variable-frequency drive (VFD) in [2]. The temperature distribution inside induction motor was experimentally determined in order to evaluate the thermal stability and ascertain whether the copper winding insulation was adequate at different conditions of operation, and to determine the hottest element that has the foremost impact on the motor operation and performance using a lump parameter thermal model [3]. A thermal model based on lump parameter method that would enable temperature prediction in different parts of induction motor was proposed by [4]. The effects of rise in temperature of three phase induction motor was examined using electrical, mechanical, and thermal model of the machine to study changes in motor parameters [5]. Thermal analysis of a 7.5 kW squirrel cage induction motor has been conducted for steady and transient states at rated-load operation [1]. The results show agreement between measured and predicted temperatures at the rated load condition.

Thus, considering some of the works regarding thermal performance of induction motor, this paper examines the transient behaviour of rotor temperature in single cage and double cage motors.

II. BASIS OF THERMAL MODEL

Mathematical equations that describe the thermal behavior of induction motor are usually derived from the basic energy balance equations that follow the general form [3]:

$$\begin{pmatrix}\text{rate of energy stored}\\ \text{within system}\end{pmatrix}=\begin{pmatrix}\text{heat flow}\\ \text{rate into system}\end{pmatrix}-\begin{pmatrix}\text{heat flow rate}\\ \text{out of system}\end{pmatrix}+\begin{pmatrix}\text{rate of heat generated}\\ \text{within system}\end{pmatrix} \tag{1}$$

For a stationary system composed of a material of density ρ, specific heat Cp, and constant volume V, the balance equation takes the form:

$$\rho C_p V\frac{dT}{dt}=Q_{in}-Q_{out}+Q_{gen} \tag{2}$$

where dT/dt is the rate of change in temperature, Q_{in}, Q_{out} and Q_{gen} are the heat flow into the system, heat flow out of the system and heat generated within the system. Equation (2) can only be used if there is a temperature distribution in the system, or a part of the system is uniform, the assumption about the uniformity of the temperature distribution implies that the system physical properties, such as density and specific heat, are constant within the system boundaries [1, 6]. The block diagram of single cage induction and double cage induction motor connected separately to an AC power supply is shown in Fig. 1.

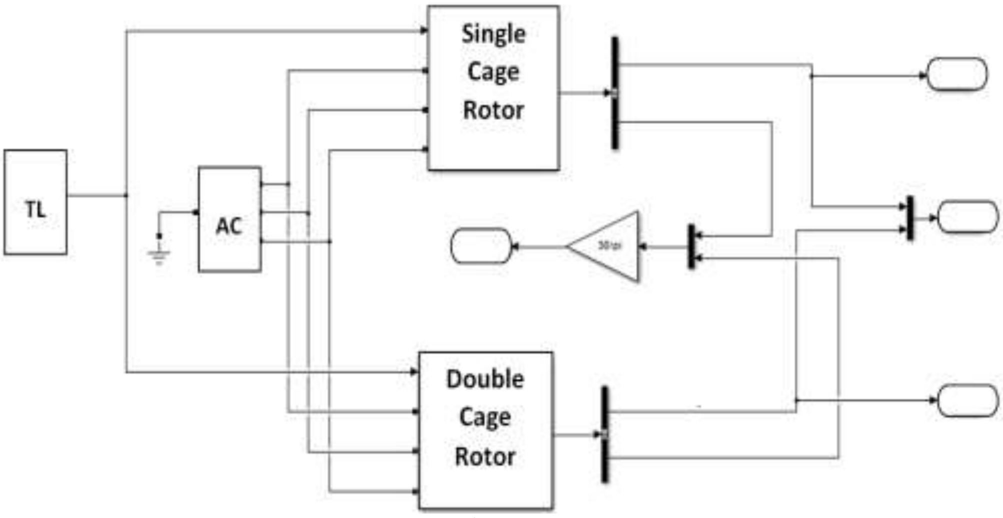

Fig. 1. Block diagram of single cage and double motors

III. THERMAL MODEL IN SIMULINK

The essence of this modelling as an integrated aspect of the system is that appropriate selection be made regarding rating of a motor so as to ensure safe operating limit without exceeding temperature. Thus, the model is developed to analyze the thermal behaviour of the motor in terms of rotor current as the motor operates. The state variable parameters of the thermal model include rotor current and the output temperature. For a given load the input parameters are the power supply (50 Hz, 400 V line voltage), and load torque (0, 5, 10 Nm). The MATLAB/Simulink model of the system is shown in Fig. 2.

For a given conductor, the differential expression for the rise in temperature assuming no heat loss is given by [7, 5]:

$$I^2R = C_T \frac{d\theta}{dt} \tag{3}$$

where I is the current through the conductor (rotor), R is the resistance of the conductor, C_T is the conductor's thermal capacity, θ is the conductor temperature, I^2R is the thermal loss, and the $d\theta/dt$ is the rate of change in temperature. Equation (3) can be expressed in terms of θ as:

$$\theta = \frac{1}{C_T}\int I^2R.dt \tag{4}$$

The thermal model for temperature measurement is developed in MATLAB/Simulink as shown in Figure 2 using the appropriate rotor currents and resistances in terms of Equation (4) given by [5]:

$$I^2R = C\frac{d\theta_o}{dt} + \theta_o \tag{5}$$

where C and θ_o are the thermal capacity per unit mass and output temperature respectively.

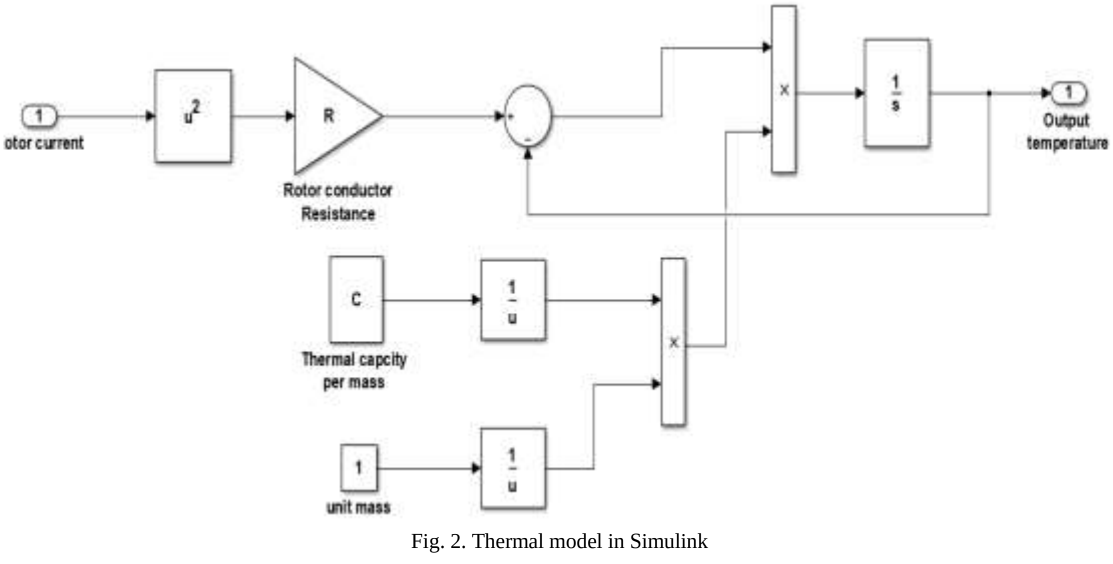

Fig. 2. Thermal model in Simulink

IV. RESULTS AND DISCUSSION

In this section, the thermal behaviour of the induction motor is evaluated in terms of temperature of the rotor conductor due to its currents for single cage arrangement and double cage arrangement. This analysis is designed to examine thermal performance of the induction motor over time in either configuration so as to further ascertain and substantiate the advantage of double cage over the single cage configuration. The simulation analysis has been conducted for no load, half load and full load conditions as shown in Fig. 3, 4 and 5.

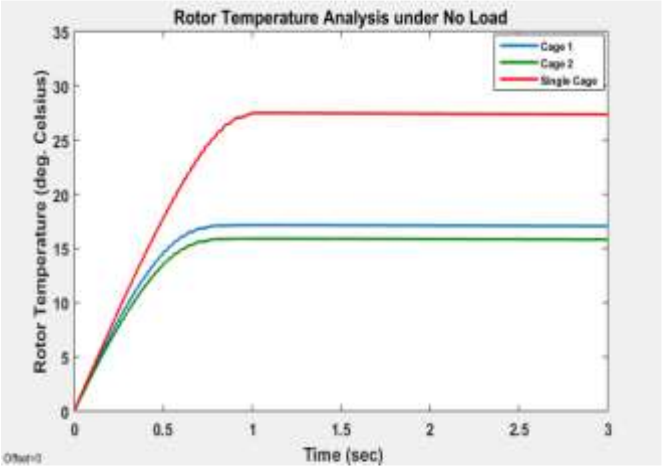

Fig. 3. Rotor temperature analysis under no load condition

Figure 3 shows the curve of thermal behaviour for a single cage and double cage rotors in terms of temperature variation when the motor is running without a load torque. The simulation analysis indicates that the temperature of the motor rises during the starting of the motor and then stabilizes to 27.4°C, 17.1°C and 15.8°C for single cage, cage 1 and cage 2 respectively as the motor reaches its rated speed in 3 s.

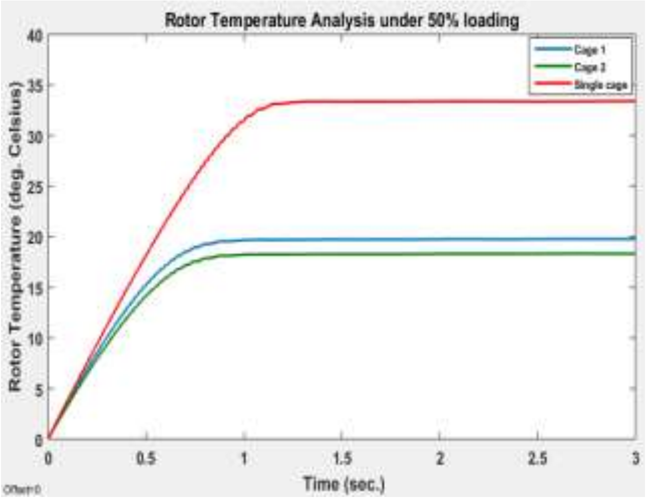

Fig. 4. Rotor temperature analysis under half load condition

The temperature curves of the single cage rotor and double cage rotors (cage 1 and cage 2) when the motor is subjected to half loading is shown in Fig. 4. The simulation analysis revealed that temperatures rise during the starting of the motor and normalize to 33.4°C for the single cage, 19.8°C and 18.3°C for cage 1 and cage 2 rotors in 3 s.

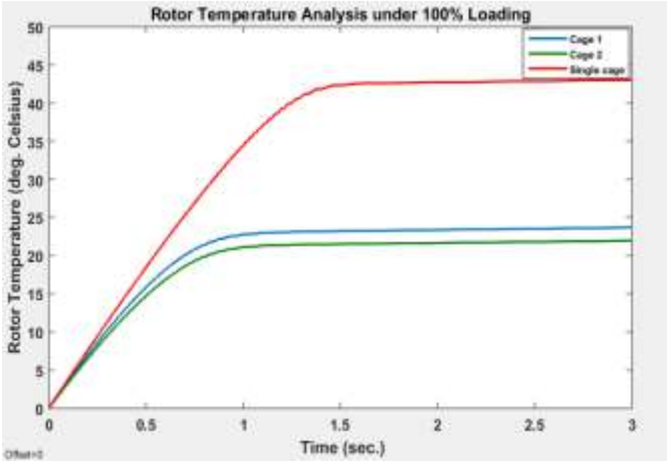

Fig. 5. Rotor temperature analysis under full load condition

The simulation curves in Fig. 5 reveal the rotor temperature of the three-phase induction motor when it is running at full load. The figure shows that the temperatures of the rotor normalizes to 43.0°C for single cage, 23.7°C and 22.0°C for cage 1 and cage 2 respectively in 3 s as the motor reaches its stable speed in each of the configurations.

The numerical performances of the motor in terms of rotor currents and temperatures during no load, half load and full load operations after 3 s are shown in Table 1.

TABLE 1. Numerical performance of motor in terms of rotor currents and temperatures

Rotor	No load		Half load		Full load	
	Current (A)	Temperature (°C)	Current (A)	Temperature (°C)	Current (A)	Temperature (°C)
Single cage	1.311e-07	27.4	2.035	33.4	4.35	43.0
Cage 1	1.120e-07	17.	1.056	19.8	2.24	23.7
Cage 2	1.011e-07	15.8	0.9763	18.3	2.07	22.0

Looking at Table 1, it can be seen that the rotor temperature for the single cage is higher in all cases of no load, half load and full load. This can be attributed to the high rotor current of the single cage at steady-state attributed to I^2R effect of electric current. However, it can be seen that the resultant temperature due to resistances of the double cage rotors resulted in higher temperature than the single cage rotor when the motor is loaded. Thus, under normal condition, the double cage will cause more thermal (heat) loss than single cage. However, during running conditions, it can be seen that due to the two current paths created by the outer and inner cage rotors, the double cage temperature is reduced or less with respect to the individual rotor conductor as shown from the simulation curves. Generally, it can be seen that the temperature of cage 2, which is regarded as the inner cage is least among the rotor temperatures. This simulation result agrees with the report in [8], which stated that the heat loss in the cage 2 rotor would not be high and thus resulting in high efficiency under transient or running conditions. Furthermore, the findings from the simulation results agrees with that in [1] that the rotor bar loss (thermal loss associated with rise in temperature) is associated with square of the rotor current.

V. CONCLUSION

The thermal performance of the motor in both single cage and double cage modes have been presented. The simulation results indicated that the single cage rotor produces highest temperature due to the high current associated to its current at steady state. However, the resultant thermal loss from double cage rotors (cage 1 and cage 2) is higher than that of the single cage because of the associated high resistances. Generally, since heating effect in metallic conductors is associated with current, at the transient state of the motor, the temperature of the single cage rotor was shown to be higher during start-up, which is associated with the transient or running performance of the machine, and can be attributed to high starting current. Finally, during transient, the temperature rise in the individual rotor bars for the double cage is lower compared to the single cage. Hence, the double cage rotor conductors are more preserved against damage by heat effect than that of the single cage model.

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