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Revisiting the effects of supply voltage unbalance on the losses of three phase induction motors

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Abstract

The impact of supply voltage unbalance (VU) on three-phase induction motors (IMs) is well known in terms of extra losses and associated derating to ensure that the motors do not prematurely fail. Theoretical studies, experimental results and standards exist in this regard. However, the approaches taken in the past are not seen be exhaustive now considering the modern tools such as Finite Element Modelling (FEM) software. Also, the relevant documentation available to-date on the subject does not cover the level of variability in the outcomes such as extra losses that can arise when an IM is subjected to the same level of VU that can be produced in a range of different ways. This paper emphasises the importance of Positive Sequence Voltage and the Complex Voltage Unbalance Factor (CVUF) in analysing the losses of a motor under different VU scenarios. Statistical analysis of the losses of three-phase IMs operating under different supply voltage unbalance scenarios is presented in this paper giving special focus to the behaviour of the core loss and copper loss. Two dimensional (2D) FEM is used to model the electromagnetics of the motor and Bertotti core loss model is used to evaluate the core losses. The outcomes of this analysis will be useful in the process of developing improved and cost effective mechanism of derating for mains connected three-phase IMs as well as in their design optimisation.

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Revisiting the Effects of Supply Voltage Unbalance on the Losses of Three Phase Induction Motors

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***Abstract*—The impact of supply voltage unbalance (VU) on three-phase induction motors (IMs) is well known in terms of extra losses and associated derating to ensure that the motors do not prematurely fail. Theoretical studies, experimental results and standards exist in this regard. However, the approaches taken in the past are not seen be exhaustive now considering the modern tools such as Finite Element Modelling (FEM) software. Also, the relevant documentation available to-date on the subject does not cover the level of variability in the outcomes such as extra losses that can arise when an IM is subjected to the same level of VU that can be produced in a range of different ways. This paper emphasises the importance of Positive Sequence Voltage and the Complex Voltage Unbalance Factor (CVUF) in analysing the losses of a motor under different VU scenarios. Statistical analysis of the losses of three-phase IMs operating under different supply voltage unbalance scenarios is presented in this paper giving special focus to the behaviour of the core loss and copper loss. Two dimensional (2D) FEM is used to model the electromagnetics of the motor and Bertotti core loss model is used to evaluate the core losses. The outcomes of this analysis will be useful in the process of developing improved and cost effective mechanism of derating for mains connected three-phase IMs as well as in their design optimisation.**

***Index Terms*—Copper Loss, Core Loss, Positive Sequence Voltage, Three-Phase Induction Motors (IMs), Voltage Unbalance (VU)**

I. Introduction

It is well known that mains connected three-phase induction motors (IMs) are the main workhorses in many industrial environments [1]. Despite being an electromagnetically symmetrical device it is a well known fact that the performance of three phase induction motors are severely affected by the presence of supply source voltage unbalance (VU), which is unavoidable in any power system [2]. A small unbalance in supply voltage can create disproportionately larger unbalance in phase current which causes increased and unequal spacial distribution of heat losses in the windings. This will lead to hotspots with higher temperature rise which can cause reduction in motor life due to degradation of the insulation [3]. Furthermore, increased noise and vibration levels, reduced efficiency and output torque are the other ill effects of VU on three-phase IMs. Therefore, motors should be derated based on Percent Voltage Unbalance (PVU) given in (1) in order to safeguard them from those ill effects, as covered in the the widely accepted standard introduced by NEMA [4]. In [5] IEC has introduced a similar guideline to derate the motors according to the magnitude of the Voltage Unbalance Factor (VUF) given in (2),

$$\mathrm{PVU} = \frac{\begin{array}{c}\text{Maximum line voltage deviation}\\ \text{from average line voltage magnitude}\end{array}}{\text{Average line voltage magnitude}} \tag{1}$$

$$\mathrm{VUF} = \frac{\text{Negative sequence voltage}}{\text{Positive sequence voltage}} \tag{2}$$

There are infinite number of ways in arranging the three-phase voltages which can yield the same PVU or VUF magnitude, but leading to different motor performance outcomes such as losses and temperature rise [6]. [7] presents a statistical study of the losses, efficiency and power factor of three different IMs on the same key issue. It shows that the stator copper loss varies over a considerable range for the same VUF produced using different three-phase voltage arrangements. This suggests that it may not be appropriate to derate three-phase IMs using single derating as suggested in standards [8]. Considerable research has been undertaken to introduce a new mechanism to precisely derate the IMs operating under supply VU [9]. Qualitative and quantitative analyses on the behaviour of losses under unbalanced voltages have attracted considerable attention as the temperature rise of a motor totally depends on the heat loss of the motor [3].

Positive sequence voltage has been identified as an influential factor in determining the performance of a motor operating under supply VU [2], [7], [10]–[12]. It has been experimentally shown in [2] that the efficiency of a motor increases and the power factor decreases with the increase in positive sequence voltage for a given VUF. If the positive sequence voltage remains constant then the efficiency of a motor reduces when the VUF increases in its magnitude [10].

Complex Voltage Unbalance Factor (CVUF) defined in [5] considers both the magnitude and angle and can be used in detailed analysis of losses of three-phase IMs operating under supply voltage unbalanced conditions where the angle contains distinct information regarding the VU condition.

Many of the recent studies have investigated the behaviour of the loss components of IMs separately under supply VU conditions. Copper losses are the most affected loss component

while the mechanical losses are the least affected. [13] shows that the VU leads to higher increase in rotor copper loss than the stator copper loss as the rotor circuit is more sensitive to the slip. [13] also analyses the effect of motor loading level on the increase of losses, concludes that the influence of VU on the losses is considerably low at lower loading levels. Limited number of studies exist on the effect of supply VU on core losses of IMs.

Most of the studies stated above have used symmetrical components based mathematical model of three-phase IM to calculate the losses of IM. However, the model is derived based on several assumptions and it has its own limitations in the accuracy of calculations. For example, the model cannot take into account the effect of magnetic saturation of the core as well as the skin effect of the rotor bars. Finite Element Modelling (FEM) is used in [14] to model the electromagnetic behaviour of the motor in order to calculate the losses. FEM methods not only allows the calculation of copper losses in the windings but also it enables accurate calculation of the iron losses in stator and rotor cores. Main difficulty in FEM methods is that they consume extensive time and resources. Compromise should be made between the accuracy and the computation time in order to achieve an appropriate result.

This study will analyse the effect of supply VU on core loss and copper losses of three-phase IM using 2D electromagnetic field simulations using Altair Flux. Compared to existing studies on loss estimation, this study considers a wide range of possible VU magnitudes while keeping the phase voltages within the allowable limits. Core loss modelling mechanism used in the study is presented in Section II and the methodology of the analysis is presented in section III. Results and the Conclusions are presented in Section IV and V respectively.

II. Modelling of Core Losses in Three-Phase IMs

Core losses are referred to as the power losses which occurred in soft magnetic materials (core) of electrical machines due to the time variation of magnetic fields. A comprehensive model to calculate the core losses can be found in [15] which is known as Bertotti method.

Core losses in a soft magnetic materials can be decomposed into two components named hysteresis (P_{hys}) and dynamic (P_{dyn}). Hysteresis losses occurs due to the energy involved in continuous reversing of magnetic dipoles in the magnetic material [16] and are associated with the currents at a microscopic scale. P_{hys} can be expressed as given in (3) where K_{hys} is a coefficient of hysteresis loss which should be experimentally determined for a given material and α_h is the Steinmetz coefficient which is considered to be equal to 2 for most modern magnetic materials. f is the frequency of the excitation magnetic field and B_m is the peak flux density.

$$P_{hys} = K_{hys} f B_m^{\alpha_h} \tag{3}$$

Dynamic component of core loss (P_{dyn}) is associated with the macroscopic behaviour of magnetic structure and is caused by the joules effect of the eddy currents induced in the material. Eddy currents induced in the material are proportional to the frequency of excitation magnetic field and therefore the associated joules loss is proportional to the square of the frequency of excitation magnetic field. Classical model of eddy current is commonly used to calculate the eddy current loss (P_{class}) as given in (4) where t is the thickness of a lamination, ρ_{iron} is the resistivity of the magnetic material and K_{class} is the coefficient of eddy current loss where $K_{class} = \frac{\pi^2 t^2}{6\rho_{iron}}$.

$$P_{eddy} = \frac{\pi^2 t^2 f^2 B_m^2}{6\rho_{iron}} = K_{class} f^2 B_m^2 \tag{4}$$

However, this classical model of eddy current neglects the skin effect of the core and also assumes homogeneous magnetization in the material. Therefore, P_{dyn} is always larger than P_{class} evaluated from (4). Therefore P_{exc} is defined in [15] as the difference between P_{dyn} and P_{class} and can be expressed as given in (5) where K_{exc} is the coefficient of excess loss and α_{e1} and α_{e2} are the exponents to be determined. It is experimentally shown in [15] that both α_{e1} and α_{e2} can be considered as equal to 1.5 for $f \leq 20$Hz as the excess loss per cycle is proportional to $\sqrt{f}$.

$$P_{exc} = K_{exc} f^{\alpha_{e1}} B_m^{\alpha_{e2}} \tag{5}$$

Therefore total core loss can be expressed by (6) as the sum of all three loss components P_{hys}, P_{class} and P_{eddy} which is commonly known as the Bertotti model of core loss.

$$P_{tot} = K_{hys} f B_m^2 + K_{class} \left(f B_m\right)^2 + K_{exc} \left(f B_m\right)^{1.5} \tag{6}$$

In FEM of electrical machines, two approaches exist to calculate the core losses. First is modelling of the hysteresis behaviour at the level of field calculations where it requires significant computation time and memory as well as it creates numerical problems of convergence and difficulties in management of the history of magnetisation process. Therefore, it is very difficult to implement this method for rotating electrical machines.

Second approach is to neglect the hysteresis behaviour at the level of field simulations and then calculate the core loss as a post processing computation. This would not affect the flux distribution of the machine if it is excited with a voltage source [14]. However it will influence the accuracy of the input current calculations. In the work presented in this paper, core losses will be evaluated using Altair Flux 2D which uses the second approach to calculate the core losses.

III. Methodology

In this study, the behaviour of the losses of a 4 pole, 2.2kW, 400V three-phase squirrel cage IM operating under different VU conditions is analysed. Electromagnetics of the motor will be modelled in Altair Flux 2D.

A. Motor Data

The name plate data of this motor are summarised in Table I and the equivalent circuit parameters are summarised in Table II. In order to model the motor in Altair Flux 2D actual dimensions of the motor were measured and are summarised in Table III. Stator winding of the motor is a simple single layer lap winding with 3 slots per pole per phase. Each coil side contains 32 conductors in series and each conductor has two strands in parallel. Rotor is a squirrel cage with 28 bars. Shapes of the stator and rotor slots are shown in Fig.1.

TABLE I: Motor Data

Full load speed	1440rpm
Rated Current (I_n)	4.54A
Rated Torque (T_n)	14.6Nm
No load current	2.6A
Locked rotor current	37.7A ($8.3I_n$)
Locked rotor torque	57Nm ($3.9T_n$)

TABLE II: Equivalent Circuit Parameters of 2.2kW motor

R_s	Stator resistance	1.73Ω
X_s	Stator leakage reactance	3.25Ω
X_m	Magnetising reactance	93Ω
R_c	Core loss resistance	2898Ω
R_r	Rotor resistance ref. to stator	2.30Ω
X_r	Rotor leakage reactance ref. to stator at stator frequency	4.88Ω

TABLE III: Physical dimensions of the actual motor

Stator		Rotor	
Internal diameter	100.5mm	Internal diameter	35.2mm
External diameter	160.6mm	External diameter	100mm
Lamination thickness	0.5mm	Lamination thickness	0.5mm
No. of slots	36	No. of slots	28
Air gap	0.25mm	skew	1 slot

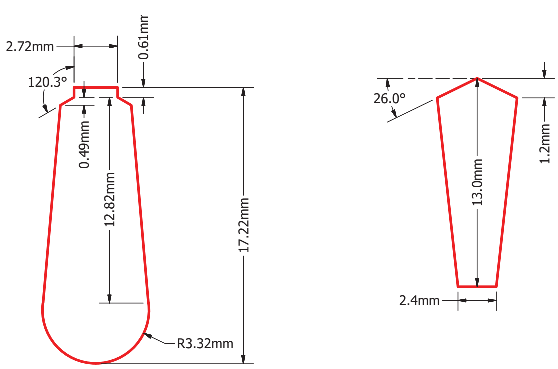


Fig. 1: Dimensions of (a) Stator and (b) Rotor Slots

B. Altair Flux 2D model of the motor

The 2D geometry with the mesh used for the simulations is shown in Fig.2 where quarter symmetry is employed. Stator and rotor cores are modelled as laminated magnetic non-conducting regions of material M-36 Electrical Grade Steel. Rotor bars are modelled as solid conductor regions in order to take the skin effect into account. Die-cast Aluminium with a resistivity of $4.9 \times 10^{-8}\Omega m$ is used as the material.

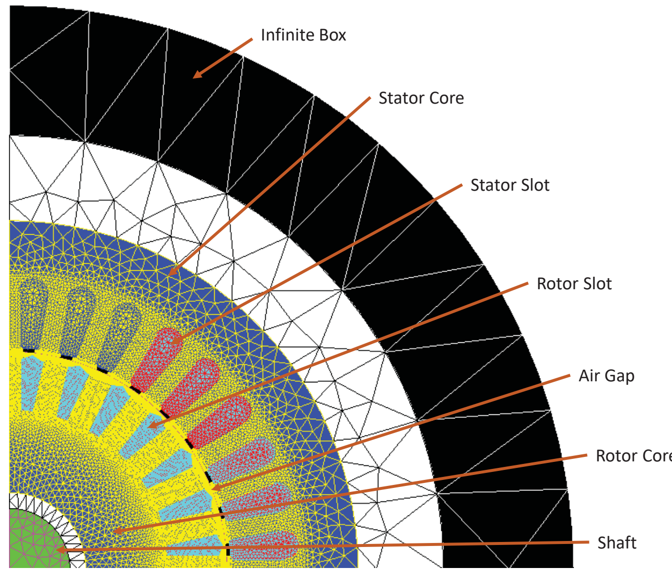


Fig. 2: 2D geometry with the mesh

Multi-static kinematic model in Steady State AC Magnetic 2D Application of Altair Flux is used to model the kinematics of the motor. Multi-static model does not take the dynamics of the motor in to consideration while the equations are solved for a given position of the rotor. Therefore the values of torque and the phase currents depend on the given rotor position as shown in Fig.3 which results in unequal currents in each phase even under balanced supply conditions. Although this is the case, the final result will not be affected as the average phase current is nearly constant for every rotor position. It can be observed from Fig.3a that a rotor angle of 1.5^0 gives the mean torque and therefore all simulations were carried out for that rotor position.

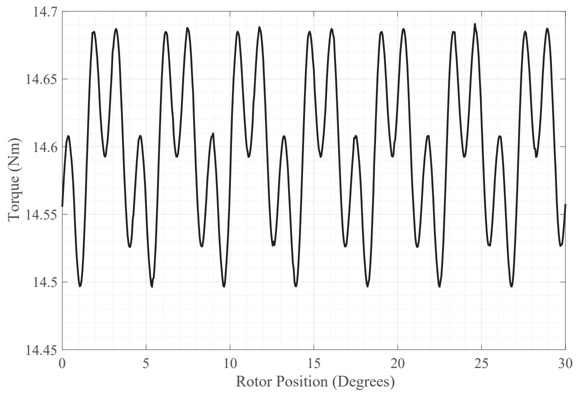
The coefficients of Bertotti model used in core loss calculations are given in Table IV.

TABLE IV: Coefficients of Bertotti model for M-36 Electrical Grade Steel

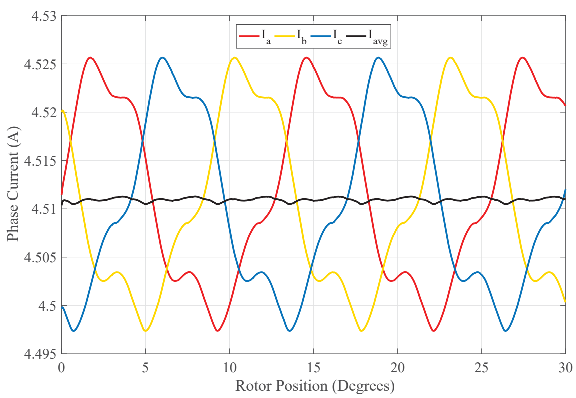
K_{hys}	$306.5Ws/T^2/m^3$
K_{class}	$4500000S/m$
K_{exc}	$0.61W/(T/s)^{1.5}/m^3$

C. Methodology of Loss Study

All possible voltage unbalance scenarios including the simultaneous voltage magnitude and angle unbalance variations



(a) Variation of torque with rotor position



(b) Variation of phase current with rotor position

Fig. 3: Variation of steady state torque and phase currents with the rotor position

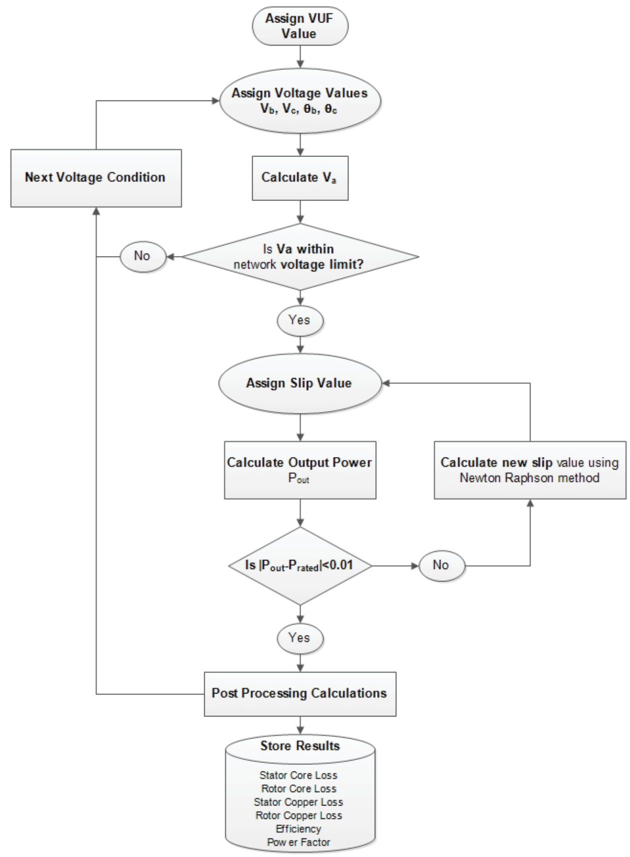


Fig. 4: Methodology of the loss study

were considered in this study within allowable supply voltage limits. Voltages were allowed to vary in the $\pm 6\%$ range while the phase angles were allowed to vary in $\pm 2.5^0$. All loss calculations were performed under constant output power condition in order to analyse the results. However slip is the only parameter available for variation in multi-static kinematic model in Flux Steady State 2D. Therefore, Newton Raphson method was used to find the value of the slip for a rated output power (2.2kW) under the given VU condition using a trial and error method where convergence was achieved after 3-4 trials. Post solving the scenario for the rated output power, stator and rotor core loss as well as stator and rotor copper losses were calculated in the post processing stage. Calculations were proceeded to the next VU condition for the given VUF after storing the results for analysis. The same process was continued for all VUF values up to 5%. The methodology adopted in the study is summarised in Fig.4.

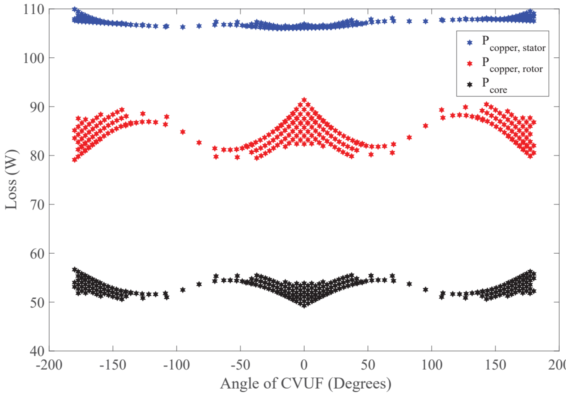
IV. Results

Analysis of the results obtained from the simulation study will be presented in this section. Loss Increase Rate (LIR) is defined as given in (7) to compare the increase in the loss components due to VU.

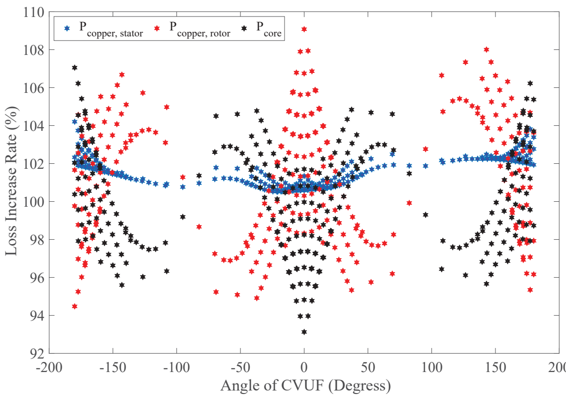
$$\text{Loss Increase Rate} = \frac{\begin{array}{l}\text{Losses under}\\ \quad\text{voltage unbalance condition}\end{array}}{\begin{array}{l}\text{Losses under}\\ \quad\text{balanced supply condition}\end{array}} \tag{7}$$

A. Effect of angle of CVUF

Variation of stator copper loss, rotor copper loss and core loss for different VU conditions having 5% VUF is shown in Fig.5a while LIR for the same is given in Fig.5b. Stator copper loss is the highest loss component in magnitude while core loss is the smallest. Under balanced rated supply condition stator copper loss, rotor copper loss and the core loss are 44%, 35% and 21% of the total loss respectively. However it can be observed in Fig.5b that the LIR of rotor copper loss is much higher than that other two loss types. Therefore, it can be concluded that the rotor copper loss is relatively more affected by supply VU than other two losses. Fig.5 shows that the range of variation of rotor copper loss is the highest while the variation of stator copper loss is the smallest. All loss components show a higher range of variation when the angle of CVUF is 0^0 or 180^0, where the positive and negative sequence components are in-phase or out of phase from each other respectively.



(a)



(b)

Fig. 5: Variation of loss components with the angle of CVUF for 5% VUF

B. Effect of positive sequence voltage

Variation of stator copper loss, rotor copper loss and core loss for a VU condition of 5% VUF with the positive sequence voltage is shown in Fig.6. It shows that the LIR of core loss is proportional to the positive sequence voltage. For low values of positive sequence voltage, LIR of rotor copper loss is much higher than the same for core loss. However the LIR of core loss is much higher for the higher values of positive sequence voltage. The LIRs of stator copper loss and total loss do not exhibit a significant variation with the positive sequence voltage compared to core loss and rotor copper loss.

C. Effect of VU on the core loss components

It can be observed from the results that the stator core loss is about 70% of the total core loss while the rotor core loss is about 30% under full load conditions. However the rotor core loss is considerably higher at high slip operating conditions and at locked rotor condition. Fig.7 shows the variation of the LIR of stator, rotor and total core loss for different VU conditions having 5% VUF with the positive sequence voltage. It shows that the LIR of the rotor core loss is considerably high, even though its contribution to the total core loss is less.

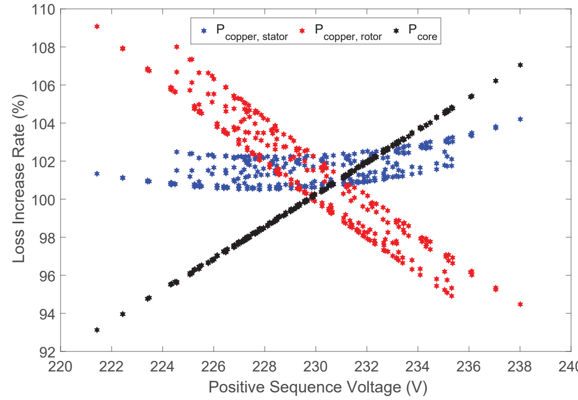


Fig. 6: Variation of loss components with the positive sequence voltage for 5% VUF

LIR of the stator and total core losses are seen to increase with the increase in positive sequence voltage. However, the rate of increase of rotor core loss is seen to reduce with the increase in the positive sequence voltage. Further, it can be observed that the LIR of rotor core loss is much higher than that of the stator core loss for low values of positive sequence voltage.

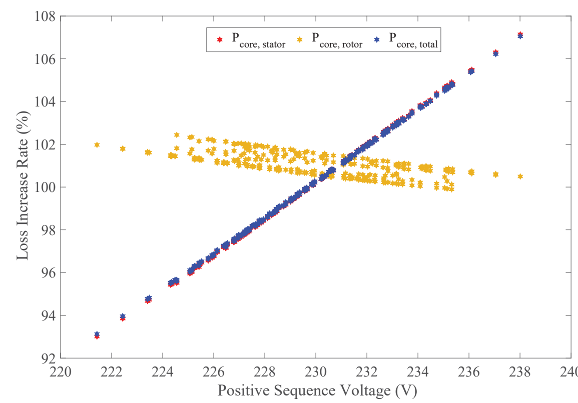
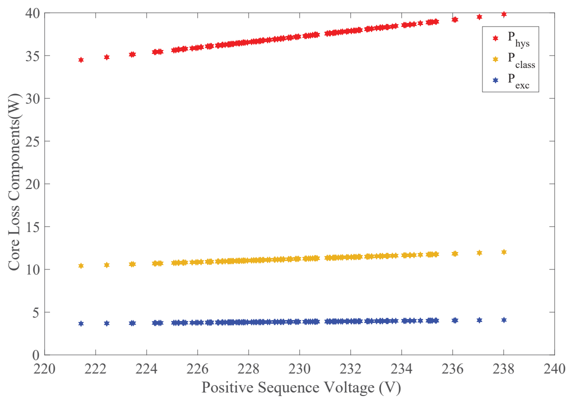


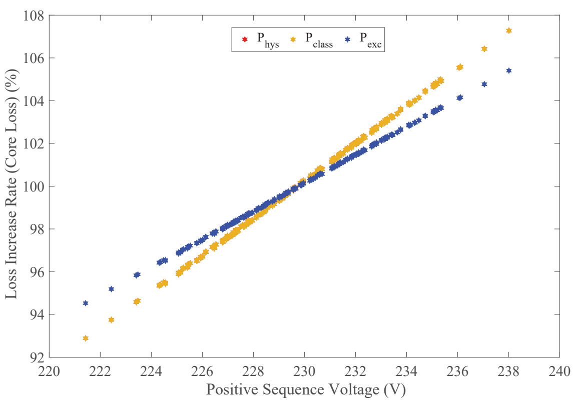
Fig. 7: Variation of stator, rotor and total core loss with the positive sequence voltage for 5% VUF

Fig.8 shows the variation of stator core loss components and their LIR for different VU conditions having 5% VUF with the positive sequence voltage. It can be observed that the hysteresis loss component has the highest contribution to the total core loss while the contribution of the excess loss component is the least. Even though all these three components are seen to increase in proportion to the positive sequence voltage, hysteresis loss component shows the highest sensitivity to the positive sequence voltage. It can be observed from Fig.8b that both hysteresis and classical loss components have the same loss increase rates. LIR of excess component is higher for low positive sequence voltages while the LIR of the hysteresis component is higher for higher positive sequence

values. However, the LIR of all three core loss components are seen to increase in proportion to the positive sequence voltage.



(a)



(b)

Fig. 8: Variation of core loss components with the positive sequence voltage for 5% VUF

V. Conclusion

It can be concluded from this study that the rotor copper loss is highly affected by the presence of supply VU. Range of variation of the rotor copper loss is much higher for different VU conditions for a given VUF. Range of variation of each loss component is highest when the angle of CVUF is 0^0 or 180^0. All core loss components and their loss increase rates are proportional to the positive sequence voltage. Even though the rotor core loss has a negligible value compared to the stator core loss, it has a higher loss increase rate for low values of positive sequence voltage. The major conclusion that can be derived from this study is that the positive sequence voltage and the angle of CVUF are the indicators of the effects of VU on the performance of three-phase IMs operating under different VU conditions even for the same VUF. Therefore, not only the VUF magnitude but also positive sequence voltage and the CVUF should be considered in evaluating the losses and the derating of the IMs. Work is in progress to experimentally validate the results presented in this paper using calorimetric measurements.

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