Importance of Accuracy for Steady State Performance Analysis of 3ϕ Induction Motor

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Abstract— **This paper brings out the need for achieving accuracy in estimating the various operating parameters like motor efficiency, losses, operating power factor etc in order to analyze the steady state conditions in non-ideal situations, with an analytical study. Core losses have been usually neglected in the analysis with the assumption that they are quite negligible in nature. Voltage variations have become a common phenomenon as of late. As core losses are dependent upon the supply voltage, it is therefore necessary to include the core loss in the analysis, however small they may be. This example takes into account both overvoltage and undervoltage conditions, with upto 5 % unbalance variations.**

I. INTRODUCTION

Induction Motors are widely used as drives for various industrial applications. Availability of electrical power is deemed to be an infrastructure requirement. Increase in the industrial sectors has led to a tremendous requirement of power such that capacity addition has not kept pace with the energy requirement, with the result that most of the industrial sectors being highly energy intensive; energy efficiency is far below world standards [5]. This has led to an increase in the demand supply gap, result being that generating stations are always subjected to varying loads at all times. Though every effort is made for power delivery at a constant voltage level, supply voltages still end up being unbalanced at the consumer's premises.

The main contributor to this situation is the non-uniform distribution of various 1ϕ loads on the supply system that vary in a random manner [4]. Thus overloading of the generating system and the subsequent voltage variations are now a reality and need to be dealt with. Though induction motors are always designed to tolerate a small degree of unbalance, the motors have to be derated when the unbalance becomes quite significant the motors have to be properly derated in order to prevent subsequent winding damage. The analysis of voltage unbalance is as per the IEC definition, which is as below

$$\%\ \text{Voltage Unbalance Factor (VUF)} = \frac{V_N}{V_P} * 100 \qquad (1)$$

An extension of the VUF is the complex voltage unbalance factor (CVUF) that is defined by the ratio of negative sequence voltage phasor to the positive sequence voltage phasor. The *CVUF* is a complex quantity having both magnitude and angle and is made use in this paper for performance analysis [3], [8].

The power system over a 24-hour period is always subjected to a varying loading pattern, which can be classified into peak demand period, normal demand and off peak demand period. The voltages available at the industrial consumers' premises will therefore be different during the three periods, and may infact vary if the load on the power system continuously varies. Undervoltages mostly occur during peak demand periods, overvoltages generally occur during off peak periods [9] while unbalanced voltages occur when there is unequal distribution of 1ϕ load on the 3ϕ system. Considering a continuous variation, the voltage unbalance can be classified into overvoltage unbalance and undervoltage unbalance, wherein the overvoltage unbalance is defined as the unbalance due to the positive sequence voltage component being higher than the balanced rated voltage and undervoltage unbalance is defined as the unbalance due to the positive sequence voltage component being lesser than the balanced rated voltage. Increase in the voltage unbalance results in an increase in the unbalance among the currents, such that there will be a considerable influence of the negative sequence component on the motor, resulting in an increase in motor winding temperature and a possible damage to motor windings in the short term

II. METHODOLOGY

The complex voltage unbalance factor is defined as

$$\text{CVUF} = K_v \angle\theta_v \qquad (2)$$

Where, $Kv = \frac{Vn}{Vp}$ and θ_v is the phase angle with which the negative sequence voltage component leads the positive sequence voltage component. Due to the absence of the neutral connection, there will not be a path for the flow of zero sequence current components, hence neglected in the analysis. Over the years, induction motor performance analyses have been done using the equivalent circuit approach with numerous assumptions, major one being the neglect of core loss and friction & windage loss. This is only done for ease of analysis. It is very important to keep in mind that ease of analysis is not the criteria but accuracy that should be the basis for estimation of induction motor operating parameters.

It will be shown in this paper that there will be a significant deviation in estimated motor parameters with and without core loss considerations. To highlight the importance of accuracy in analysis, the following assumptions are made (a) All circuit elements are taken to be constants (b) Friction & Windage losses in addition to Core losses are taken into account (c) Supply frequency remains constant.

The equivalent circuit without core loss consideration is as shown in Fig 1 below

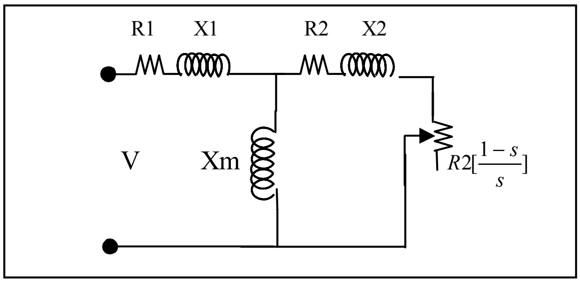

Fig 1 : Equivalent circuit without core loss resistance

Core Loss and friction and windage loss is estimated by the no load test. The stator power input minus the stator copper loss is plotted vs applied voltage, and the curve so obtained is extended to zero voltage. The intercept with the zero voltage axes is the friction and windage loss. The intercept may be determined more accurately if the stator power input minus stator copper loss is plotted against the voltage squared for values in the lower voltage range. It is important to keep in mind that the all the three phase voltages applied to the motor for core loss determination are balanced. But in the field, due to regular unbalance occurring across the power system and subsequently at the motor terminals; it is not correct to use the core loss value determined by the above method for analysis. Hence the equivalent circuit needs to be slightly modified so as to incorporate the effect of phase voltage unbalance.

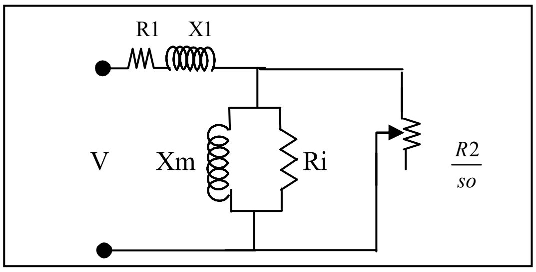

Fig 2 : Circuit model on No Load

The no load power input = stator cu loss + [(core loss + friction & windage loss) = rotational loss]. Appropriately the no load equivalent circuit representation is as shown in Fig 2. The equivalent circuit [11] is therefore modified and is represented as shown in Fig 3 below.

The deviation of voltages from the balanced rated value leads to positive and negative sequence voltages. As such the induction motor now needs to be treated as two separate motors in operation, one operating with a positive sequence terminal voltage V_p and at slip (s), while the other operating with a negative sequence terminal voltage V_n and at slip (2 - s) [7].

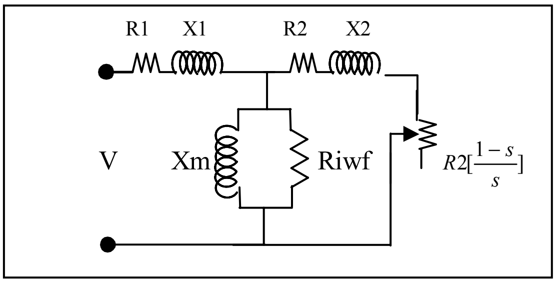

Fig 3: Equivalent circuit with resistance representing the core loss and friction and windage loss.

The total motor power output is the sum of the power output P_p due to the positive sequence voltage component V_p and power output P_n due to the negative sequence voltage component V_n. The input power in symmetrical components is given by $P_{in} = \mathrm{Real}[3*(V_p I^*_{1p} + V_n I^*_{1n})]$ (3)

The efficiency is given by $\eta = (P_p + P_n) / P_{in.}$ (4)

III. MOTOR PARAMETERS

A 3ϕ, 50 Hz, 3.7 kW, 400 V, delta connected, squirrel cage IM used as a drive for supplying a constant torque load is analyzed for voltage variations from 360 V to 440 V. Both over voltage unbalance and undervoltage conditions are also studied with voltage unbalance variations upto 10 %. The motor parameters are as follows : $R_1 = 5.25\ \Omega$, $X_1 = 7.29\ \Omega$, $R'_2 = 12.08\ \Omega$, $X'_2 = 7.29\ \Omega$, $R_{iwf} = 584.98\ \Omega$. When applied with balanced three-phase voltage of 400 V, current drawn = 6.5 A, slip = 0.0818 under rated conditions, and torque exerted on the shaft was found to be 17.1 Nm. Under ideal working conditions or rated power, total motor losses inclusive of all losses = 472.51 W, motor efficiency = 77.12 %, operating power factor = 0.7105.

IV. PERFORMANCE ANALYSIS

The presence of unbalance among the phase voltages can cause serious effects not only to the machine across which it is applied but also to power system in general [3]. By applying the symmetrical component techniques, the unbalanced set of voltages are considered to be made of two components: positive sequence voltage component causing the flow of positive sequence currents and negative sequence voltage component causing the flow of negative sequence currents. In general, the net effect of voltage unbalance on the induction motor is reduced efficiency, increased losses resulting in temperature leading to subsequent damage.

In the process of determining the operating parameters, accuracy is most important especially when it comes to estimating the life, power factor correction device ratings, methodologies to correct unbalance, loading of machine and also derating of machine.

A. Efficiency

It is a well-known fact that core loss is dependent on the voltage while friction & windage losses are dependent on speed. Steady state analyses have always been performed with the assumption that core loss is quite small in magnitude that it can be easily neglected and friction & windage losses are neglected, as there is a very small change in operating speed. The only consideration was that the applied voltage was kept constant and is balanced among phases. The core loss determined by the standard method holds good when we take into consideration only balanced overvoltage and balanced undervoltage. Core loss obtained by this method and used in unbalance analysis surely leads to erroneous results. Moreover with conditions varying existing throughout the day, it does make the situation a bit more complicated. In such situations to avoid complications and with the notion that it is quite small in magnitude, core loss and friction & windage losses are usually neglected in the analysis. The effect of positive sequence component on core loss is quite the same as that of normal voltage while core loss is severely affected by the negative sequence component ie; increase in core loss can be attributed to the negative sequence component more than due to the positive sequence component.

TABLE 1
% DEVIATION IN EFFICIENCY ESTIMATION

%	*Undervoltage*			*Overvoltage*		
UB	380	390	395	405	410	420
1	9.51	10.01	10.25	10.76	11.02	11.54
2	11.22	11.89	12.23	12.93	13.29	14.03
3	13.94	14.87	15.35	16.34	16.85	17.89
4	17.48	18.74	19.38	20.71	21.38	22.78
5	21.66	23.25	24.06	25.73	26.58	28.31

The importance of accuracy with respect to estimating the motor efficiency is tabulated in Table 1, wherein for a normally existing case of 1 % unbalance, if core loss is not taken into account, efficiency will be wrongly estimated to be in the range of 9.51 % to 11.54 % higher than that with core loss taken into account. The % error, if we may denote this, will increase as the unbalance increases. The worst possible scenario is a 22 % to 29 % error range for 5 % unbalance case, which is highly objectionable. By neglecting the core loss, on the basis of estimation, we may end up either choosing a lower efficiency motor to be of reasonably good efficiency or the efficiency estimation of a motor with good efficiency value may exceed 100 %, which is practically absurd. Thus, with possibilities of varying voltage unbalance at the motor terminals, it therefore necessary to consider core loss when estimating the efficiency.

B. Power Factor

As the load on the power system has increased over the years, in addition to use of inefficient equipment with decreasing efficiencies and poor power factors, the VA demand for power has increased to such an extent that state electricity boards are now making it mandatory for industrial power consumers to maintain a plant power factor of 0.9 or above. This necessitates use of power factor correction devices either at plant level or individual equipment level, in order to comply with the requirements. Most of the times the motor loads tend to dominate the loads that are connected in the industrial plant; as such plant power factor is now dependent on the motor power factor. This in turn is depended on the amount of load being handled by the motor. If the motor is full loaded, power factor is quite close its rated specification while if partially loaded or lightly loaded, the power factor would be quite low in nature, thereby increasing the reactive power consumption. Accurate estimation of power factor is quite essential as it does play an important role in the electricity bill of the industrial consumer. Normally capacitor banks are so chosen that even after their installation, power factor is still slightly lagging but quite close to unity.

TABLE 2
% DEVIATION IN POWER FACTOR ESTIMATION

%	*Undervoltage*			*Overvoltage*		
UB	380	390	395	405	410	420
1	4.038	4.439	4.646	5.069	5.286	5.728
2	3.928	4.301	4.490	4.879	5.076	5.478
3	3.823	4.168	4.344	4.701	4.883	5.250
4	3.723	4.044	4.207	4.538	4.704	5.041
5	3.626	3.926	4.078	4.384	4.538	4.848

The importance of accuracy with respect to estimating the operating power factor for corrective purposes is tabulated in Table 2, wherein for a normally existing case of 1 % unbalance, if core loss is not taken into account, power factor will be wrongly estimated to be in the range of 3.76 % to 5.33 % lower than that with core loss taken into account.

The % error, if we may denote this, will decrease as the unbalance increases. By neglecting the core loss, on the basis of this estimation, we may end up either choosing higher value of capacitors to be sufficient enough to achieve closer to upf operation when infact the power factor value would be such that it may be a leading case, which is highly unnecessary. It is also important to note that though capacitor banks help in power factor improvement, incorrect estimation or application may lead to significant equipment damage. The negative sequence component has little effect on the operating power factor ie; power factor is affected mainly by the positive sequence component [1]. Thus with possibilities of varying voltage unbalance at the motor terminals, it is therefore necessary to consider core loss in view of varying voltage conditions when estimating plant / equipment power factors.

C. Total Losses

Temperature rise is attributed mainly due to the flow of currents through the respective windings [6]. As already indicated, existence of unbalance results in the presence on the negative sequence voltage component, which is more dangerous as the unbalance increases. The degree to which the voltages are unbalanced has a significant effect on the loss component. Voltage unbalance is always accompanied by an unbalance in the currents ie; current through the 3 phase windings are not the same, leading to additional heating of both stator and rotor. Additional heating will not only damage the winding but also shortens the life of insulation considerably. It is therefore important for all practical purposes that the losses that may occur due to unbalance be estimated accurately so that correct design and estimation of protective relay system is achieved.

TABLE 3
% DEVIATION IN TOTAL LOSS ESTIMATION

% UB	*Undervoltage*			*Overvoltage*		
	380	390	395	405	410	420
1	10.18	10.75	11.03	11.60	11.89	12.45
2	10.04	10.59	10.87	11.42	11.69	12.23
3	9.83	10.35	10.61	11.13	11.38	11.89
4	9.54	10.03	10.27	10.74	10.98	11.44
5	9.20	9.64	9.86	10.28	10.49	10.90

The importance of accuracy with respect to estimating the total losses is tabulated in Table 3, wherein for a normally existing case of 1 % unbalance, if core loss is not taken into account, total losses will be wrongly estimated to be in the range of 10.18 % to 12.45 % lower than that with core loss taken into account. The % error, if we may denote this, will decrease as the unbalance increases. By neglecting the core loss, on the basis of this estimation, temperature rise will not be in consideration and a better efficiency will be valued for the machine, thereby wrongfully estimating the motor loading. It will also be concluded that motor will be in a position to take more load that what it can do so. As the voltages become more unbalanced rotor losses increase at a faster rate than stator losses such that both stator and rotor circuits now begin to experience excessive heating [10]. Thus from the point of view of estimating the temperature rise due to process requirements, accuracy is a must else working life of the motor will be shortened considerably.

D. Current Unbalance

The degree to which the phase voltages are unbalanced has a significant effect on the unbalance among the current components. As already proved by the results tabulated above, it is wrong to neglect the core loss when voltage unbalance in the form of either undervoltage unbalance or overvoltage unbalance exists. The maximum possible voltage unbalance, which a motor can withstand, depends entirely on the heat produced. The stator winding must be protected against overheating by monitoring the stator current using thermal overload relays used for motor protection. The other simplest option is to derate the motor in a manner such that due to voltage unbalance, the temperature rise is within permissible limits [7]. As a result, all the three line currents must be carefully monitored to prevent relay operation even under normal conditions. Moreover, the motor being quite sensitive to negative sequence voltage, small level of negative sequence voltage is quite sufficient for significant level of negative sequence current to flow through the motor windings. The % variation of stator currents with respect to normal current with core loss component taken into consideration is as tabulated in Table 4 and without core loss component taken into consideration is as tabulated in Table 5.

TABLE 4
STATOR CURRENT ESTIMATION WITH CORE LOSS

% UB	*Undervoltage*			*Overvoltage*		
	380	390	395	405	410	420
1	6.884	6.876	6.877	6.883	6.890	6.908
2	7.245	7.249	7.254	7.271	7.283	7.312
3	7.607	7.621	7.632	7.660	7.677	7.716
4	7.970	7.994	8.010	8.048	8.070	8.120
5	8.332	8.367	8.388	8.437	8.464	8.524

As can be seen from the Table 4, correct estimation of stator current magnitude would ensure that the motor can withstand upto 2 % of voltage unbalance either way while from Table 5, incorrect estimation leads us to a conclusion that the motor can withstand upto 4 % voltage unbalance either way. Though the unbalance % may be quite close in number, it is widely accepted that the relation between temperature rise due to voltage unbalance is

$$\%\ \text{Increase in temp} = 2 * [\%\ \text{Voltage Unbalance}]^{2} \tag{2}$$

TABLE 5
STATOR CURRENT ESTIMATION WITHOUT CORE LOSS

% UB	*Undervoltage*			*Overvoltage*		
	380	390	395	405	410	420
1	6.565	6.556	6.557	6.563	6.570	6.589
2	6.928	6.930	6.935	6.952	6.964	6.993
3	7.290	7.304	7.314	7.341	7.358	7.397
4	7.654	7.677	7.692	7.730	7.752	7.801
5	8.017	8.051	8.071	8.119	8.146	8.205

If these are not taken into account for thermal relay settings, relay may either trip repeatedly or remain inoperative trip thereby causing a disturbance in the working process. If neglected, the additional heating may severely damage the motor windings and may even damage the motor's insulation system [2]

V. CONCLUSION

As the core loss is dependent on the applied voltage, under unbalance conditions ie; overvoltage or undervoltage situations, the core loss component in performance analysis cannot be neglected. The results tabulated above for various voltage values and unbalance cases, highlights the importance of accurate estimation of induction motors parameters like efficiency, losses, power factor etc so as to avoid errors when it comes to derating the motor or estimating the capacitor bank requirements for power factor improvement.

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