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Performance Investigation of Three Phase Induction Motor's Rotor under Unbalanced Positive Sequence Voltage through Simulations

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Abstract

The greatest potential for energy savings is in electric motor applications and induction motors constitute over 60% of such usage. A significant amount of investment on low losses motor materials and drives could be made in order to achieve energy efficiency, but many a times it has been found that performance variations of electric motors are mainly due to external factors, in particular, the quality of the incoming supply. Therefore, when it comes to identifying energy efficiency opportunities, it is essential to study the influence of voltage variations on electric motors. This work investigated the impact of positive sequence rated voltage, under voltage and over voltage unbalance on induction motor's rotor operational performance using the International Electrotechnical Commission's (IEC) definition of voltage unbalance. MATLAB® Simulink was used to build a model for the performance analysis of a 2h.p induction motor and operated under balance and unbalance voltages at no load and various loaded condition using IEC's definition of voltage unbalance. The results obtained indicated gross rotor inefficiency when the motor operated under various unbalanced conditions of rated voltage, under voltage and over voltage. The worst adverse effect of unbalance was most severe at under voltage conditions; drastic load reduction did not produce good motor performance even with a low Voltage Unbalance Factor (VUF). At over voltage unbalance however, motor's rotor indicated fair performance at VUF of 2-4% with a load reduction of 50%. At rated voltage unbalance with VUF of 2-4%, good performance was observed on load reduction of 50%. Above VUF of 4% for all types of unbalance, motor's rotor operation became grossly inefficient and load reduction did not improve the operational performance of the induction motor's rotor.

Index Terms: Unbalanced Voltage, Simulations, Performance, Investigations, Positive sequence

I. Introduction

The widening power supply and demand gap is due to the increasing number of domestic, commercial and industrial loads. As power generation has not kept pace with the power demand, there has been an increasing stress towards energy management in the industrial sector as they are the major consumers. Adjustable speed drives (ASDs) are finding increasing acceptance in industrial and commercial utilities for energy saving purposes [1]. Increasing and varying load demand by domestic consumers have led to continuous switching of single phase loads like computers, fluorescent lamps etc. has led to the power system network being subjected to time varying loads. This has led to a power quality problem, the harmful effects of which is quite damaging in the long run and has become one of the major concerns in recent years [2]. Power quality is a combination of voltage quality and current quality and is mainly concerned with the deviations of voltage and/or current from the ideal, and is termed as a power quality disturbance [3]. Of the various power quality events, voltage variations and unbalance seem to be the most commonly occurring power quality problem. The main contributor to the voltages becoming unbalanced at the three-phase terminals is the unequal distribution and operation of single-phase loads across the power system network [4]. This situation may also occur due to conditions within the utility premises as well. Though there may be fixed operating times within the utility premises, single-phase loads across the power system network continuously varies, usually with large hourly fluctuations, resulting in voltage variation and unbalance [5]. Most importantly; the three-phase voltages tend to become asymmetrical in nature and application of asymmetrical voltages to three phase induction motor driven system severely affects its working performance.

Three-phase induction motors are widely used in industrial, commercial and residential systems, because of their ruggedness, simplicity and relatively low cost. Approximately
65% of the electricity consumed in industry is used to drive electrical motors. Therefore, the efficiency and reliability of induction motors operation is of major importance, in order to improve the energy efficiency in industry.

The IEC standard [6] and the European Commission's report [7] show that induction motors in the power range from 0.75 kW to 4 kW represent a particularly attractive opportunity for electricity savings.

The operation of three-phase induction motors under unbalanced voltages can cause serious ill effects such as overheating, drop of efficiency and reduction in output torque. In order to avoid the excessive heating in the windings the motor load has to be reduced so as to limit the temperature rise to the rated value. Therefore to maintain the operational life of the motor, the international standards [8], [9] recommend the derating of the motor. The continuous voltage variation and unbalance throughout the day does have a big impact on the working performance.

II. Induction Motor Model

Steady state performance of three-phase induction motors have been analysed by neglecting the core loss and friction and windage loss components, the reason being to facilitate ease of understanding and analysis [10]. While core loss was determined experimentally in [10], core loss was ignored but friction and windage loss was considered in [11]. In industrial situations, the utility energy bill is dependent on components like plant power factor, total active power usage and overall efficiency of operation. It is therefore important to keep in mind that ease of analysis is not the criteria but accuracy as close as possible that should be the basis for estimation of motor parameters, especially when it comes to energy auditing and management in industrial utilities. Though it is extremely difficult to be as exact as possible but still, it is important to consider all possible quantifiable parameters during analysis. Therefore accurate estimation of losses is extremely important else there will be a significant error in the efficiency estimation [12]. The core loss depends on the applied voltage while friction and windage loss depends on the operating speed. The power input on no load is only to account for the no load losses in the form of stator copper loss, core loss, windage and friction loss.

The steady state equivalent per phase equivalent circuit is suitably modified to take into consideration core loss and, friction and windage loss under running conditions as shown in Figure 2.3 [13]. In Figure 1, V is the applied voltage, R_1 and X_1 are stator resistance and reactance respectively, and rotor resistances, R'_2 and X'_2 are equivalent rotor resistance and reactance as referred to the stator, R_C is the core loss resistance, R_{FW} is the resistance representing the friction and windage loss, X_M is the magnetizing reactance, s is the operating slip, I_1 is the stator current, I_o is the no load current component and I'_2 is the rotor current referred to stator side. The equivalent circuit parameters of X_1, X'_2, X_M, R_C and R_{FW} can be obtained from the no load and blocked rotor tests data [13].

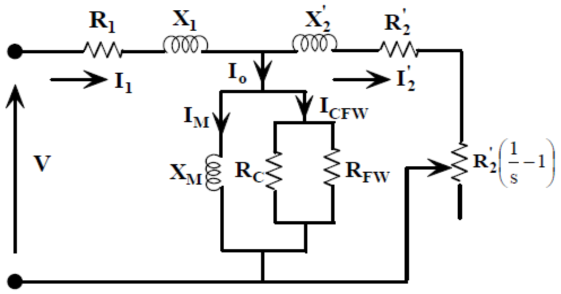


Fig.1 Per-phase equivalent circuit of induction motor [13]

Under conditions of asymmetry, with the application of symmetrical component technique, per phase induction motor equivalent circuit can now be split up into a positive sequence equivalent circuit and negative sequence equivalent circuit. Let V_{RY}, V_{YB} and V_{BR} be the measured line-to-line voltage magnitudes, with V_{RY} being taken as the reference phasor.

For the positive sequence equivalent circuit,

$$V_p < \theta_p = \frac{V_{RY} < 0 + aV_{YB} < \theta_{YB} + a^2 V_{BR} < \theta_{BR}}{3} \qquad 1$$

$$I_{1P} < \theta_{CP} = \frac{V_P < \theta_{VN}}{Z_P \emptyset_P} \qquad 2$$

For negative sequence equivalent circuit,

$$I_{1N} < \theta_{CN} = \frac{V_N < \theta_{VN}}{Z_N < \emptyset_N} \qquad 3$$

Where, $V_P\angle\theta V_P$ and $V_N\angle\theta V_N$ are the positive sequence and negative sequence voltages; $I_{1P}\angle\theta_{CP}$ and $I_{1N}\angle\theta_{CN}$ are the positive sequence and negative sequence stator currents; $Z_P\angle\phi_P$ and $Z_N\angle\phi_N$ are the positive sequence and negative sequence input impedances; operator $a_1 = \angle 120°$ and $a_2 = 1\angle -120°$. Thus under voltage unbalance conditions, the induction motor can be considered as two separate motors in operation, one operating with a positive sequence voltage V_P and slip 's', and other operating with a negative sequence voltage V_N and slip ' (2 - s) ' [10].

The individual line currents can now be written as

$$I_R < \theta_R = I_P < \theta_{CP} + I_N < \theta_{CN} \qquad 4$$

$$I_Y < \theta_Y = a^2 I_P < \theta_{CP} + aI_N < \theta_{CN} \qquad 5$$

$$I_B < \theta_B = aI_P < \theta_{CP} + a^2 I_N < \theta_{CN} \qquad 6$$

The actual power output is the sum of the power output components,

$$P_O = P_P + P_N \qquad 7$$

Positive sequence power output,

$$P_P = \frac{3(I'_{2N})^2 R'_2\,(s-1)}{(2-s)} \qquad 8$$

Negative sequence power output,

$$P_N = \frac{3(I'_{2N})^2 R'_2\,(1-s)}{(2-s)} \qquad 9$$

Where, I'_{2P} and I'_{2N} are positive and negative sequence rotor current components. For steady state operation,

$$T_M = T_N \qquad 10$$

Where, T_M is the torque developed by motor and T_L is the load torque. Under conditions of voltage unbalance,

$$T_M = T_P + T_N \qquad 11$$

Where, T_P and T_N are the positive and negative sequence torque components. The total power input,

$$P_{IN} = Real\,[3(V_P I^*_P + V_N I^*_N)] \qquad 12$$

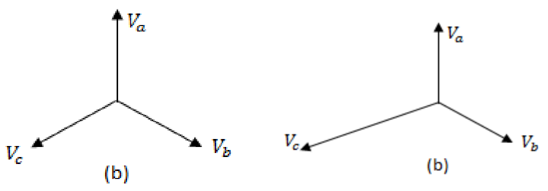
Where '*' indicates the conjugal value

Motor efficiency is given by

$$\%\,\eta = \frac{P_P + P_N}{P_{IN}} \times 100\% \qquad 13$$

III. Voltage Unbalance

Voltage unbalance combined with over- or under-voltage is a voltage quality problem. In three-phase power systems, the generated voltages are sinusoidal and balanced but they will be unbalanced commonly at the distribution end and the point of utilization for several reasons. In a balanced sinusoidal supply system the three line-neutral voltages are equal in magnitude and are phase displaced from each other by 120 degrees (Figure 2a). Any differences that exist in the three voltage magnitudes and/or a shift in the phase separation from 120 degrees is said to give rise to an unbalanced supply as shown in Figure 2b below.



(a) Balanced voltage (b) Unbalanced voltage

Fig.2 Balanced and unbalanced voltage

Some causes of voltage unbalance are the uneven distribution of single-phase loads in three-phase power systems, asymmetrical transformer winding impedances, open-Y, open-Δ transformer banks, incomplete transposition of transmission lines, blown fuses on three-phase capacitor banks and etc. [15-22]. Note that, between mentioned causes of voltage unbalance, rule of the uneven distribution of single-phase loads is significant clearly. For more about, the rural electric power systems with long distribution lines and large urban power system with heavy single-phase demands are examples for problem areas that the single-phase loads are not uniformly spread among the three phases [15, 16].

According to the above description performance analysis of equipment in power systems under voltage unbalance condition is very important. Three-phase induction motor is one of the most widely used equipment in industrial, commercial and residential applications for energy conversion purposes. Based on U.S. Department of energy, industrial motors consume seventy percent of electricity, and induction motors consists eighty percent of the loads in a typical industry [23]. Because of various techno-economic benefits, the three phase induction motors are used more than ever before. However, most of them are connected directly to the electric power distribution system and they are exposed to unbalanced voltages unfortunately. Supplying a three-phase induction motor with unbalanced voltages has many undesirable effects on its performance. In theoretical point of view, the unbalanced voltages induce negative sequence current and mentioned current produces a backward rotating field in addition to the forward rotating field produced by the positive sequence one[24]. The interaction of these fields produces pulsating electromagnetic torque and ripple in speed [25, 26]. Such condition has severe negative effects on the performance of an induction motor. The influence of unbalance on the efficiency [27], derating in the machine [28], increase of losses, and the undesirable effects on the insulation life and life reduction due to temperature rise [29,30], are some contributions in this area.

IV. Definitions of Voltage Unbalance

Three general definitions for measuring the voltage unbalance are founded in standards namely;

a. Phase Voltage Unbalance Rate (PVUR) defined by IEEE (International Electrical and Electronics Engineers) Standard 141, the ratio of maximum voltage deviation from average phase voltage magnitude to the average phase voltage magnitude:

$$PVUR = \frac{\max\,[|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|]}{V_{avg}} \times 100$$

14

where
V_a, V_b, V_c are phase voltages and

$$V_{avg} = \frac{V_{ab} + V_{bc} + V_{ca}}{3} \times 100 \qquad 15$$

b. Line Voltage Unbalance Rate (LVUR) or Percent Voltage Unbalance (PVU) given by the National Electrical Manufactures Association (NEMA) as follow[36]:

$$PVU = 100 \times \frac{MVD}{V_{avg}} \qquad 16$$

Where *MVD* is the maximum voltage deviation from the average line voltage magnitude and V_{Avg} is the average line voltage magnitude and

$$V_{Avg} = \frac{V_{ab} + V_{bc} + V_{ca}}{3}$$

V_{ab}, V_{bc}, V_{ca} are line-to-line voltages.

c. Voltage Unbalance Factor (VUF) that this definition has been given by International Electrotechnical Commission (IEC) as follows

$$VUF = \left|\frac{V_-}{V_+}\right| \times 100 \qquad 17$$

V. Methodology

For this investigation, the International Electrotechnical Commission's (IEC) definition of voltage stated in section 4 was selected for use. The technical data of the three phase induction motors investigated is presented in Table 1.
In order to evaluate the performance of the motor, it was first subjected to test operations under rated conditions with balanced voltage at no load. Thereafter, to evaluate the influence of unbalanced voltage on its performance, the motor was tested with three types of three-phase voltage unbalance (Table 1) under load.

To study the under voltage unbalanced condition, the positive sequence voltage was fixed at 95% of the rated voltage and the simulation was performed for six different values of VUF between 2% and 10%. To study the rated-voltage unbalanced condition, the positive sequence voltage was fixed at the rated voltage and simulation conducted for six different grades of VUF from 2% to 10%. Finally, to study the over-voltage unbalanced condition, the positive sequence voltage was fixed at 105% of the rated voltage and simulation performed for six different values of VUF from 2% to 10% (Table 1).

Table 1: Induction motor data

Parameter	Value
Rated Voltage (V)	$415_{(L-L)}$
Power (kW)	0.75
Frequency (Hz)	50
Speed (rpm)	1500
Mutual Inductance	0.2037
Number of Poles	4
Stator Resistance	1.115Ω
Stator Inductance	0.00597
Rotor Resistance (Ω)	1.083
Rotor Inductance (H)	0.00597H

VI. Results and Discussion

The investigation revealed that the presence of ripples on the rotor current waveform is an indication of distorted electromagnetic fields caused by voltage unbalance and that rotor flux became increasingly distorted as voltage unbalance surges. However, a load reduction lessens this effect as shown on the resulting waveforms from Fig. 3 through Fig14. The distorted electromagnetic fields also indicated rotor noise and vibration during the operation of the motor. These can increase significantly, the frictional and windage losses as well as stray losses. For all types of unbalance, motors should never be operated on full load. It was observed that the adverse effect of unbalance is most severe at under voltage conditions; drastic load reduction did not produce good motor performance with a low VUF. Proved simulations can indicate presence of rotor noise and vibration during operation of induction motor under voltage unbalance.

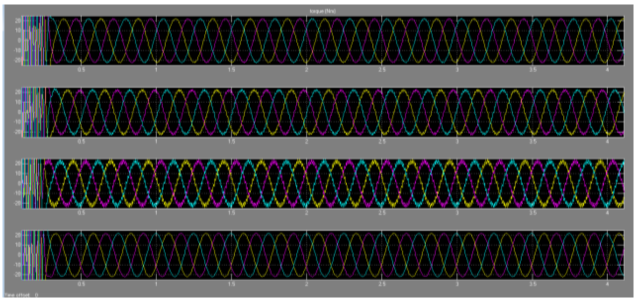


Fig.3 Rotor currents on full load

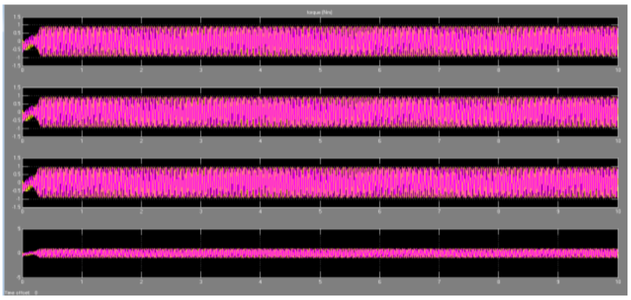


Fig.4 Rotor flux at full load

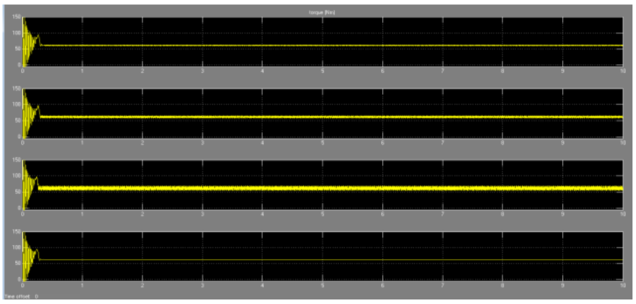


Fig.5 Torque at full load

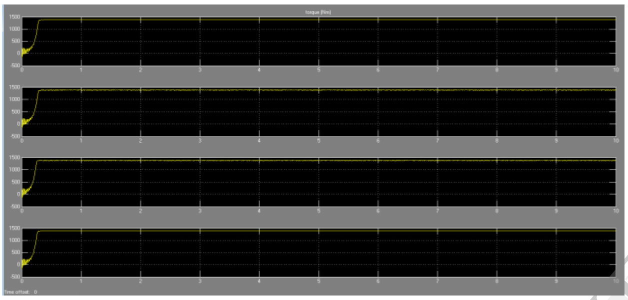


Fig. 6 Rotor speed at full load

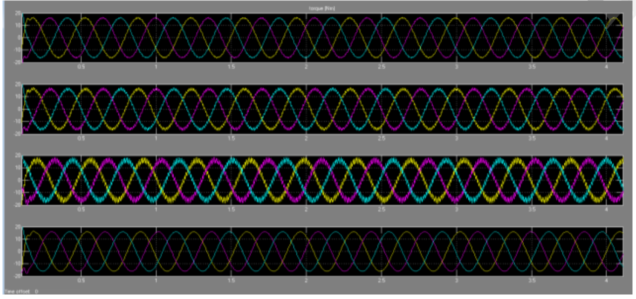


Fig. 7 Rotor currents at 75% of full load

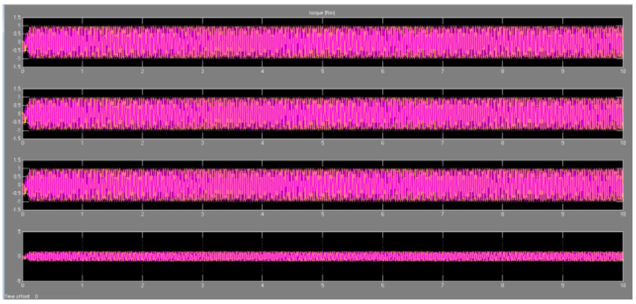


Fig. 8 Rotor flux at 75% of full load

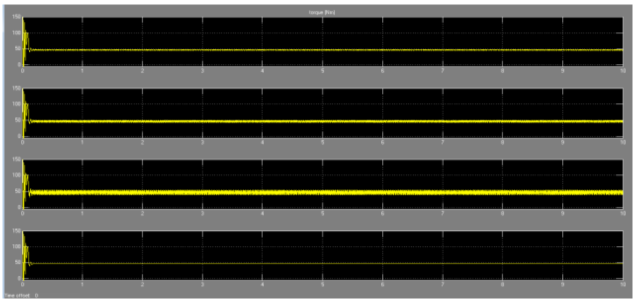


Fig. 9 Torque at 75% of full load

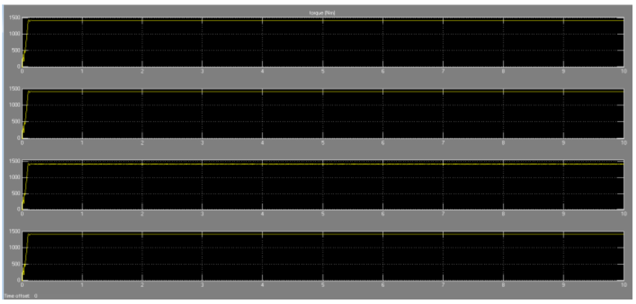


Fig. 10 Rotor speed at 75% of full load

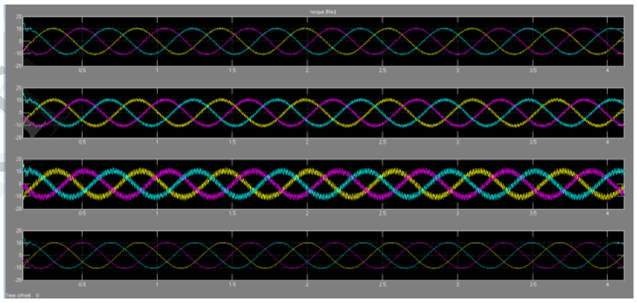


Fig. 11 Rotor currents at 50% of full load

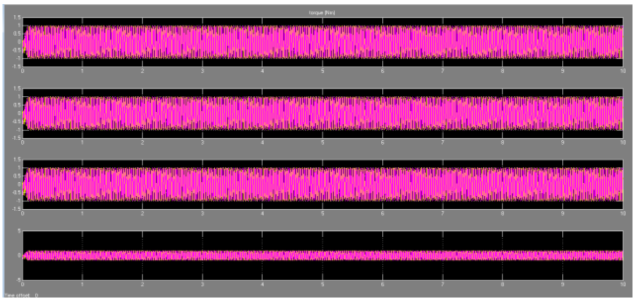


Fig. 12 Rotor flux at 50% of full load

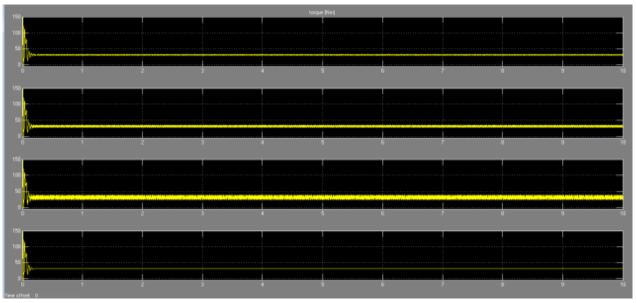


Fig. 13 Torque at 50% of full load

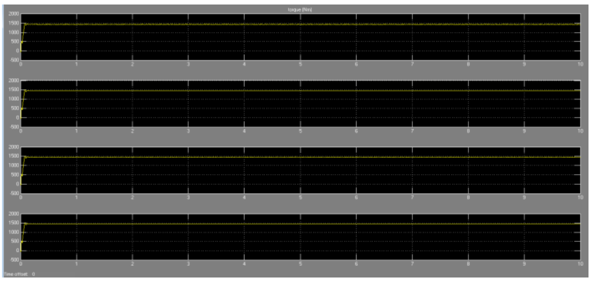


Fig. 14 Rotor speed at 50% of full load

VII. Conclusion

The investigation has shown that there is a noteworthy difference in the performance of a 2h.p induction motor operating under unbalanced source positive sequence voltages compared to balanced source positive sequence voltages. The results proved that simulations can indicate the presence of rotor noise and vibrations during operation of induction motor under voltage unbalance and that the operational performance of an induction motor can be studied using simulated result from MATLAB® Simulink without going through the arduous analytical method. However, laboratory experiments to compare results would be desirable. Since unbalanced conditions cannot be completely eradicated, it is therefore essential that motors be protected against all types of unbalances with NEMA, IEC and IEEE specifications and appropriately derated for effective and efficient performance.

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