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Behavior of Induction Motor at Voltage Unbalanced

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Abstract— A three phase induction motors are very commonly employed in power system because of their features like good self-starting capability, offers users simple, rugged construction, easy maintenance, low cost and reliability. Due to extensive use of Induction Motors in industry, Motors can be exposed to different hostile environments, mis-operation, manufacturing defects etc. As a result Motors are subjected with different internal & external faults. External faults are expected to happen sooner or later. One of the most common type of External fault is abnormal supply conditions such as loss of supply voltage, unbalanced supply voltage, over Voltage, Under Voltage, and Single Phasing. This paper discusses about the negative effect of Unbalance Voltage on performance parameters of 3HP Induction Motor such as current, efficiency, temperature rise, speed, Torque etc. These effects are verified by MATLAB simulation results. The proposed set-up has been simulated using" MATLAB/Simulink" Software and tested for various possible cases of voltages unbalance conditions. This paper also includes the various causes of unbalance voltage fault. As per test result it is verified that unbalanced voltages at motor terminals cause phase current unbalance ranging from 6 to 10 times the percent voltage unbalance. Efficiency decreases significantly above 1% of voltage unbalance so a motor must be derated for it to operate successfully.

Keywords—Induction Motor,Voltage Unbalanced ,MATLAB Simulation

I. INTRODUCTION

In past two decades, Electrical Systems were formed principally by linear loads. The fast increasing technologies have led to an ever increasing use of electronic devices, consisting nonlinear load which requires non sinusoidal current. The supply voltage is distorted due to propagation of this current in supply network. Similarly there are various causes which results in power system voltage unbalance. As induction motors are widely used in Industrial, Commercial & Residential Systems, once the supply voltage is unbalanced the ill effects on Induction motors will cause an enormous impact on Utilities, Manufacturers & Consumers. This paper discusses the various causes of Voltage Unbalanced in system & its ill effect on Induction motor performance. The proposed set up of an Induction Motor has been simulated on well-known MATLAB Simulink software. The Simulink is simulated for various possible cases of unbalance condition & from simulation result performance behavior of Induction motor under all possible cases of voltage unbalance condition is studied. The MATLAB results are analyzed to see the negative effects of voltage unbalance on performance parameters of a three-phase induction motor of rating 3HP, 414 V, 6.4A, 50Hz Sq Cage 1480 rpm Induction Motor such as current, efficiency, temperature rise, speed, Torque etc.

II. VOLTAGE UNBALANCE

Unbalanced voltages are unequal voltage values on 3-phase circuits that can exist anywhere in a power distribution system. Unbalanced voltages can cause serious problems, particularly to motors and other inductive devices. Perfectly voltage-balanced circuits are not possible in the real world.

Voltage Unbalanced is defined as a power quality problem where V in 1 or 3 phases gets increased or decreased in phase & magnitude above/below tolerance limit.

A various Cases of possible Voltage Unbalance condition are Single phase under voltage unbalance-(1ø UV), Two phases under voltage unbalance (2ø UV), Three phase under voltage unbalance (3ø UV), Single phase over voltage unbalance (1ø OV), Two phases over voltage unbalance (2ø OV), Three phases over voltage unbalance (3ø OV), Unequal Single phase displacement (1ø A), Unequal Two phases displacement (2ø A)[3]

Percentage voltage unbalance factor & percentage current unbalance is defined as follows

1) $\%\ voltage\ unbalance\ factor\ (VUF)$

$$= \frac{\text{Negative sequence V component}}{\text{positive sequence V component}} \text{x } 100$$

2) Line voltage unbalance rate (LVUR) as defined by National Electrical Manufactures Association (NEMA) Standards (MG1) part 14.35

$$\%\ \text{LVUR} =$$

$$\frac{Max\ V\ deviation\ from\ avg\ \ line\ \ V\ \ magnitude}{average\ line\ voltage\ magnitude} X\ 100$$

$$= \frac{\max[|V_a - V_{avg}\ ||V_b - V_{avg}||V_c - V_{avg}|\ \ ]}{V_{avg}} x100$$

Percentage Current Unbalance is defined in Similar manner.[3]

As per NEMA standards polyphase motors shall operate successfully under running conditions at rated load when the voltage unbalance at the motor terminals does not exceed 1%.

Further, operation of a motor with above a 5% unbalance condition is not recommended, and will probably result in damage to the motor.

III. Causes of Voltage Unbalance

In practice Induction Motors experiences Over Voltage & Under Voltages depending on location of motor & length of feeder used. During peak hours, some consumers with three phase motor could experience minimum voltage. Furthermore supply voltage is not always balanced. Therefore motor will experience combination of over & under voltages with unbalance voltages. The various causes are as listed below-

- Adjustable speed drive motors are fed from inverters that can produce significant voltage distortion.
- Induction Motors, even under normal operating conditions, involving perfectly sinusoidal voltage supply produce relatively limited amount of current harmonics due to winding arrangement & iron core nonlinear behavior.
- Unbalanced voltages usually occur due to variations in the load on phase i.e the load on one or more of the phases is unequal. This can be due to different impedances, or type and value of loading on each phase. Essentially, the resulting current unbalance is caused not only by the system voltage unbalance but also by the system impedance, the nature of the loads causing the unbalance, and the operating load on equipment, particularly motors. Single-phasing, which is the complete loss of a phase, is the ultimate voltage unbalance condition for a three phase circuit.
- Voltage sag in a bus of system may occur due to fault or motor starting can affect any Induction motor operation which is installed in any point of system.
- Power System disturbance may be due to incomplete transposition of transmission lines.

So A voltage unbalanced fault may be created due to harmonics due to electronics equipment, adjustable speed drive fed from inverter, unbalanced incoming utility supply, uneven distribution of single phase load , malfunctioning of p.f correction equipment, open delta connections, unbalance transformer tank, improper tap settings of transformer, sudden changes in load conditions, faults on transmission & distribution lines, heavy reactive single phase loads such as welders, current harmonics due to winding arrangement & iron core nonlinear behavior.[1]

IV. Effects of Voltage Unbalance Fault on Induction Motor Performance.

The most common symptoms of unbalanced voltages are the deleterious effects they impose on electric motors. Also the damaging effects are on power supply wiring, transformers, and generators. Unbalanced voltages at motor terminals cause phase current unbalance ranging from 6 to 10 times the percent voltage unbalance for a fully loaded motor. As an example, if voltage unbalance is 1%, then current unbalance could be anywhere from 6% to 10%[5] This causes motor over current resulting in excessive heat that shortens motor life, and hence, eventual motor burnout. Stator especially the rotor is heated excessively results in reduction in efficiency & possibly leading to faster thermal ageing.

The following graph as in figure 1 shows typical percentage increase in motor losses and heating for various levels of voltage unbalance as per NEMA standard

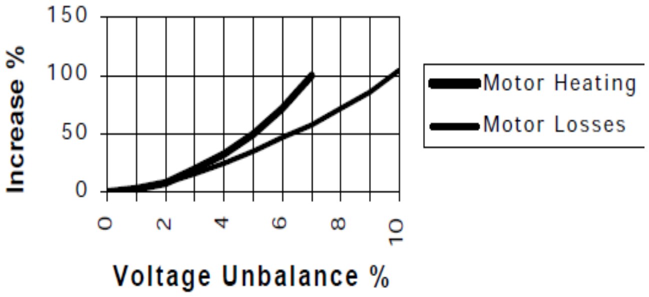

Figure 1 Variation of Losses & temperature Rise with VUF

The increase in losses will result in an increase in motor temperature & decrease in rated horsepower of motor. To avoid overheating of motor, its rated horsepower should be also reduced so as to maintain the temperature within thermal class limits. So in case of considerably distorted voltage supply, the induction motor performance is heavily affected & derating must be applied. When voltage unbalance exceeds 1%, a motor must be derated for it to operate successfully. The derating curve, shown below in Figure 2, indicates that at the 5% limit established by NEMA for unbalance, a motor would be substantially derated, to only about 75% of its nameplate horsepower rating.[5]

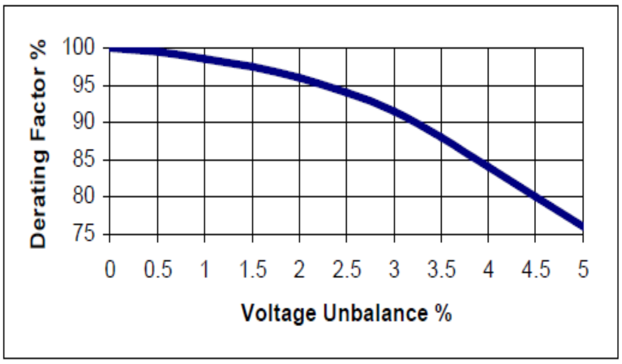

Figure 2 Variation of Derating factor with VUF

The basic observed effects of voltage unbalance on induction motors are current and torque transients associated with both voltage reduction and recovery. As the torque developed by an induction motor is proportional to the square of the applied voltage; therefore, any small reduction in voltage has a marked effect on the developed torque. The reduced torque may cause the motor to lose speed and draw more current.

Large induction motor is very sensitive to unbalance in supply voltage. The negative sequence component, which comes into picture because of the unbalance in the supply, is particularly troublesome. This is because the motor offers very small impedance to the negative sequence currents. In fact the negative sequence impedance is less than the positive sequence standstill-impedance as shown in figure 3. Further, the magnetic field due to negative sequence rotates at synchronous speed NS in the direction opposite to that of the rotor which is rotating at a speed equal to (sNS), which is slightly less than synchronous speed, where s is the slip of the motor this causes currents of [f(2-s)] frequency, i.e. almost double the supply frequency, to be induced in the rotor circuit.

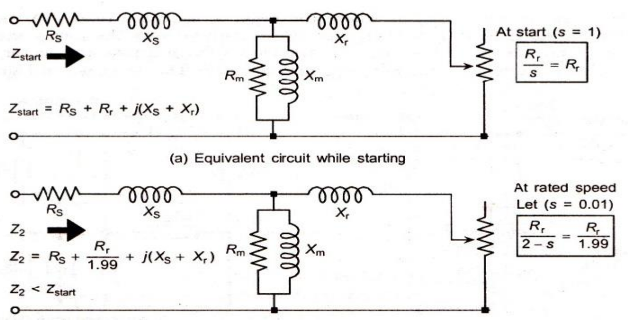

Figure 3 Equivalent circuit of induction motor

Due to voltage unbalance, machine cannot produce its full torque as the inversely rotating magnetic field of the negative sequence system causes a negative braking torque that has to be subtracted from base torque linked to normal rotating magnetic field.

Also bearing may suffer mechanical damage because of induced torque components at double system frequency.
From Customers viewpoint, the efficiency reduction of motor due to supply voltage unbalance results in higher electricity charge for same work done. [5] So far an utility is considered, the efficiency reduction leads to an increase in total load & decrease in spinning reserve of total generators.

So the Voltage Unbalanced Fault results in decrease in full load torque production, de-rating in motor characteristic, drawing unbalance current which causes overheating of rotor & stator, increase in losses so reduction in working efficiency, increase in resistance due to overheating results in thermal runaway & faster thermal ageing, additional charges to consumer & extra load to utility, shorter life span of motor, mechanical damage of bearing due to induced torque component of double system frequency, slight reduction in full load speed , increase in Shaft vibration noise, change in working pf.
Therefore, for large motors any unbalance in the supply voltage needs to be quickly detected and corrective action taken.

TABLE 1 Performance of Induction motor at various possible unbalance voltage conditions

Case	Voltage (peak) Vr	Voltage (peak) Vy	Voltage (peak) Vb	Positive Seq. Volt. Vp	Negative Seq. Volt. Vn	VUF = (Vn/Vp)*100	LVUR	Current Ir	Current Iy	Current Ib	% Current Unbalance	speed rpm	torque N-m	% Efficiency	Pf
Normal	585	585	585	585	0	0.00	0.00	7.63	7.65	7.63	0.17	1487	15.73	88.31	0.26
V variation within limit	580	585	585	583.3	1.67	0.29	0.29	7.29	7.69	7.85	3.15	1483	17.18	87.01	0.27
	560	585	585	576.7	8.33	1.44	1.45	5.98	7.99	8.755	15.58	1473	21.56	69.73	0.33
	580	560	585	575	7.64	1.33	1.74	8.43	6.03	8.1	12.10	1499	18.68	73.4	0.32
	600	585	585	590	5	0.85	1.69	8.61	7.58	6.98	11.48	1499	10.2	80.78	0.28
	605	590	585	593.3	6.01	1.01	1.97	8.72	7.88	6.69	12.32	1499	6.663	77.32	0.29
1 ø UV	550	585	585	573.3	11.67	2.04	2.03	5.36	8.23	9.23	21.34	1472	23.92	60.91	0.38
1 ø UV	500	585	585	556.7	28.33	5.09	5.09	3.05	10.08	12.12	44.00	1444	45.3	34.99	0.56
1 ø UV	480	585	585	550	35	6.36	6.36	2.48	11.09	13.07	47.18	1424	46.23	28.59	0.64
2ø UV	540	530	585	551.7	16.91	3.07	3.02	7.83	5.01	10.23	33.03	1483	39.24	53.15	0.44
2ø UV	500	510	585	531.7	26.82	5.04	5.02	7.52	5.53	12.38	46.05	1488	60.1	39.48	0.55
2ø UV	480	500	585	521.7	32.19	6.17	6.07	6.85	6.42	12.95	48.17	1468	54.16	33.79	0.63
3 ø UV	500	520	540	520	11.55	2.22	1.92	5.4	6.87	8.87	25.88	1472	22.06	61.74	0.44
3 ø UV	500	510	560	523.3	18.56	3.55	3.50	6.41	5.89	10.42	37.59	1465	37.86	50.78	0.49
3 ø UV	500	550	440	496.7	31.8	6.40	5.37	8.35	12.63	4.58	48.24	1442	24.42	35.03	0.64
1 ø OV	630	585	585	600	15	2.50	2.50	10.6	7.88	5.84	30.76	1515	-3.52	53.13	0.40
1 ø OV	680	585	585	616.7	31.67	5.14	5.14	14.11	9.57	5.11	47.03	1541	-24.1	29.29	0.58
1 ø OV	700	585	585	623.3	38.33	6.15	6.15	15.56	10.5	5.353	48.60	1554	-33.7	24.38	0.64
2 ø OV	620	640	585	615	16.07	2.61	2.03	7.91	11.07	6.09	32.47	1472	-10.2	48.3	0.40
2 ø OV	624	700	585	636.3	33.77	5.31	5.00	7.36	15.11	8.19	47.85	1431	-24.9	24.44	0.60
2 ø OV	620	720	585	641.7	40.45	6.30	6.10	7.32	16.56	9.52	48.74	1412	-27.1	20.14	0.65
3 ø OV	625	640	675	646.7	14.81	2.29	2.19	7.73	6.98	11.32	30.46	1489	44.12	48.59	0.37
3 ø OV	620	635	730	661.7	34.44	5.20	5.16	10.03	6.03	15.51	47.39	1501	84.21	23.67	0.59
3 ø OV	630	625	750	668.3	40.86	6.11	6.11	11.98	5.18	16.71	48.01	1519	98.71	20.07	0.65

V. MATLAB SIMULINK & RESULTS

Motor Specifications
3HP, 414 V, 6.4A, 50Hz Sq Cage IM 1480 rpm
R1=1.405ohm, L1 = 0.005839 H
R2'= 1.395ohm, L2' = 0.005839 H

The MATLAB Simulink as shown in Figure 4 is developed for the above motor specification. This Simulink is simulated for all various cases of possible voltage unbalance Conditions by varying voltages magnitude & phase.

The various performance parameters of motors like all three currents, active & reactive power, negative phase sequence voltage component by phase sequence analyzer, torque, pf, efficiency, speed, mechanical output are studied for normal & all possible voltage unbalance conditions by observing display & scope

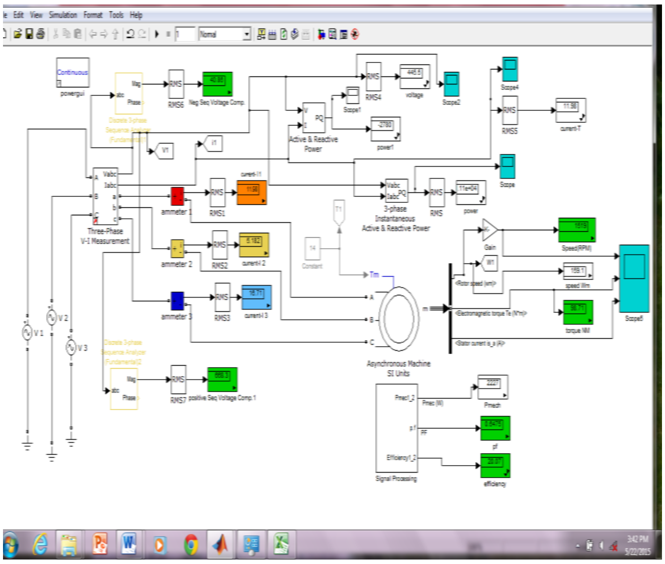

Figure 4 Matlab Simulink of Induction Motor

A table no 1 shows the variation of performance parameters of Induction motor with voltage unbalance. The table is prepared from simultion result of MATLAB simulink of Induction motor as shown in figure 4. A simulink is simulated for normal balanced voltage & voltage variation within permissible tolerance limit as per Indian Standard (+/- 5 %).It is also simulated for vrious possible cases of Voltage unbalanced conditions.A table shows few cases of Voltage unbalanced conditions.

It is obsrved that when voltage variation is within permissible tolerance limits, variation in Speed, efficiency, p.f,.Torque is very less & voltage unbalance factor is near about to 1%. When motor is simulated for voltage unbalance factor of nearly at 5%, below 5% & above 5 % for variou cases, it is observed that there is variation in currents, percentage Current unbalance, so in Efficiency, pf.& torque and also in negative phase sequence component of voltage.It is also seen that Percentage Current Unbalance varies by 6 to 10 times of that of Percentage Voltage Unbalance Factor.

Figure 5 shows the graphical relation betwwen Vaiation of Percentage Current Unbalance, Efficiency, Positive Sequnce Voltage Component, Negative Phase Sequence Component , p.f. & Speed with Percentage Voltage Unbalance Factor (VUF). From. Figure 5 it is seen that, Percentage Current Unbalance increases linearly with VUF. So due to increase in losses Efficiency decreases with VUF. Negative sequence

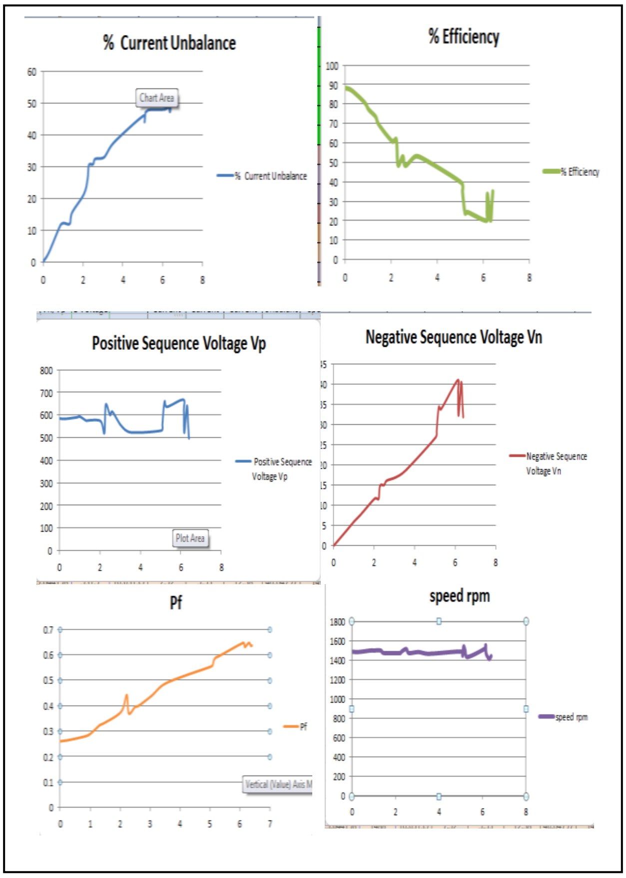

Figure 5 Co-relation between various parameters with VUF

Compmonent is very sensitive with VUF but Variation in Positive sequence Components is less.Similarly there is less variation in speed with VUF. As current increases with increase in VUF, p.f also increases with VUF. Figure 6 shows MATLAB Simulation Scope results for normal voltage balanced conditions & for single phase under voltage unbalance condition when VUF = 6.36 %. A balance condition waveforms are sinusoidal.Unbalance condition introduces negative sequence component.Voltage unbalance in one phase creates large unbalance in currents.The current in one phase in which voltage is reduced, decreses while currents in remaining two phases increase.this creates large unbalance in current as shown in waveforms.

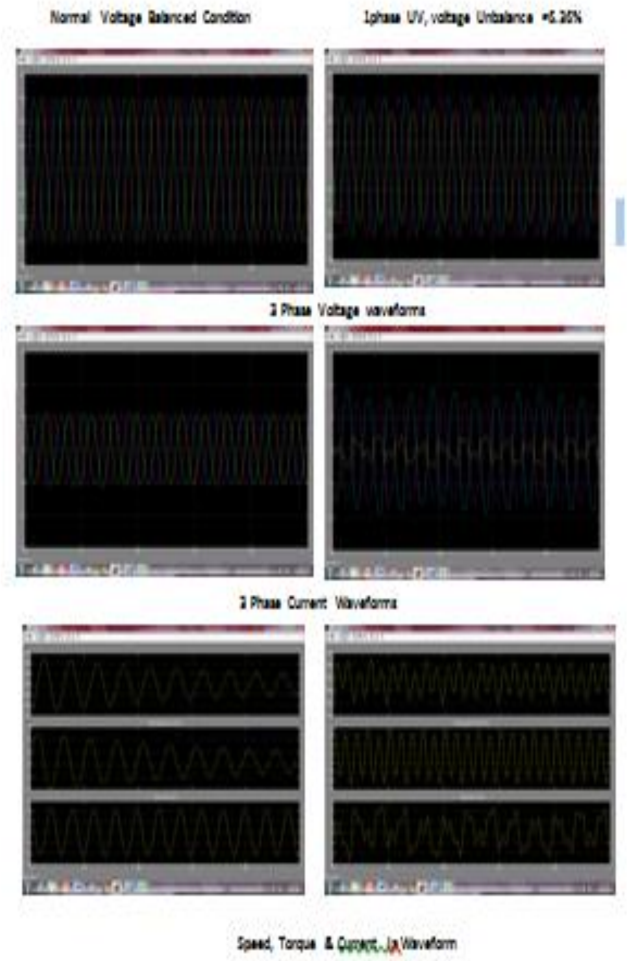

Figure 6 Matlab Simulation Scope results for normal voltage balanced conditions & for 1 phase UV unbalance condition when VUF = 6.36 %.

VI CONCLUSION

The negative effects of voltage unbalance on three phase Induction motor is studied by Simulation results of Matlab Simulink setup for proposed motor setup. Simulink is simulated for normal balanced voltage & voltage variation within permissible tolerance limit as per Indian Standard (+/- 5 %) & all various cases of possible voltage unbalance Conditions by varying voltages magnitude & phase of source. It is obsrved that when voltage variation is within permissible tolerance limits voltage unbalance factor is near about to 1%. variation in Speed, efficiency, p.f,.Torque is very less & When motor is simulated for voltage unbalance factor of nearly at 5%, below 5% & above 5 % for variou cases, it is observed that there is variation in currents, percentage Current unbalance, so in Efficiency, pf.& torque and also in negative phase sequence component of voltage. Motor must be derated for it to operate successfully above 1% of voltage unbalance as Efficiency decreases significantly.A operation of a motor with above a 5% unbalance condition is not recommended due to significant decrease in efficiency which will results increase in temperature rise, and so may probably result in damage to the motor. It is also seen that unbalanced voltages at motor terminals cause phase current unbalance ranging from 6 to 10 times the percent voltage unbalance.

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