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Performance Analysis of 3-Phase Asynchronous Motor under Various Voltage Conditions

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Abstract

Induction Motor being the most popular one in industry, it is very important to carry out studies about the effects of power quality in the efficiency and reliability of induction motor. The effect of unbalanced supply conditions on the performance of three-phase induction machine is examined in MATLAB environment. The induction motor experiences several types of electrical/incipient faults such as over/under voltage, phase reversing, unbalanced voltage, over load, single phasing and earth fault. The main fault considered in this work is unbalanced supply voltage. To analyze the behavior of induction motor during unbalanced supply voltage, the induction motor is modeled using arbitrary reference frame theory in MATLAB/ Simulink environment, the faults are created (Balance Over Voltage, Balance Under Voltage, Unbalanced Over Voltage, Unbalanced Under Voltage) and the variations of the induction motor parameters are observed. Variation in speed, rotor losses, efficiency, torque and power factor are calculated and observed during unbalanced supply.

Keywords: Unbalance voltage, Matlab Simulink, Derating, BOV, BUV, UBOV, UBUUV.

INTRODUCTION

Power quality issues are day by day becoming important because of increasing use of sensitive electronic equipments. Power quality problem is any problem manifested in voltage, current or frequency deviations those results in failure or mis-operation of customer equipment. Before connection of a sensitive piece of an equipment to supply system it is essential to assess the compatibility between the piece of equipment and the supply. In any industrial or commercial facility, assured reliable operation and better performance of various equipments requires understanding of all issues, probable problems, their causes and cost effective solutions. [1]

Voltage unbalance is regarded as a power quality problem of significant concern at the electricity distribution level. Although the voltages are quite well balanced at the generator and transmission levels the voltages at the utilization level can become unbalance three phase power systems the generated voltages are sinusoidal and equal in magnitude, with the individual phases 120^o apart. However, the resulting power system voltages at the distribution end and the point of utilization can be unbalanced for several reasons. The nature of the unbalance includes unequal voltage magnitudes at the fundamental system frequency (under-voltages and over-voltages), fundamental phase angle deviation, and unequal levels of harmonic distortion between the phases. A major cause of voltage unbalance is the uneven distribution of single phase loads that can be continuously changing across a three-phase power system. Example problem need due to the unequal system impedances and the unequal distribution of single-phase loads. An excessive level of voltage unbalance can have serious impacts on mains connected induction motors. The level of current unbalance that is present is several times the level of voltage unbalance. Such an unbalance in the line currents can lead to excessive losses in the stator and rotor that may cause protection systems to operate causing loss of production

Voltage unbalance also has an impact on ac variable speed drive systems where the front end consists of three-phase rectifier systems. The triplen harmonic line currents that are uncharacteristic to these rectifier systems can exist in these situations leading to unexpected harmonic problems areas can be rural electric power systems with long distribution lines, as well as large urban power systems where heavy single-phase demands, such as lighting loads, are imposed by large

Assessment of Voltage Unbalance

Voltage variations are random variations of voltage magnitudes, mainly due to arc furnaces loads, frequent or cyclic motor operations involving speed variations etc. Voltage unbalance is the nonequality of voltage magnitudes and /or voltage angles among the three-phases at any given point of time, mainly due to the unequal distribution of single-phase loads, asymmetry of line and transformer winding impedances, time varying operation of single-phase loads, traction loads, blown out fuses on three-phase capacitor banks, adjustable speed drives operations etc. The most important reason for voltage unbalance is a mismatch of reactive power demand between the industrial utilities and the generating stations. Due to varying operating times of single-phase and three-phase loads, there exists definite possibility of voltage variations above and below the rated value, in both balanced and unbalanced form. Thus, voltage variation and unbalance can be classified into balanced over voltage (BOV), balanced under voltage (BUV), unbalanced over voltage (UBOV) and unbalanced under voltage (UBUV). [2]

BOV is the condition wherein the three-phase voltages are individually and equally greater than the rated voltage value, BUV is the condition wherein the three-phase voltages are individually and equally lesser than the rated voltage value. UBOV is the condition wherein the three phase voltages are not equal to each other, in addition the positive sequence component of the voltage is greater than the rated voltage value while UBUV is the condition wherein the three phase voltages are not equal to each other, in addition the positive sequence component of the voltage is lesser than the rated voltage value.

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 2). Any difference that exists 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 (Figure3).

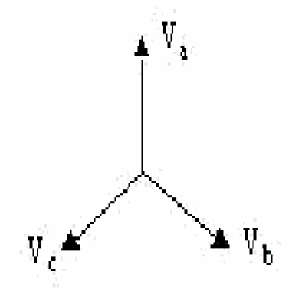

Fig: 2 A balanced system

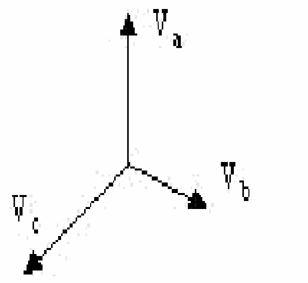

Fig: 3 An unbalanced system

Causes of voltage unbalance include unequal impedances of three-phase transmission and distribution system lines, large and/or unequal distribution of single-phase loads, phase to phase loads and unbalanced three-phase loads. When a balanced three-phase load is connected to an unbalanced supply system the currents drawn by the load also become unbalanced. While it is difficult or virtually impossible to provide a perfectly balanced supply system to a customer every attempt has to be taken to minimize the voltage unbalance to reduce its effects on customer loads.

Definitions of Voltage Unbalance

The level of voltage unbalance that is present in a system can be specified using two commonly used definitions.

Widely used in European standards, the first definition originates from the theory of Symmetrical Components which mathematically breaks down an unbalanced system into three balanced systems as shown by Figure 4 .These three are called positive sequence, negative and zero sequence systems. For a perfectly balanced system both negative and zero sequence systems would be absent.

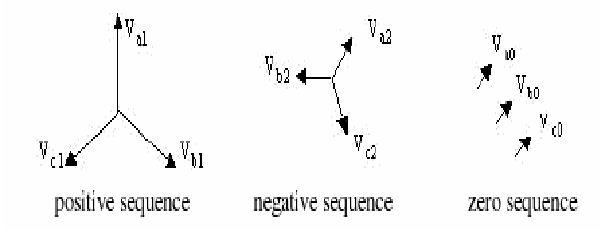

Fig: 4. Symmetrical components of an unbalanced system of voltages

These sequence systems can be given some physical interpretation. The direction of rotation of a three-phase induction motor when applied with a negative sequence set of voltages is opposite to what is obtained when the positive sequence voltages. Having no phase displacement between the three voltages in the zero sequence system, when applied to a three-phase induction motor, it will not rotate at all as there will be no rotating magnetic field. [3]

Strictly speaking, there should be two definitions for unbalance based on the symmetrical components. They are: (a) negative sequence voltage unbalance factor = V_n /V_p and (b) zero sequence voltage unbalance factor=V_o /V_p (where $V_{p,}$ V_n ,V_o are positive, negative and zero sequence voltages respectively). However, as zero sequence currents cannot flow in three wire systems such as three-phase induction motors the zero sequence voltage unbalance is of little practical value. The negative sequence unbalance is the quantity of practical significance as it indicates the level of that attempt to turn a three-phase induction motor in a direction opposite to established by the positive sequence voltages. The negative sequence voltage can also be expressed in a more user-friendly form as given by equation (1) which requires only the three line-line voltage readings.

$$\% \text{ voltage unbalance} = V_n /V_p \quad *100\% \text{ (1)} \qquad (1)$$

For a set of unbalanced voltage, $V_{ab,}$ $V_{bc,}$ V_{ca} the positive sequence and negative sequence voltages V_p and V_n are given by

$$V_p =(V_{ab+}a*V_{bc+}a^2*V_{ca})/3 \qquad (2)$$

$$V_n=(V_{ab+}a^2* V_{bc+} a* V_{ca})/3 \qquad (3)$$

Where

$$a= -0.5+j0.866 \quad \text{and} \quad a^2=-0.5-j0.866 \qquad (4)$$

This is also sometimes known as the Voltage Unbalance Factor (VUF) or the IEC definition in some literature.

However NEMA standard MGI 1993 and the IEEE community use the following definitions:

$$\% \text{ unbalance}= \frac{\text{(Maximum voltage deviation from average voltage)}*100}{\text{average voltage}} \qquad (5)$$

NEMA definition avoids complex algebra. However both definitions give different results.
For example if three unbalance line to line voltages are:

V_{ab} =450∟0^o, Vbc =363.6∟-121.44^o, Vca=405∟130^o
Then the positive sequence voltage V_{abp} is 404.625∟2.89 and the negative sequence voltage is V_{abn} is 50.217∟-23.98.Then using the IEC definition, equation (1), the % unbalance is:

$$\% \text{ Voltage unbalance} = \frac{50.217}{404.625} * 100 = 12.41\%$$

But if we use NEMA definition, equation (5), the average voltage is 406.2 and the maximum voltage deviation from average voltage is 450-406.2=43.8.Then the % unbalance is:

$$\% \text{ Voltage unbalance} = \frac{43.8}{406.2} * 100 = 10.78\%$$

Table 1: Motor Parameters at Torque =2 Nm,BOV

S.No.	Motor Parameter	Rated voltage	1%	2%	3%	4%	5%
1	Stator Loss	12.32	15.76	18.77	0.8849	8.542	10.05
2	Stator Current	5.321	6.019	6.588	1.426	4.431	4.805
3	Rotor Loss	1.353	0.0505	1.387	1.658	0.2646	1.442
4	Rotor Current	1.288	0.249	1.304	1.425	0.5895	1.329
5	Slip(p.u.)	0.053	0.0048	0.00488	0.0048	0.0043	0.0047
6	Speed (rpm)	1790	1791	1791	1791	1792	1792
7	Output Power(watt)	378.5	379.8	379.3	379	380.4	378.9
8	Efficiency(p.u.)	0.9221	0.92	0.92	0.9186	0.9178	0.9168
9	power factor 1	0.2263	0.2231	0.2198	0.2115	0.2105	0.2073
10	power factor 2	0.2247	0.2197	0.2181	0.2134	0.2098	0.2063
11	power factor 3	0.227	0.2226	0.2164	0.2147	0.2114	0.2082

Then we observed that there are different results when we use each one of definition. An extensive analysis made by Pillay [4], revealed that the difference in the definitions do not result in significant difference when operated by unbalance supply in the 5% range.[5]

4. Matlab Simulation

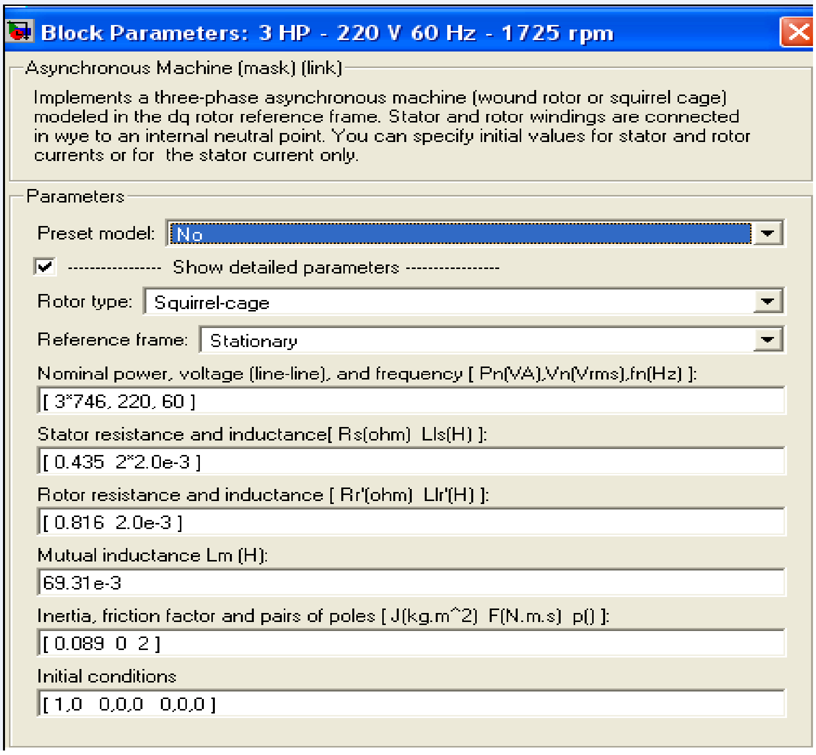

Table 2: Motor Parameters at Torque =8 Nm,BOV

S.No.	Motor Parameter	Rated voltage	1%	2%	3%	4%	5%
1	Stator Loss	3.572	0.0421	5.498	9.582	34.31	29.96
2	Stator Current	2.866	0.311	5.98	4.744	8.881	8.299
3	Rotor Loss	0.5457	0.004873	1.057	9.582	17.72	25.87
4	Rotor Current		0.07727	1.138	3.42	4.66	5.631
5	Slip(p.u.)	0.0275	0.02715	0.02656	0.02597	0.02516	0.02483
6	Speed (rpm)	1750	1751	1752	1753	1755	1755
7	Output Power(watt)	1470	1470	1471	1472	1474	1474
8	Efficiency(p.u.)	0.9381	0.9387	0.9392	0.9397	0.9401	0.9406
9	power factor 1	0.6486	0.642	0.6355	0.6294	0.6226	0.6172
10	power factor 2	0.6493	0.6433	0.637	0.6294	0.6224	0.6147
11	power factor 3	0.6502	0.6433	0.636	0.6296	0.6224	0.6165

Table 3: Motor Parameters at Torque =10 Nm,BOV

S.No.	Motor Parameter	Rated voltage	1%	2%	3%	4%	5%
1	Stator Loss	1.187	34.25	41.79	43.69	0.4153	21.46
2	Stator Current	1.652	8.874	9.801	10.02	0.9771	7.029
3	Rotor Loss	14.06	0.1767	13.51	42.39	6.198	7.569
4	Rotor Current	4.151	0.4853	4.069	7.208	2.756	3.046
5	Slip(p.u.)	0.03574	0.03473	0.0339	0.03265	0.03241	0.03188
6	Speed (rpm)	1736	1737	1739	1741	1742	1743
7	Output Power(watt)	1820	1823	1825	1828	1828	1828
8	Efficiency(p.u.)	0.93	0.9308	0.9316	0.9326	0.9332	0.9339
9	power factor 1	0.7196	0.7143	0.7082	0.6997	0.6947	0.6902
10	power factor 2	0.7199	0.7141	0.7078	6996	0.6964	0.6901
11	power factor 3	0.7199	0.7128	0.7073	0.6996	0.6968	0.6904

Table 4: Motor Parameters at Torque =25 Nm,BOV

S.No.	Motor Parameter	Rated voltage	1%	2%	3%	4%	5%
1	Stator Loss	180.5	188.1	7.168	47.78	141.9	14.89
2	Stator Current	20.37	20.79	4.059	10.48	18.06	5.5851
3	Rotor Loss	134.8	237	2.582	304	291.2	231.8
4	Rotor Current	12.85	17.04	1.76	19.3	18.89	16.86
5	Slip(p.u.)	0.1035	0.1008	0.0985	0.09538	0.09381	0.0915
6	Speed (rpm)	1641	1619	1623	1628	1631	1635
7	Output Power(watt)	4229	4241	4251	4266	4273	4284
8	Efficiency(p.u.)	0.8399	0.843	0.8472	0.85	0.8536	0.8567
9	power factor 1	0.863	0.8629	0.8616	0.861	0.8615	0.8593
10	power factor 2	0.863	0.8626	0.8632	0.8625	0.8614	0.8601
11	power factor 3	0.863	0.8626	0.8632	0.8625	0.8614	0.8601

Table 5: Motor Parameters at Torque =8 Nm,UBOV/A

S.No.	Motor Parameter	Rated voltage	condition 1	condition 2	condition 3	condition 4	condition 5
1	Stator Loss	3.572	28	28.36	93.21	73.6	20.66
2	Stator Current	2.866	8.023	8.074	14.64	13.01	6.891
3	Rotor Loss	0.5457	2.857	1.227	33.48	27.02	78.87
4	Rotor Current		1.871	1.226	6.405	5.755	9.831
5	Slip(p.u.)	0.0275	0.0271	0.02742	0.02934	0.0346	0.02957
6	Speed (rpm)	1750	1751	1751	1747	1736	1747
7	Output Power(watt)	1470	1374	2530	2976	1849	1566
8	Efficiency(p.u.)	0.9381	0.9497	0.8456	0.8504	0.745	0.7723
9	power factor 1	0.6486	0.6369	0.4419	0.9857	-0.0157	0.5189
10	power factor 2	0.6493	0.6766	0.9994	0.4916	0.09628	0.3513
11	power factor 3	0.6502	0.6137	0.8512	-0.8206	0.979	0.9986

Table 6:Motor Parameters at Torque =2 Nm,UBOV/C

S.No.	Motor Parameter	Rated voltage	condition 1	condition 2	condition 3	condition 4	condition 5
1	Stator Loss	12.32	11.31	29.31	35.78	103.4	20.22
2	Stator Current	5.321	5.099	8.183	9.069	15.42	0.6818
3	Rotor Loss	1.353	0.049	24.85	12.28	31.68	13.8
4	Rotor Current	1.288	0.2451	5.519	3.88	6.231	4.112
5	Slip(p.u.)	0.053	0.0051	0.004978	0.00616	0.0093	0.0066
6	Speed (rpm)	1790	1791	1797	1789	1783	1788
7	Output Power(watt)	378.5	303.1	1139	406.4	331.2	1658
8	Efficiency(p.u.)	0.9221	0.9516	0.8223	0.5354	0.9186	0.812

Where condition 1is V 1=179.62,V 2=181.42,V 3=183.22
Where condition 2 is V 1=179.62 ∟10,V 2=181.42 ∟-100,V 3=183.22 ∟-220
Where condition 3 is V 1=179.62 ∟20,V 2=181.42 ∟-120,V 3=183.22 ∟-250
Where condition 4is V 1=180 ∟-10,V 2=180 ∟-100,V 3=180 ∟-200
Where condition 5 is V 1=182 ∟0,V 2=181∟-130,V 3=181 ∟-23

CONCLUSION

Voltage unbalance causes problems with 3 phase motors. It is typically caused by load unbalance by the uneven connection of single phase loads.

The National Electricity Rules (NER) provides a practical allowance for voltage unbalance. Network operators and electricity users have an obligation to maintain voltage unbalance below the NER requirement.

Various options are available for the network operator and electricity user to mitigate or prevent problem. If voltage unbalance cannot be maintained below 1% then 3 phase motor will need to be derated.

- Even a small voltage unbalance will result in large current unbalance during the running of motor by a great factor.

- Negative phase sequence components will lead to heating of motor.
- Negative phase sequence currents leads to reduction in motor output torque.
- Motor is forced to run at higher slip leading to increased rotor loss and reduced efficiency.
- Electricity boards should look in to this phenomenon seriously where irrigation pump sets suffer the voltage imbalance, even 1% loss of efficiency for the country like India would mean a great loss.

This paper has investigated the different operating conditions that can exist when 3 phase induction motor is subjected to various unbalance voltage conditions (BOV, BUV, UBOV, UBUV).The paper has clearly investigated the performance of three phase induction motor, listed its results and some vagaries in efficiency are exposed and discussed .Finally, some important techniques to save energy is presented. . From the tabulated results its clear indication that the performance is very different than the theoretical study. At times the losses are reduced and performance is improved under unbalancing and at times a little unbalance can create havoc and abnormal behavior of motor can be seen. Till date many literatures have thrown light upon voltage unbalance and its impact/effects with equations and formulas. Keeping the above norms and knowledge gained, I have tried to show all type of conditions within permissible unbalancing. In future I hope to take optimization of motor performance taking into considerations derating and unbalancing. Finally,some important techniques to save energy are presented.

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