THE EFFECT OF PRACTICAL OPERATION CONDITIONS ON THE PERFORMANCE OF INDUCTION MACHINES.

Annick DEXTERS
KHLim – Belgium
annick.dexters@khlim.be

Wim DEPREZ
K.U.Leuven – Belgium
wim.deprez@esat.kuleuven.be

Ronnie BELMANS
K.U.Leuven - Belgium
ronnie.belmans@esat.kuleuven.be

ABSTRACT

The effect of practical operating conditions on induction motors and generators and their performance is addressed. In particular the effect of voltage unbalance on their efficiency will be investigated. Therefore, the paper also gives a brief overview of the most prevalent standards and definitions of efficiency measurements and voltage unbalance. An other focus lies on causes and effects of grid unbalance on (small) induction machines and how they might adversely influence the grid.

INTRODUCTION

The Kyoto protocol, the limitation of fossil fuels, the deregulation of utilities and the emerging power markets all tend to increase the efforts towards a more efficient use of energy and the penetration of distributed generation. Consequently there is an increased interest in the efficiency of induction motors because they represent the bulk users of energy in industry. On the other hand the market of small or micro electric energy generation units, often combined with local heat production (CHP), is emerging. For these applications the classical induction machine with cage rotor is an interesting generator.

The efficiency class and the numerical value of the nominal efficiency are relevant parameters in terms of competitive energy conversion. Based on relevant standards the determination of the nominal efficiency occurs for continuous operation, steady state thermal conditions and at rated output. But under practical operation conditions other boundary conditions are present. Generally the electric machine is operated under different load conditions and operating temperatures. This has a great impact on stator and rotor losses as they change linearly with the temperature at around 4% for each 10K. Also electrical supply conditions such as line supply voltage fluctuations, voltage unbalance and harmonics have a significant influence on the motor efficiency. [1]

In a three-phase system, a voltage unbalance is the phenomenon in which the rms values of the voltages or the phase angles between consecutive phases are not equal.

Voltage unbalance is a frequently encountered power quality issue in weak power networks like rural grids and in power systems that supply large single-phase loads. Moreover, voltage unbalance at the motor terminals can also be caused within the infrastructure of companies themselves. Industrial and commercial facilities may have well balanced incoming supply voltages, but unbalance can develop within the building due to non uniformly distributed single-phase loads, unbalanced or overloaded equipment, high impedance connections (e.g , bad or loose contacts), badly repaired motors (e.g. when a short on a winding is only isolated), etc. Sometimes, unbalance and/or overvoltages are also caused by improper power factor correction. [2]

EFFECTS OF VOLTAGE UNBALANCE.

Unbalanced voltages can result in adverse effects on equipment and on the power system. It is common to study the behavior of the positive and negative sequence components of the unbalanced supply voltage to understand the effect of an unbalance on an induction motor. The positive sequence voltage (V1) produces the desired positive torque, whereas the negative sequence voltage (V2) gives rise to an air gap flux rotating against the forward rotating field, thus generating a detrimental reversing torque. So when neglecting non-linearities, for instance due to saturation, the motor behaves like a superposition of two separate motors, one running at slip s with terminal voltage V_1 per phase and the other running with a slip of (2-s) and a terminal voltage of V_2. The result is that the net torque and speed are reduced and torque pulsations and acoustic noise may be registered.

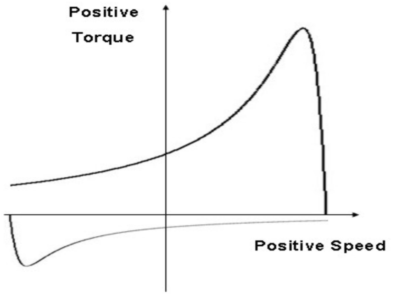


Figure1. Positive and negative sequence torques of an induction motor subjected to unbalanced supply voltages

From Fig.1 it is clear that the entire torque-speed curve is reduced. Three points of particular interest on the resulting curve are the starting, the breakdown and the full load torque. It is clear that the motor takes longer to speed up. This changes the thermal behaviour of the motor and leads to decreased service life if not early failure. Moreover, if full load is still demanded, the motor is forced to operate with a higher slip, increasing rotor losses ($R'_2/(2\text{-}s)$) and thus heat dissipation. The reduction of peak torques compromises the ability of the motor to ride through dips and sags. In generator mode a larger driving torque is required and the supplementary iron and copper losses in the rotor due to the inverse rotating field will also increase the total losses.

Due to the low negative sequence impedance (R'$_2$/(2-s)), the negative sequence voltage V_2 gives rise to large negative sequence currents. The unbalanced voltages cause the line currents to be unbalanced in the order of 6 to 10 times the voltage unbalance. As a consequence the connection of an induction motor or generator to an unbalanced grid tends to magnify the system unbalance. The net effect of the voltage unbalance is reduced efficiency and decreased life of the machine. Premature failure can only be prevented by derating the machine.

STANDARDS AND DEFINITIONS

Energy efficiency standards

The IEEE 112-B and IEC 34-2 international standards represent the most important references for efficiency measurements on three-phase induction motors. These standards recommend different measurement methods and calculation procedures, in particular for the determination of the stray load losses (SLLs), the reference temperature and the thermal correction of the copper losses. In the IEC 34-2 the reference temperature is determined by the insulation class, there is no thermal correction of the copper losses and the SLLs are arbitrarily estimated to be equal to 0.5% of the input power.at rated load. In the IEEE 112-B standard, the reference temperature is the temperature at rated load, the copper losses are corrected and the SLL's are measured. The SLL's are that part of the total losses, obtained by measurement of the electrical input power and the mechanical output power (direct method), that are not covered by the copper, core and the friction and windage losses The average SLLs values vary slightly with the motor power. Because of the adopted procedures, the efficiency values obtained from the two standards can differ significantly. The IEC 34-2 standard compared to the IEEE 112-B standard is less accurate and is currently under review. The European Standard Draft IEC 61972 (direct method), is similar to the IEEE 112-B method to evaluate the SLLs. The IEC 61972 (indirect method), determines the SLLs from assigned values in a predefined curve, which depend on motor output power. [3]

Voltage unbalance definitions

There are several definitions of voltage unbalance in standards and literature:

NEMA (National Electrical Manufacturers Association) defines voltage unbalance as the line voltage unbalance rate (LVUR) :

$$\%LVUR = \frac{\text{Max Voltage Deviation from Avg Line Voltage}}{\text{Avg Line Voltage}} \cdot 100$$

IEEE uses the phase voltage unbalance rate (PVUR):

$$\%PVUR = \frac{\text{Max Voltage Deviation from Avg PhaseVoltage}}{\text{Avg Phase Voltage}} \cdot 100$$

IEC defines the voltage unbalance factor (VUF) :

$$\%VUF = \frac{V_2}{V_1} \cdot 100$$

V_1 and V_2 are the positive and negative sequence voltages respectively, which can be obtained by symmetrical component transformation. This is the only definition which includes information of both magnitudes and angles. Yet, often only the magnitude of the VUF is considered.

For every condition of supply voltage, these three definitions provide different values to characterize the unbalance. On the other hand the percentage voltage unbalance does not define the terminal voltages. For any percentage unbalance, there are an infinite number of terminal voltages, each having a different influence on the performance of the machine. To reduce the range of input voltage variations for a given VUF one can specify the positive sequence voltage component which has the main role in the performance of the induction machine. [4]

Voltage unbalance standards

The ANSI (American National Standards Institute) standard C84.1-1995 "for Electric Power Systems and Equipment" recommends that electrical supply systems should be designed and operated to limit the maximum voltage unbalance to 3% when measured at the electric-utility revenue meter under no-load conditions. Concerning voltage unbalance, the European voltage characteristics standard, EN50160, states the following: *Under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of the negative phase sequence component of the supply shall be within the range 0 to 2 % of the positive phase sequence component. In some areas with partly single phase or two phase connected customers' installations, unbalances up to about 3 % at three phase supply terminals occur."*

Concurrently, NEMA recommends in the standard NEMA MG1-1993 "Motors and Generators" that induction motors should be derated for voltage unbalance greater than 1% . The IEC 60034-26 standard also requires a derating of the machines if unbalance is greater than 1%. [2]

MEASUREMENT RESULTS

For each VUF value, there are indefinite possibilities of terminal voltages. The cases represented in Table 1 were chosen to investigate the influence of the positive sequence voltage on the machine performance and to eliminate the influence of the angle between the positive and negative sequence voltage. The no load losses seem to be a sinusoidal function of this angle. [5]

The efficiency tests for unbalanced grid voltages were performed on two four-pole squirrel-cage induction machines with the same rated voltage and power: 230/400V-7.5 kW but with different efficiency classes: respectively EFF1 and EFF3. The rated currents were 15 and 13.9 A. Except for the presence of unbalanced supply voltages, the efficiency measurements were conducted conform the IEEE 112- B standard. This standard recommends performing measurements at rated temperature and permits a temperature difference of 10K during load test.

Table 1: Voltage unbalance cases

VUF 4%	Ua (V)	Ub (V)	Uc (V)	V1 (V)	V2 (V)	angle (º)
balanced	230∟90º	230∟-30º	230∟-150º			
3Φ-OV	235∟90º	270∟-30º	249∟-150º	251.32	10.16	3
2Φ-OV	230∟90º	264∟-30º	241∟-150º	244.99	10.01	2
1Φ-OV	230∟90º	259∟-30º	230∟-150º	239.66	9.67	2
1Φ-UV	230∟90º	230∟-30º	203∟-150º	220.99	9.00	1
2Φ-UV	230∟90º	208∟-30º	201∟-150º	212.99	8.74	0
3Φ-UV	220∟90º	195∟-30º	195∟-150º	203.32	8.34	0

Motor mode

The maximum efficiency for conventional motor designs lies in the range of 60 to 80% of the rated power. This provides a favourable energetic behaviour at partial load. The machines examined here comply with this quality feature.

The efficiency curves presented in Fig. 2 and Fig. 3 show a possible serious decrease of efficiency dependent on the load of the machine and the unbalance case chosen. Although the EFF1-machine is less prone than the EFF3- machine to voltage unbalance.

Figure 2: Efficiencies for several cases with 4% voltage unbalance EFF3-machine: motor mode

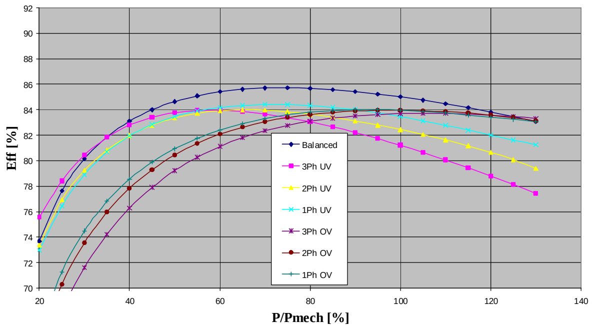
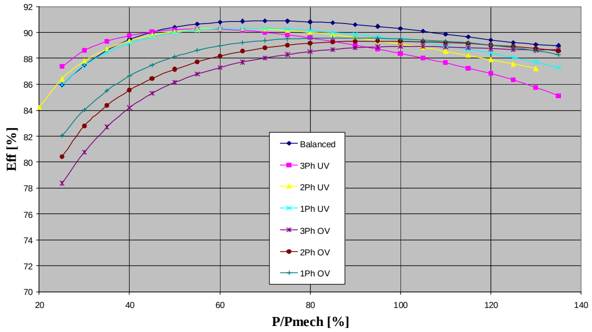
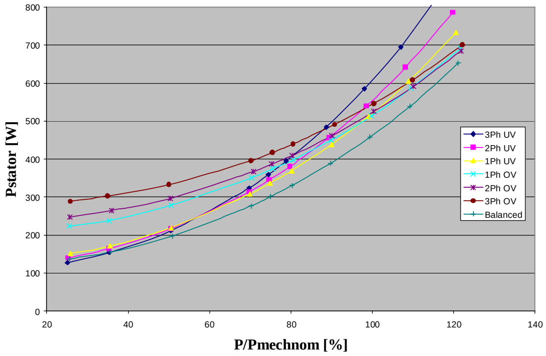


Figure 3: Efficiencies for several cases with 4% voltage unbalance EFF1-machine: motor mode



Unbalance due to undervoltages has little effect on partial loads but very strong at rated load. Unbalance due to overvoltages has the opposite effect. So the curves will intersect. At partial load the influence of the iron losses is more significant. They rise with average voltage (Tab 2) but especially when saturation occurs. Moreover in the presence of voltage unbalance there will be supplementary iron losses in the rotor due to the reverse air gap field. At rated load the stator and rotor losses are more significant than the iron losses. With a greater magnetization due to overvoltage, the current required for torque build up is less and so the rotor losses too. These effects explain also the shape of the curves of the stator losses because the stator current will not only provide the current to magnetize the machine but also to produce the torque.(Fig.4)

Figure 4: Stator losses for several cases with 4% voltage unbalance EFF3-machine: motor mode



One could think that for voltage unbalance the efficiency at rated load increases when the positive sequence voltage increases. [6]. This is only true when there are no saturation effects in stator and rotor. From Tab.2 is clear that efff1 machine has better core material –lower iron losses- however, measurements show both machines tested were slightly saturated at rated voltage.

One can see that for a lower supply voltage the position of the maximum efficiency shifts in the partial load area. Depending on the load condition and voltage amplitude this can therefore result in a significantly better or poorer efficiency. [1]

The efficiency curves are measured at rated temperature. The efficiencies for balanced voltage are underestimated for partial loads and the efficiencies for voltage unbalance are overestimated at full load. The thermal equilibrium was not desirable to prevent damage to the machine. So the difference in efficiency between balanced voltage and unbalance voltage is worse.

Table 2:
Iron losses and average voltages

VUF 4%	Uav (V)	EFF3 Piron (W)	EFF1 Piron (W)
3Φ-OV	252.60	534	342
2Φ-OV	246.24	492	297
1Φ-OV	240.46	475	267
balanced	231.21	339	194
1Φ-UV	221.97	363	184
2Φ-UV	213.87	351	174
3Φ-UV	204.62	312	154

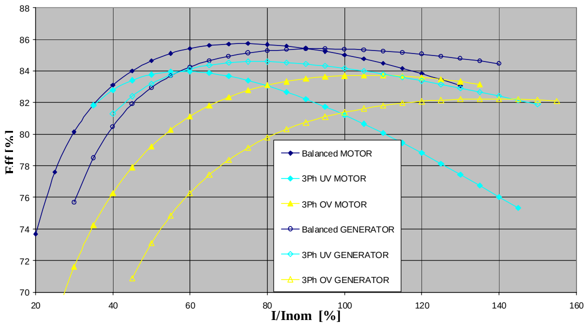
Table 3:
Current unbalances (%)

VUF 4%	EFF3		EFF1	
	mot	gen	mot	gen
3Φ-OV	16.2	17.0	14.2	14.3
2Φ-OV	15.4	17.0	14.2	14.2
1Φ-OV	14.5	17.8	14.8	15.3
balanced	0.5	1.2	0.6	0.9
1Φ-UV	13.5	14.5	13.8	13.2
2Φ-UV	13.2	12.3	12.4	12.5
3Φ-UV	12.2	12.2	12.2	12.3

A squirrel cage induction motor is very sensitive to voltage unbalance. This influences the thermal conditions of the machine and necessitates derating.

Comparison motor - generator mode

Figure 5: Efficiencies for 3Ph OV and 3Ph UV voltage unbalance of 4%
EFF3-machine: motor + generator mode



To compare efficiencies in motor and generator mode the efficiency curves were plotted in function of the stator current. In generator-mode the induction machine is much more prone to unbalances due to overvoltages than in motor mode.(Fig 5) For small machines in general the stator resistance and consequently the stator voltage drop are not negligible. The voltage at the terminals of the motor will be greater than the air gap voltage (induced voltage or emf), i.e. the voltage determining the air gap flux. This effect increases with load. Consequently, the magnetizing current and the core losses decrease. In generator mode on the contrary the air gap voltage will increase due to the stator voltage drop. This requires a higher magnetizing current and consequently core losses will increase. This increase can be significant when the machine is already in saturation at no load. Voltage unbalances due to overvoltages aggravate this effect Also the additional core losses in the rotor increase [7].

Generator mode

Fig. 6 and Fig. 7 present the efficiency curves for the EFF1 and EFF3- generators as a function of the electrical output of the generator. The nominal value is the electrical input of the machine in motor mode at rated load. The 100% load point for the balanced voltage condition is already an overload point as the current in generator mode is far more reactive. Also here the EFF1-machine is less prone to voltage unbalance than the EFF3-machine and the required derating can be smaller.

Current unbalance

Current unbalances were calculated for the load point where the root mean square value of the 3 line currents was equal to rated current. The results are not quite consistent but in general one can state that the current unbalance was 3 to 4 times the voltage unbalance. (Tab. 3). The current unbalance increases as load decreases. For partial load current unbalances six times the voltage unbalance were recorded. During the load tests , the voltage source was kept constant at the voltages of the no-load test. Under real circumstances the unbalanced currents would cause unbalanced voltage drops over the line impedances and so worsen the voltage unbalance at the terminals of the machine.

Figure 6: Efficiencies for several cases with 4% voltage unbalance
EFF3-machine: generator mode

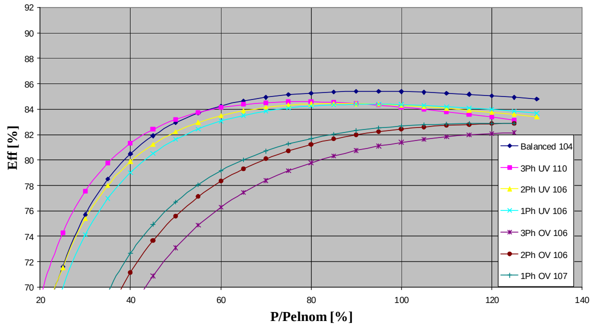
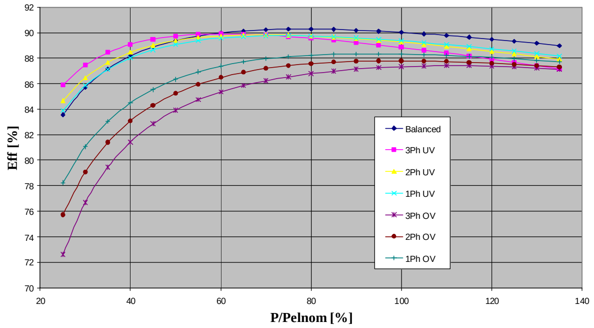


Figure 7: Efficiencies for several cases with 4% voltage unbalance
EFF1-machine: generator mode



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