The combined effect of practical operating conditions and material choice on the performance of induction machines

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Abstract

In this paper, the effect of practical operating conditions on induction motors and their performance is addressed. Mainly the effect of voltage unbalance on the efficiency will be investigated. The performance of an electromagnetic actuator depends on design or technological choices and on the volume and characteristics of the materials that are used. Therefore, this paper focuses on the influence of these design aspects on the performance of induction motors which are supplied by unbalanced voltage. Experiments reveal that differences in material choice in induction motors, e.g. Al vs. Cu rotor technology, result in interesting differences in behaviour in the presence of voltage unbalance. These results are thoroughly discussed and explained in the paper.

Introduction

In the context of the various worldwide efforts and initiatives towards a more efficient use of energy, there is an increased focus on the energy efficiency of motor driven systems. Those electric drive systems, mostly equipped with induction machines, are the bulk users of energy in industry. More than 50% of the electricity consumption in the developed countries and approximately 65% of the electricity which is used in industry is consumed by electrical motors [1-3]. Even though induction machines already have reasonable high energy efficiencies, a modest increase in motor efficiency would yield considerable benefits in both environmental and economical terms. This explains the increased interest in the evaluation of energy efficiency of induction machines. However, focus should lie on the losses and efficiency of entire motor driven systems. The total savings potential for motor driven systems in EU-25 is estimated to be about 200 TWh [1-4].

To realize this, mandatory regulations, voluntary agreements or initiatives, such as 'The European Motor Challenge Programme' [2], SEEEM [5] or efficiency classifications –e.g. the new IEC draft for efficiency classifications - are indispensable. Unfortunately, due to the diversity of implemented motor systems in practice, it is very difficult, maybe impossible, to regulate on systems level. Consequently, most initiatives focus on the standardised energy efficiency of the motor alone. Moreover, 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 an important 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. [6] One should also realise that in turn also motor specific design issues – for instance material choice – make that the behaviour under these practical conditions is different for every machine.

In order to give engineers the tools to asses the systems interactions and to realise substantial energy savings in motor systems, industry and academia should provide them with more than just one efficiency label or value. As a first step in this process, this paper concentrates on the interaction between material choices and unbalanced voltage supply conditions and their influence on the efficiency characteristic. This discussion is backed-up with experimental results which were obtained in the laboratories of the Electrical Engineering Department at the KULeuven. This research was conducted in cooperation with the department of Electrical Engineering of the University of L'Aquila which provided the different prototypes.

Voltage Unbalance & Induction Machines

Description, Causes and Definitions

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 over-voltages are also caused by improper power factor correction. [7]

There are several definitions of voltage unbalance in standards and the literature [8-9]. In this paper, the definition of the IEC is adopted; the committee defines a voltage unbalance factor (VUF):

$$\%VUF = \frac{\mathrm{V}_2}{\mathrm{V}_1} \cdot 100 \qquad (1)$$

V_1 and V_2 are the positive and negative sequence voltages respectively, which can be obtained by symmetrical component transformation.

There are also 'Power Quality' standards that describe the framework of what can be considered as normal operating conditions [10-11]. In those descriptions, which use different boundary conditions and measuring protocols, an unbalance of 3% is indicated as the maximum allowed asymmetry. However, within companies higher values might occur, therefore, in this paper a VUF of 4% will be investigated.

Effect of Voltage Unbalance on Induction Motors

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 V1 per phase and the other running with a slip of (2-s) and a terminal voltage of V2. The result is that the net torque and speed are reduced and torque pulsations and acoustic noise may be registered.

In fact, the entire torque-speed curve is reduced, influencing 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 ($R'_2/(2-s)$) and thus heat dissipation. The reduction of peak torques compromises the ability of the motor to ride through dips and sags. 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 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.

Experiments

Project and Tested Motors

As described above, it is the intention to study the energy efficiency of induction machines subjected to unbalanced voltage supply. More specifically, the focus lies on how different material choices, intended to increase the energy efficiency, influence the performance under these unbalanced conditions. In this context, 4 four pole, 50Hz, 230/400V, 7.5 kW TEFC induction machines were tested. These machines were already described and tested in [12]. The first machine is a classical, commercial eff3 machine. It has a classical construction with an aluminium rotor cage and the laminations of stator and rotor are realised with standard steel. This machine is labelled SSAL (standard steel aluminium). For the second machine, the aluminium cage is replaced by a copper one. This machine has the same electrical steel, dimensions, winding, etc. ; it is labelled SSCU (standard steel copper). The third machine is labelled, PSCU (premium steel copper). For this machine, with respect to the second one, the standard steel is replaced by a premium steel. The fourth machine is a commercial eff1 machine, labelled HE (high efficient). It is produced by a different manufacturer as the first three prototypes. This machine has a different design (e.g. a higher stack length), an aluminium rotor cage and different premium electrical steel.

Voltage Unbalance Cases

For each VUF value, there are indefinite possibilities of terminal voltages. The locus of the phase voltages of a 230V motor for a VUF of 4% is a cylinder (Figure 1). In fact, in the context of energy efficiency of induction machines, the possible definitions of voltage unbalance are not complete [10,13-14] Therefore, six specific unbalanced voltage conditions were chosen to study the different motors. These cases are represented in Table 1, it are one-, two- and three phase over and under voltages respectively. They are intended 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. [15] No cases of voltage asymmetry caused by phase shifts are considered in this project.

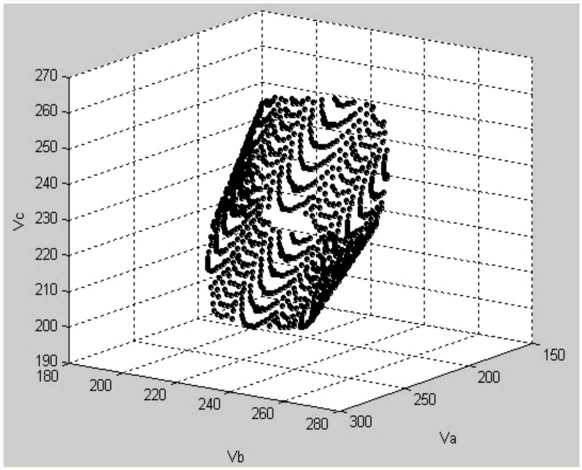

Figure 1: Phase voltage variation for VUF of 4%

The unbalance is applied to the terminals of the tested machine and is kept constant during the entire test. That is; for each motor and each phase voltage situation, a no load test and a load test (see below). This corresponds to a situation where the grid is very strong. In fact, the unbalance of the line currents (in %) of an induction machine connected to an unbalanced voltage system can be a few times the VUF. In weak grids, this can result in considerable differences in line voltage drops aggravating the original voltage unbalance. And as a consequence, the resulting unbalance in currents can be six to ten times the original VUF [16]. That means that the results presented in this paper are rather optimistic concerning the general negative influence of voltage unbalance on the efficiency of induction machines.

Table 1: Considered Phase Voltage Unbalance Cases

	Ua	**Ub**	**Uc**	**VUF**	**V_1**	**V_2**
	(V)	**(V)**	**(V)**	**%**	**(V)**	**(V)**
balanced	230∟90°	230∟-30°	230∟-150°			
3Φ-OV	235∟90°	270∟-30°	249∟-150°	4.044	251.322	10.164
2Φ-OV	230∟90°	264∟-30°	241∟-150°	4.086	244.989	10.009
1Φ-OV	230∟90°	259∟-30°	230∟-150°	4.035	239.656	9.670
1Φ-UV	230∟90°	230∟-30°	203∟-150°	4.071	220.991	8.996
2Φ-UV	230∟90°	208∟-30°	201∟-150°	4.103	212.991	8.739
3Φ-UV	220∟90°	195∟-30°	195∟-150°	4.100	203.325	8.336

Efficiency Standards and Measurement Routine

For the determination of the efficiency of induction machines, there exist different standards worldwide. For instance there is a Japanese standard, a Canadian one, … , and of course the well-known IEC and IEEE standards [17-18]. Disturbingly, different efficiency values are obtained for the same machine from the same test depending on which standard is taken as the basis of efficiency determination. Obviously, there are possible consequences of such discrepancies in measured efficiency values when they are used for the purpose of optimising the energy efficiency of motor driven systems. These differences and other relevant aspects are well documented in literature [6,9,19-20]. In fact, since it is the goal of this project to asses the interaction between material choice and voltage unbalance on the efficiency, the absolute efficiency values are of minor importance. The results will only be compared relatively to each other. Additionally, the standards do not allow unbalanced supply voltages larger than 0.5%.

Nevertheless, for the determination of the energy efficiency of the motors, the IEEE standard 112-B was adopted disregarding the presence voltage unbalances. All calculated efficiency values in the context of the measurements described here are based on the segregation of losses and with the necessary (temperature) corrections. This standard recommends performing measurements at rated temperature and permits a temperature difference of 10K during the load test.

Situations with unbalanced voltage supply are (thermal) overload conditions for induction machines if they are not derated [10]. Temperature can rise very fast under unbalanced conditions; therefore, for every test with unbalanced voltage, the same measurement routine was followed. Each time, the temperature of the machine was stabilised by running the machine at rated load with balanced voltage supply before the test started. For almost the same boundary conditions, the surrounding temperature in the lab for each test was between 24 and 26 degrees Celsius, the motor end-winding temperature was monitored. For each run an equal number of load conditions were recorded in order to keep the test-run as short as possible. The measurement equipment was in compliance with the standard and all parameters, including the motor end-winding temperature, were recorded by a Labview® based data acquisition system.

Results

In figures 2 to 4, the efficiency characteristics of the SSAL-, SSCU-, PSCU- and HE-motor are represented respectively for the balanced and the six unbalanced voltage conditions. For the first three machines, the successive steps of changing the rotor cage material and next the electrical steel and the consequent influence on the efficiency are clear. For balanced conditions, the SSCU-motor moves toward the eff2 boundary and the PSCU-motor is comfortably eff2. The effects of the asymmetrical voltage supply conditions will be discussed in the next section.

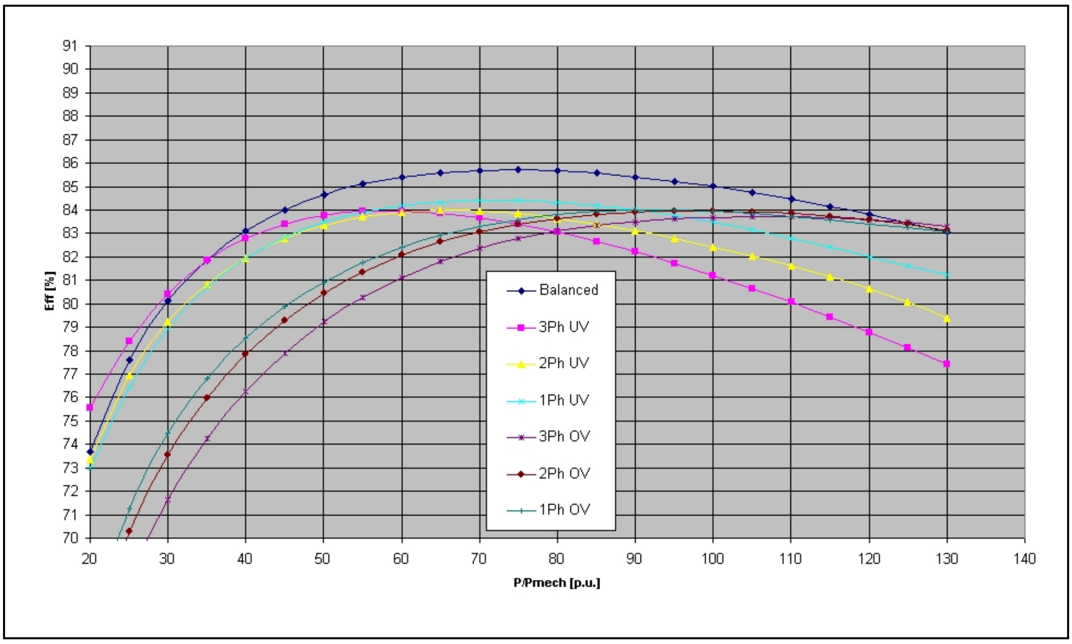

Figure 2: Efficiency Characteristic according to IEEE112-B (except for the presence of unbalance) for the SSAL-motor. The unbalanced cases represent a VUF of 4% by a three phase, a two phase and a one phase over or under voltage.

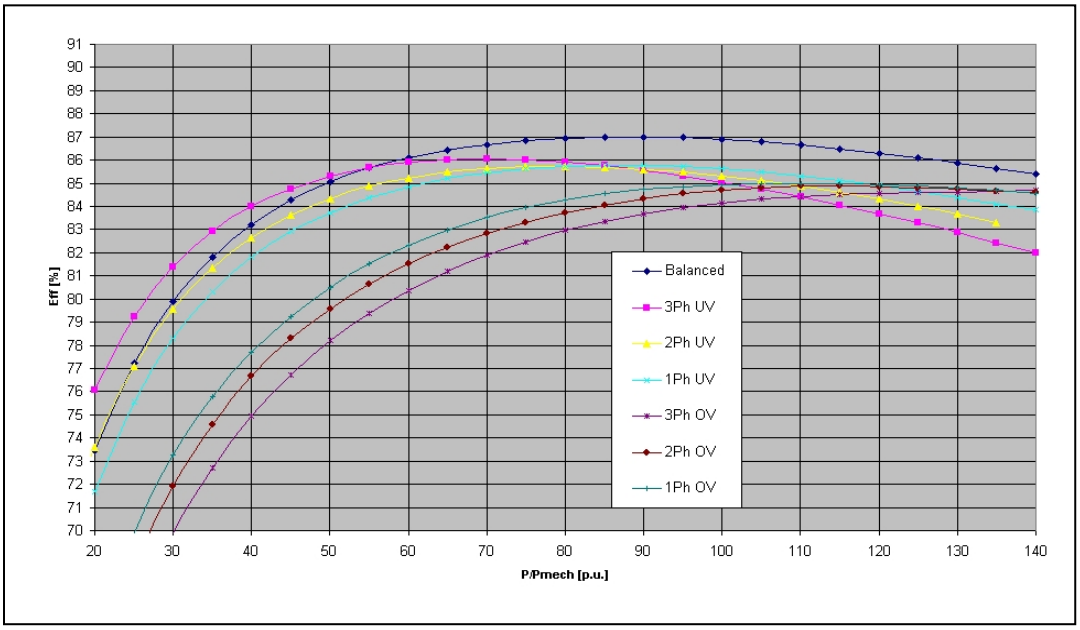

Figure 3: Efficiency Characteristic according to IEEE112-B (except for the precense of unbalance) for the SSCU-motor. The unbalanced cases represent a VUF of 4% by a three phase, a two phase and a one phase over or under voltage.

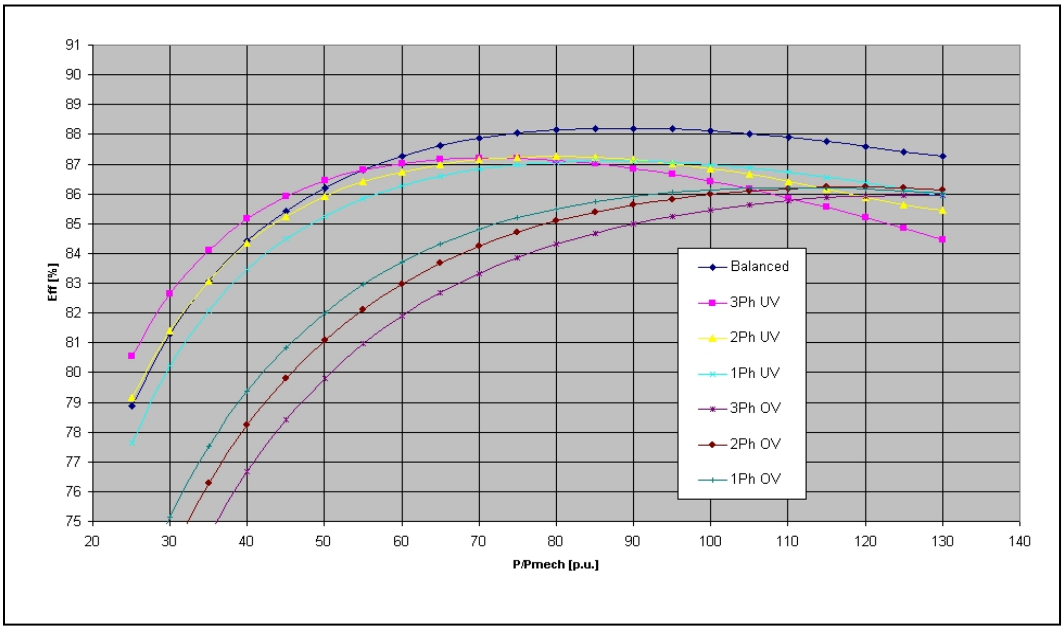

Figure 4: Efficiency Characteristic according to IEEE112-B (except for the precense of unbalance) for the PSCU-motor. The unbalanced cases represent a VUF of 4% by a three phase, a two phase and a one phase over or under voltage.

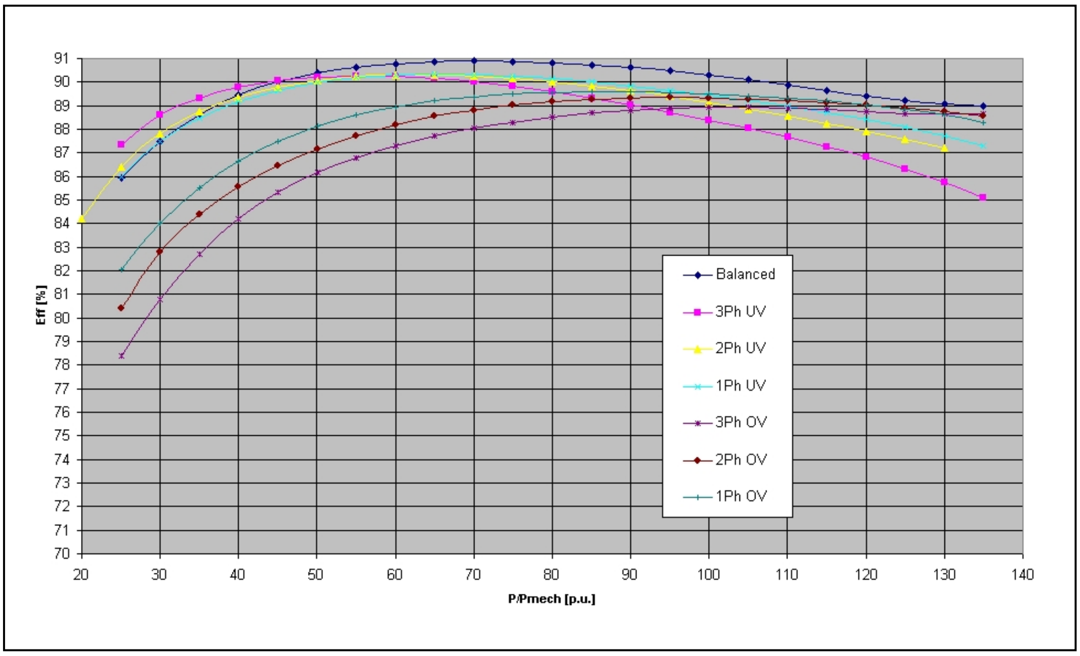

Figure 5: Efficiency Characteristic according to IEEE112-B (except for the presence of unbalance) for the HE-motor. The unbalanced cases represent a VUF of 4% by a three phase, a two phase and a one phase over or under voltage.

Discussion of the results

General Trends

It is known that the load dependency of the efficiency (at constant reference temperature) can be mathematically defined [6]. This approach splits the losses at rated power (P_N) into a load independent component V_o and a load dependent component $V_L.(P/ P_N)^2$, the efficiency can therefore be described as:

$$\eta_{(p)} = \frac{1}{1 + \frac{v_0}{p} + v_L \cdot p} \qquad \text{with: } p = \frac{P}{P_N},\ v_L = \frac{V_L}{P_N} \text{ and } v_0 = \frac{V_0}{P_N} \qquad (2)$$

From this, it can be found that the maximum efficiency is located at the load point $p^* = (v_0/v_L)^{1/2}$. This is the point for which the load dependent losses become equal to the constant losses, the latter include the friction and windage losses, the iron losses and the no-load stator losses, i.e. the total no-load power.

For the balanced voltage situation, this general behaviour can be clearly noticed on figures 2 and 3. Due to the copper rotor, the load dependent copper losses and as a consequence also the stator losses decrease, so the maximum efficiency shifts towards a higher load. And of course, due to this decrease of losses the maximum efficiency is higher. It should be noted that this shift is based on the proportion of both loss components. For the PSCU-motor, the losses decrease further, but the ratio v_0/v_L remains unchanged; the location of the maximum efficiency is practically the same as for the SSCU-machine. For the HE-machine, the losses are even lower, but the ratio falls back to a classical value, comparable with that of the SSAL-motor.

For voltage fluctuations, the behaviour can be explained based on the same theory if it can be assumed that the constant losses vary directly and the load dependent losses inversely proportional with the voltage squared. In general, this assumption is valid. Clearly, when the voltage decreases, so do the iron and the no-load stator losses, but for the same mechanical power, with less magnetisation of the machine, more load current is required. This means that for symmetrical under voltages, the top of the efficiency characteristic remains the same but shifts to the left, for over voltage, it moves toward higher loads.

Unbalanced voltage supply can be considered as a special case of these symmetrical over or under voltage conditions. For the applied asymmetrical conditions (Table 1) it can be noticed that there are three over voltage and three under voltage conditions. The three phase unbalanced over voltage condition has the highest average voltage and the three phase under voltage the lowest. The same applies for the positive sequence voltage; the negative sequence component is more or less the same for each unbalanced situation. This explains the general trend that for the under voltages, the maximum efficiency is shifted more and more to lower load conditions, whereas for the over voltage conditions the peak is gradually shifted to the right. However, this is not the only phenomenon. Namely, in contrast with symmetrical over or under voltage conditions; the maximum efficiency for the unbalanced cases is lower. Thus, for each unbalanced voltage condition the ratio v_0/v_L changes and also the losses increase. It is the combination of specific motor parameters – read material and design choices – and the kind of unbalance that determine to what extend the efficiency curve is shifted in these two dimensions. Apparently, unbalance due to under voltages has little effect on partial loads but very strong at rated load. Unbalance due to over voltages has the opposite effect. So the curves will intersect.

Losses due to unbalanced voltage supply

In this section the influence of unbalanced voltage supply on the different loss components will be discussed in general, apart from material or design specific differences.

At partial load the influence of the constant losses, mainly iron losses, is more significant. They rise with average voltage 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. From Figure 6 these two effects can be quantified for the SSAL-motor. Note that the iron losses are only one part of the constant losses, the no-load stator losses depend also on the iron losses.

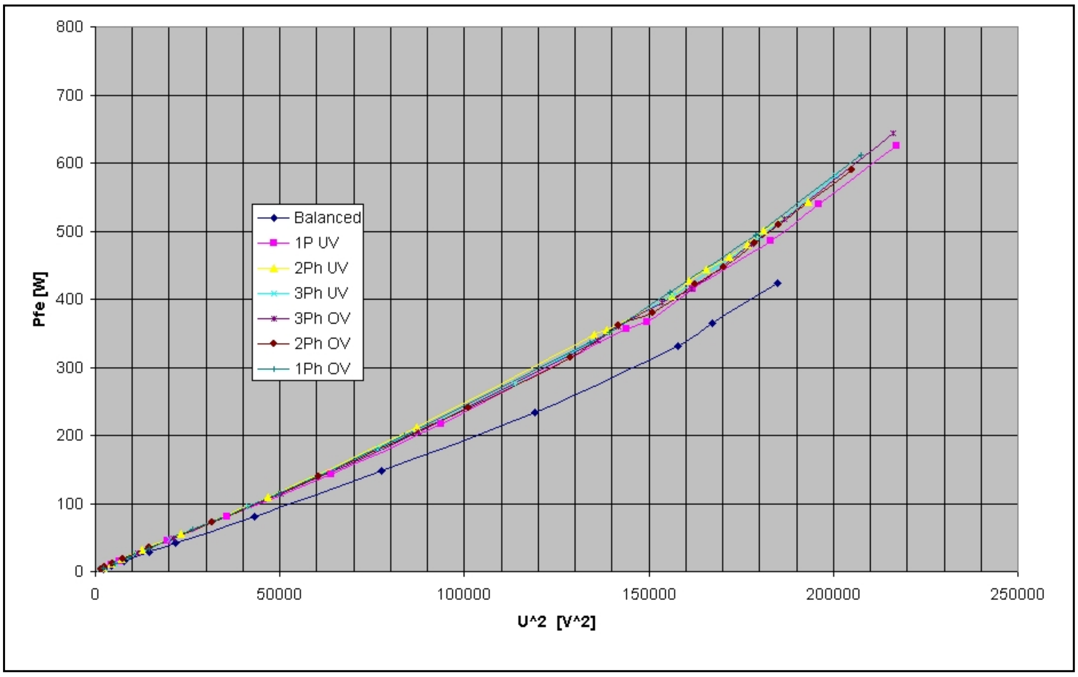

Figure 6: Iron losses as a function of voltage squared of the SSAL-motor for the balanced voltage and six asymmetrical voltage conditions with a VUF of 4%

At rated load the stator and rotor losses are more significant than the iron losses. With a higher magnetization due to over voltage, the current required for torque build up is lower and consequently the rotor losses will be lower too. These effects also explain 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 (Figure 7). From this it is clear that all loss mechanisms both depend on the design and material choice and interact in such a way that for the same VUF, the efficiency can vary strongly as a function of loading and type of unbalance.

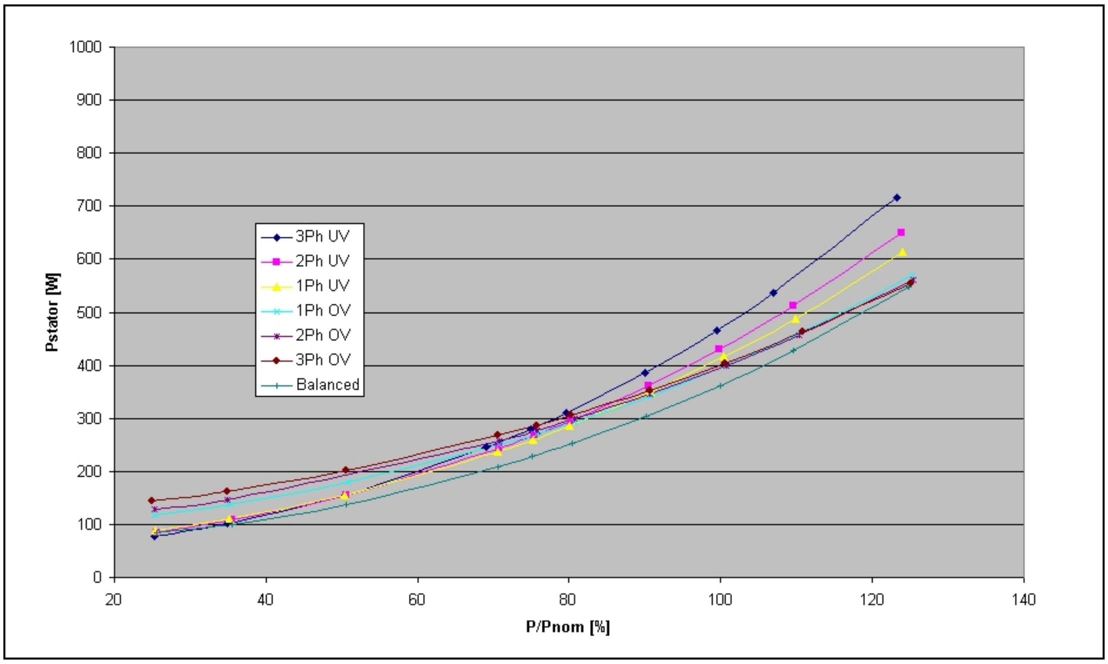

Figure 7: Stator losses as a function of the load condition of the HE-motor for the balanced voltage and six asymmetrical voltage conditions with a VUF of 4%

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 [6]. In general, the efficiency for unbalanced condition is lower than the balanced efficiency, so the losses are higher. However, the efficiency curves were measured at rated temperature. Therefore, 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. In practical conditions, in absence of protective devices or without derating, the difference in efficiency – read temperature – between balanced voltage and unbalance voltage is even worse.

Comparison with literature

In literature, other measurement results can be found indicating that in some conditions over voltage unbalanced situations yield higher rated efficiency [10]. Even though these findings also confirm that there is a certain consistency between the different unbalanced situations, care should be taken when interpreting these results. First of all, it should be noted that due to the fact that it concerns only values for rated power output, only part of the picture is given. Second, it is not clear at which temperature the different conditions were recorded. So it is not clear whether this result is the consequence of simply a horizontal shift of the characteristic or that the peak value of efficiency supersedes that of the balanced case.

Apparently, for voltage unbalance the efficiency at high loads could increase for increasing positive sequence voltage [10]. This is only true when there are no saturation effects in stator and rotor. These are characteristics of over dimensioned machines with low stator resistances and good magnetic properties (e.g. premium electrical steel).

From the measurements in the context of this paper, it could be deducted that all machines were slightly saturated at rated voltage. The machine which meets these conditions the closest is the HE-motor. For the over voltage cases, it has relatively spoken, the lowest increase in iron loss. The rotor losses decrease, as indicated above (but also see Figures 9 to 11), with respect to the balanced case. And as can be noticed from Figure 7, the combination of these two effects also makes that the stator losses have, compared to the balanced case, that specific behaviour. Namely, due to the relatively lower rotor losses, they tend to become lower than the balanced case for high load conditions.

Material & Motor Specific Issues

From Figures 2 to 4, it can be noticed that the overall detrimental effect of unbalance seems to be lower for machines with copper rotor. However, Figure 5 indicates that this is also the case for high efficient machines. An other possible way to visualise the sensitivity to unbalance is used in Figure 8, namely the difference between the average unbalanced efficiency and the balanced case efficiency.

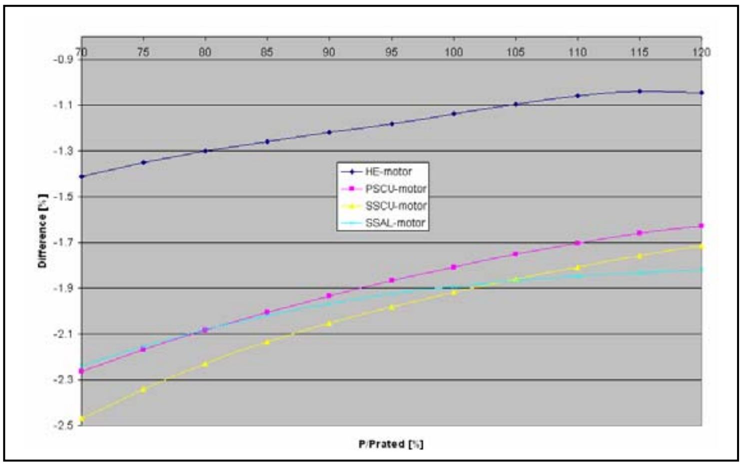

Figure 8: Difference of average efficiency of the six unbalanced voltage cases and efficiency for balanced voltage condition for loading between 70 and 120 % of rated power.

From this figure, it is clear that the high efficient machine is less prone to unbalanced voltage supply conditions. What the influence of rotor cage material choice in this context is concerned, it is too early for generalised conclusions. Additional tests on different machines are required. However, some interesting effects can be reported with regard to this matter. The curves related to the same rotor material seem to be parallel.

The combination of the unbalances and the material choices for the first three machines has an important influence on the rotor losses (Figures 9 to 11).

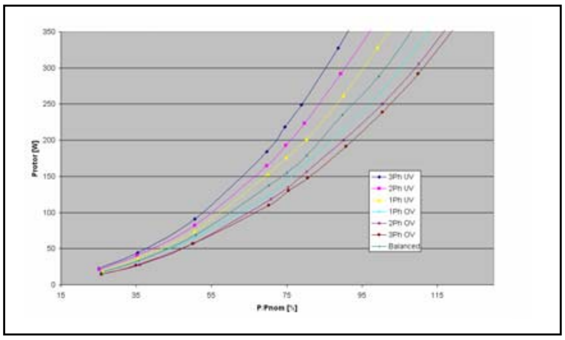

Figure 9: Rotor losses for the SSAL-motor.

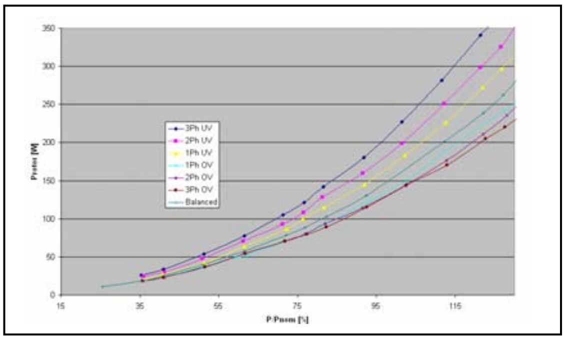

Figure 10: SSCU-motor Rotor losses.

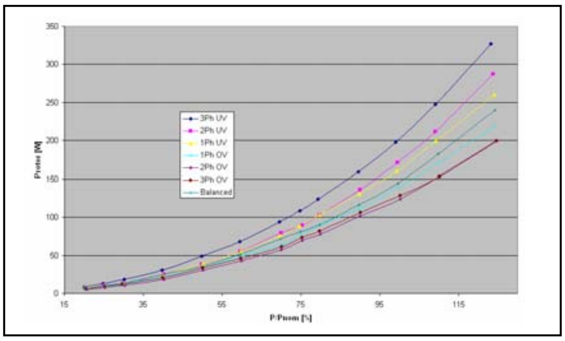

Figure 11: PSCU-motor Rotor losses.

The rotor losses, which are the slip fraction of the airgap power, decrease strongly for the transition to the copper rotor. This can be explained by the lower rotor resistance, i.e. a steeper torque vs. speed characteristic, which makes that the required slip for a certain rotor current – read torque – is lower. The additional losses show a similar behaviour for the different supply conditions. And in general, the additional losses are lowest for the PSCU-motor and highest for the SSAL-machine.

The determined iron loss for the different voltage situations of the four machines is given in Table 2. Some interesting phenomena can be indicated by means of this table. First of all, from the balanced case the influence of the premium steel can be noticed. But also the fact that the HE-motor has a better magnetic design (e.g. the stack length is slightly higher).

For the copper rotor in the standard steel machines, the span (the difference between the highest and lowest iron loss) is higher than for the aluminium motor. This can be an indication of the lower rotor resistance in combination with the influence of the reverse rotating field. The according components of rotor flux and current have compared with the positive sequence components higher frequencies. What this is concerned, the application of premium steel apparently reduces these effects, the span is reduced by half the difference. The location of the losses for the unbalanced cases with respect to the balanced one seems to be related the rotor cage material (or rotor design). For under voltage unbalanced voltage supply, the copper rotors show that two cases result in lower iron losses. The location for the HE-motor, where all the under voltage conditions result in lower iron losses, is probably related to the rotor design. However, this should be further investigated.

Table 2: Iron losses for the seven supply voltage situations for each of the four machines with the same geometrical design AND additionally the span of these losses for each machine

[w]	Balanced	3Ph OV	2Ph OV	1Ph OV	1Ph UV	2Ph UV	3Ph UV	Span
SSAL	**343**	532	493	473	363	**353**	**312**	220
SSCU	**346**	588	538	499	**364**	**335**	285	303
PSCU	312	517	478	422	**321**	**288**	258	259
HE	193	343	297	**265**	**183**	175	155	188

Conclusion

From the test results of the three machines with the same design it is clear that by introducing copper rotor technology and the application of premium steel, the standardised energy efficiency improves substantially. From manufacturers point of view this is an interesting conclusion. The balance between the constant losses and the load dependent losses changes and as a result, the maximum efficiency shifts towards higher loads.

However, the main focus lies on practical operating conditions. The sensitivity of the different motors to unbalanced voltage supply conditions was investigated. There are several aspects that influence the efficiency of a motor supplied with unbalanced voltage. Firstly, there is the type of unbalance in correlation with the load condition of the machine. This can result in remarkable differences in the distinct efficiency values for a specific motor. Second, there is an important interaction between different design considerations such as material choice, magnetic design, etc.

Depending on the machine design, average efficiency deficits of higher than 2% for a reasonable range in load conditions were found. When looking at average efficiency values for the different unbalance conditions, it can be assumed that for partial load situations the copper rotor technology gives worse efficiencies. For overload conditions, the efficiency becomes better than for the aluminium case. But it should be reminded that overload conditions are not desirable and on top of that, in general, unbalanced conditions are overload conditions. With respect to that, the efficiency values are even optimistic.

This could be explained by the magnetisation condition of the machines. Clearly, when only considering the under voltage situations, the copper rotor motors behave much better. The location of maximum efficiency indicates relatively high constant losses with respect to the load dependent losses. Further research is required to clarify if changes in design could make that these higher efficient copper rotor machines would be less prone to unbalance in general.

With the losses for the rated conditions as known data and under the assumption of constant motor temperature, the behaviour of the efficiency can be quite correctly described by a mathematical expression. This raises the question whether it should not be required to print some typical loss components on the nameplates of machines. By doing so, the engineers can have a feeling of how the efficiency characteristic will behave under practical supply conditions.

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