Comparitive Study of the Influence of Harmonic Voltage Distortion on the Efficiency of Induction Machines versus Line Start Permanent Magnet Machines

Colin Debruyne*†, Stijn Derammelaere*†, Jan Desmet*† and Lieven Vandevelde†
* Department of Electrotechnical Engineering
Technical University College Howest, Kortrijk, Belgium
e-mail: Colin.Debruyne@howest.be
† Electrical Energy Laboratory (EELAB)
Department of Electrical Energy, Systems and Automation (EESA)
Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

***Abstract*—Induction machines have nearly reached their maximal efficiency. In order to further increase the efficiency the use of permanent magnets in combination with the robust design of the induction machine is being extensively researched. These so-called line start permanent magnet machines have an increased efficiency in sine wave conditions in respect to standard induction machines, however the efficiency of these machines is less researched under distorted voltage conditions. This paper compares the influence of harmonic voltage distortion and the phase angle of the harmonic content on the overall motor efficiency of line start permanent magnet machines and induction machines.**

***Index Terms*—Permanent magnet machines, Induction motors, Energy efficiency, Power system harmonics, Power quality**

I. INTRODUCTION

Induction Machines (IM) have a lot of advantages, but mainly their robust character, in respect to many other electrical machines, is the reason why 90 % of the installed electrical machines are IM's. [1] Efficiency becomes more important for both economic and ecological reasons, therefore has the efficiency of these machines been extensively researched and improved. [2] In case of IM, the magnetizing power for both rotor and stator needs to be externally delivered, resulting in additional losses. The use of Permanent Magnets (PM) in the rotor is the most common way to tackle this problem. However, a machine consisting of only PM in the rotor is unable to start at line frequency, therefore additional startup methods are needed. If the rotor consists of both PM and rotorbars, the motor can start as a IM and once near synchronism the MagnetoMotoric Force (MMF) of the PM can synchronize with the MMF induced in the stator. In this way the machine combines the advantages of both induction and synchronous machines. This machine is commonly known as a Line Start Permanent Magnet Machine (LSPMM)

Due to the large implementation of Power Electronic convertors, background distortion will occur. The effects of a distorted voltage on the energy efficiency are well studied for standard IM's used as a motor. [3] Several standards even give an estimation of the reduced efficiency of IM in case of distorted supply voltage. [4] [3] [5] Recently also the influence of harmonic distortion on IM's as generators has been given some attention. [6] The influence of voltage harmonics on LSPMM has not yet been published. The presented research compares the energy efficiency of LSPMM and standard IM in motor operation when supplied with a distorted voltage. Within this paper the derating methods for IM supplied with a distorted voltage will be applied for LSPMM and evaluated.

II. STRUCTUAL ASPECTS OF LSPMM

In order to compare the behavior of LSPMM and IM when supplied with a distorted voltage, the electro-mechanical design of both machines has to be addressed. LSPMM have a lot of constructional aspects in common with IM. Stator winding lay-out is identical for both machines and commercial LSPMM are build according to the IEC 60034-7 [7] to facilitate changeability with standard IM. Two of the most distinctive differences are [8]:

1) The induction level of a LSPMM is not only a function of the applied voltage as is the case for a IM. [4] The presence of PM in combination with the stator MMF are determining the peak induction. Due to the more difficult construction and the increased unbalanced magnetic pull of the rotor, a larger air gap is obtained in a LSPMM in reference to a standard IM.

2) It is commonly assumed that for a LSPMM the flux rotates in synchronism with rotor. Therefore no currents are induced in the rotor. This sometimes leads

to a simplified construction of massive rotors. The massive rotor not only simplifies construction, this is also an addition to start-up the motor. A massive rotor construction will have an increased skin effect at start-up thus increasing start-up capability. The construction of a massive rotor is also more appropriate to magnetically adjusted the rotor in order to increase the flux density in the air gap.

Common rotor configurations of LSPMM rotors are presented in Fig. 1. [8]

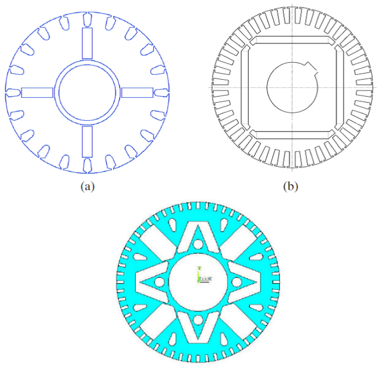
(a) (b) (c)

Fig. 1. common rotor configurations for a LSPMM

When the machine is supplied with a non sine waveform these two design parameters are assumed to have a more pronounced effect on LSPMM with respect to standard IM because:

1) The larger airgap, in combination with the presence of PM, leads to a higher magnetic reluctance. The high reluctance means a decrease of the inductivity. For the same harmonic voltage distortion, the decrease of inductivity results in larger harmonic currents thus leading to an increase of harmonic MMF in the machine and increased stator joule losses. This will result in a increased influence of the magnetization of the machine (additional magnetising losses) and an increase of torque due to these harmonics. These problems will be elucidated in Section III

2) If the rotor is constructed as a massive structure, there will be an increase of induced harmonic currents and a more pronounced skin effect in the rotor. When the rotor temperature increases, the induction of the PM will decrease. Although of interest, the skin effect will be not be further addressed within this paper.

3) As the rotor is rotating at synchronous speed, harmonic content will interact in a very specific manner. Harmonic evaluation cannot be done for each harmonic component. Interaction of different harmonic components will be explained in paragraph III-E

III. COMPARISON OF THE LOSSES

A. *Magnetising losses of IM*

IM are designed to work close to the saturation level conditions. In this way the magnetic material is used at its optimum weight/energy ratio. For commonly used magnetic steels an induction of 1.2T to 1.5T is targeted. According to the Steinmetz equation Eq. 1, the magnetizing losses are function of the peak induction. Although the Steinmetz equation is only valid for sine wave voltages, the equation does give an indication on the evolution of the magnetizing losses when a IM is supplied with distorted voltages.

$$P_{iron} = C_m f^{\alpha} B_p^{\beta} \quad (1)$$

With P_{iron} being the iron losses/magnetization losses [W], C_m the first Steinmetz coefficient, f the frequency [Hz], α the second Steinmetz coefficient, B_p representing the peak induction [T] and β the third Steinmetz coefficient. [9]

For standard IM the average voltage is the main parameter to calculate the peak induction. This is also the case if the machine is supplied with a distorted voltage. In order to calculate the peak induction level when the machine is working under distorted supply voltage conditions, Eq. 2 can be used.

$$\frac{V_{h_avg}}{V_{avg}} = \frac{\Phi_{max}}{\Phi_{rmax}} = \frac{\sum_h \frac{V_{hRMS}}{h} cos(\phi_h)}{V_{RMS}} \quad (2)$$

With $\mathrm{V_{h_avg}}$ the total average voltage of the distorted voltage[V], $\mathrm{V_{h_avg}}$ the average voltage of a ideal fundamental sine wave voltage,$\mathrm{\Phi_{max}}$ the maximum peak induction when supplied with distorted voltage[T],$\mathrm{\Phi_{rmax}}$ the reference peak induction, h the harmonic order,$\mathrm{\phi_h}$ the harmonic angle referred of the harmonic voltage of order h in reference to the fundamental component[°].

In [4] it is shown that for IM the magnetizing losses are function of the harmonic magnitude, order and phase angle. The magnetization of the IM is mainly function of the applied voltage. For a fifth harmonic with a phase angle of 0° the average voltage is higher in reference to the same amount of distortion but with a shift a harmonic phase of 180°. This will lead to an increase of magnetizing losses if the harmonic phase content is in phase and thus a decrease of overal efficiency.

B. *Magnetising losses of LSPMM*

For continuous loading of a LSPMM, the peak induction is a function of the characteristics of the permanent magnet, the air gap line and the MMF in the stator. Since the MMF in the stator is function of the loading ratio of the machine, the resulting induction is function of the loading ratio. The vector sum of both MMF in rotor and stator determines the saturation point of the machine. For the modeling of a synchronous machine, it is common practice to use the Thevenin equivalent scheme. However, to show the interaction of the stator and rotor MMF the Norton equivalent scheme is used.(Fig. 2)

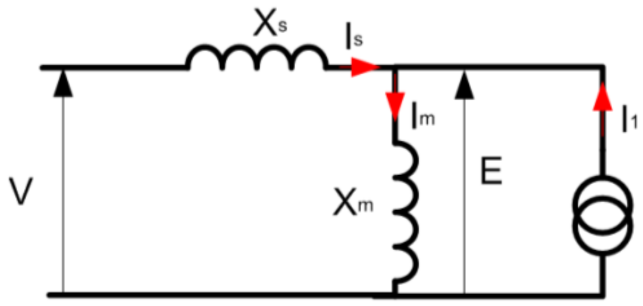

Fig. 2. Norton Equivalent scheme of LSPMM

I_1 is the current [A] equivalent with the MMF [Aw] from the PM's, I_s is the current equivalent with the stator MMF, and I_m is the resulting magnetizing current equivalent to the resulting MMF. The resulting MMF determines the resulting induction level and thus the induced voltage E [V]. The clamp voltage V in [V] is the combination of the induced voltage and the voltage drop over the stator leakage inductance X_s.

The induction level inside the LSPMM will shift linearly as function of the loading. This is due to the fact that PM machines work in the second quadrant of the magnetizing characteristic. When dimensioning a PM machine one tries remaining on the first part of the demagnetization characteristic.(Fig. 3) This is done to prevent permanent demagnetization of the magnets. As the MMF in the stator is reduced the induction will increase according to the recoil line.

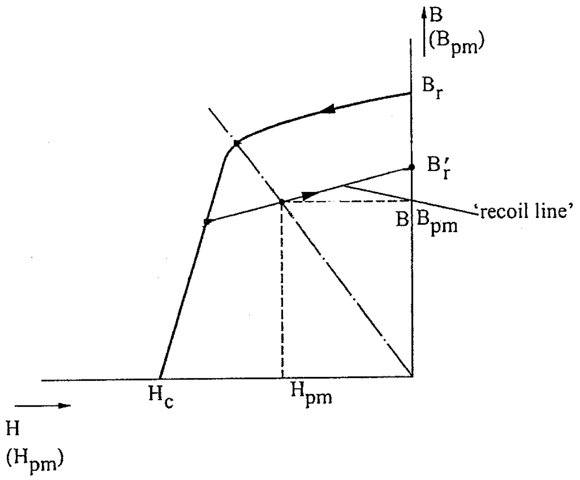

Fig. 3. Demagnitisation Characteristic of a PM

In which the B_{PM} denotes the resulting induction level in the machine, B_r the remanent induction level,and H_{PM} the MMF level of the PM's.

LSPMM are always designed in order that the stator is electrically excited to produce demagnetisation. [10]. When a LSPMM supplied with a distorted voltage, the average voltage will change as a function of the harmonic phase angle. For a fifth harmonic with a phase angle of 0° the average voltage is higher in reference to the same amount of distortion but with a shift a harmonic phase of 180°. The reduced demagnetisation of the stator due to the increased average voltage, results in an overall decrease of MMF. The decrease of MMF results in a higher peak induction and will lead to an increase of magnetizing losses.

The previous deduction concludes that, concerning the magnetizing losses, the influence of the harmonic phase angle is similar for LSPMM in respect to IM.

C. Torque reduction of IM

When a distorted voltage is applied to an IM, additional torques are generated. If the torque production for IM is to be analyzed, a linear induction is assumed. This assumption is valid due to the fact that energy efficient machines are constructed with materials which have a small hysteresis band and sufficient magnetic material in order to decrease the magnetizing losses.

The fact that a linear induction may be assumed, facilitates the calculation of the average torque of an IM when supplied with a distorted voltage. Due to linearization, torques originating of separate harmonics can be calculated independent of each other, consequently superposition of harmonic torques is allowed.

In order for an IM to generate torque, current has to flow in the rotor bars. Therefore the rotor rotates at a mechanical speed slightly differing from the synchronous speed of the magnetic field inside the machine. The parameter s, often referred to as slip value, is the difference between the mechanical rotation speed and the rotation speed of the fundamental magnetic field. The frequency of the induced currents in the rotor originate due to difference between the harmonic content of the induction and the actual mechanical speed of the rotor.

If Ω_{m} is the mechanical speed of the rotor, ω_{s} the electrical speed and N_{p} the number of pole pairs and Ω_{s} the synchronous speed:

$$\Omega_{\mathrm{m}} = (1-s)\Omega_{\mathrm{s}} = (1-s)\frac{\omega_{\mathrm{s}}}{N_{\mathrm{p}}} \tag{3}$$

The frequency of the induced harmonic currents in the rotor is function of the relative movement of the rotor in reference to these harmonic MMF fields. [Eq. 8].

$$\Omega_{\mathrm{sh}} - \Omega_{\mathrm{m}} = (1-6k)\frac{\omega_{\mathrm{s}}}{N_{\mathrm{p}}} - (1-s)\frac{\omega_{\mathrm{s}}}{N_{\mathrm{p}}} = (-6k+s)\frac{\omega_{\mathrm{s}}}{N_{\mathrm{p}}} \tag{4}$$

Parameter Ω_{sh} is the synchronous speed of the MMF induced by the harmonic current of order h. It is common practice to denote harmonic orders in the form of $h = 1 - 6k$.

In this expression, k not only denotes out the harmonic order, it also indicates the sequence of the field. If k equals 1, a h of -5 is obtained and the value of $-6 + s$ is obtained in Eq. 4. If k equals -1, h equals $+7$ and the value of $6 + s$ is obtained. If k equals 0, the fundamental value of s is obtained. The previous indicates that a fifth harmonic generates a invers field and thus a breaking torque in motor operation. A seventh harmonic generates a direct field.

In case of an IM a fifth and seventh harmonic voltage distortion will generate different frequencies. Therefore there is no interaction between different harmonics and this also confirms that, if the harmonic phase angle of the distortion is altered, this will not affect the frequency of the injected rotor current. Although harmonic field and current of the same order will generate fundamental torque, it can shown that shifting the phase angle of a harmonic voltage does not influence the average torque. For a more detailed analysis there can be referred to [6].

D. Torque reduction of LSPMM

If a LSPMM is supplied with a distorted voltage, the average torque is a combination of the synchronous torque originating from the PM's and a asynchronous torque due to a higher frequencies in the supply voltage.

In case of a asynchronous torque the value of $s \neq 0$, for a synchronous torque the value of $s = 0$. For LSPMM supplied with a pure sine wave the value of s equals zero and thus no currents are induced inside the rotor. In contrast, asynchronous torques originate due the fact that higher frequencies in the current, create fields that rotate at a higher frequency. When a machine, either IM or LSPMM, is supplied with a distorted voltage, harmonic MMF's will induce harmonic currents in the rotor.

The main problem in estimating the average torque is that a Fourier Transform cannot be used in case of a LSPMM. The Fourier Transform is only valid for a linear function, which complies to the criterion as stated in Eq. 5

$$f(a + b) = f(a) + f(b) \tag{5}$$

The induction level of a LSPMM can be linearized according to the recoil line in Eq. 7 and as shown in (Fig. 3) :

$$B_{PM} = B_r + \mu_m H_{PM} \tag{6}$$

In which the $\mathrm{B_{PM}}$ denotes the resulting induction level in the machine,$\mathrm{B_r}$ the remanent induction level, μ_m the relative permeability, and $\mathrm{H_{PM}}$ the MMF level of the PM's.

However, Eq. 7 dues not comply with the criterion stated in Eq. 5, thus a commonly used Fourier Transform can not be used to analyze the interaction between the MMF and the induction. The latter implies that a harmonic content in the supply voltage will interact with the fundamental induction level and thus the fundamental torque. As the harmonic content will shift this will influence the synchronous torque, as stated in the previous, but it will also influence the asynchronous torque. Simple analytical equations cannot be deducted to calculate the influence of harmonic voltage distortion on the average torque production.

E. Interaction of different harmonics for LSPMM

The voltage distortion of the grid does not hold one single frequency of distortion. [11] [12] Besides a fifth harmonic also seventh, eleventh etc are present. For IM's the value of s differs from zero and thus the fifth and the seventh harmonic induce different currents in the rotor. Eq. 4. When the additional losses due to skin effect wants to be calculated the harmonic components can be evaluated separatly in case of a IM.

For LSPMM the rotor rotates at synchronism with the fundamental frequency. Therefore the parameter s equals zero in Eq. 4. This means that for a fifth harmonic, k equals 1, and for a seventh harmonic, k equals -1, the same frequency is induced namely 6. If one wants to estimate additional losses due to harmonic distortion the fifth and the seventh harmonic cannot be examined separately, in contradiction with IM's.

Although the conclusions of section III-D and of section III-E are topics of interest, this problem will not be adressed within this paper.

IV. DERATING OF IM SUPPLIED WITH A DISTORTED VOLTAGE

In several normative references an estimation is given of the reduction of efficiency for a IM supplied with a distorted supply voltage. However, these derating methods have not yet been analyzed if applicable for the derating for LSPMM.

In order to determine the additional losses in accordance to the IEC60034-17 the Harmonic Voltage Factor HVF is calculated as:

$$HVF = \sqrt{\sum_{h>1} \frac{(v_h)^2}{h}} \tag{7}$$

v_h being the per unit value of the magnitude of the voltage of harmonic order h in reference to the magnitude of the fundamental voltage. Notice that in Eq. 7 no phase reference of the distinctive harmonics is needed. Triple n-harmonics are not considered within the IEC60034-17 nor the NEMA MG1. Once the HVF is calculated a Derating Factor (DF) can be derived by using Fig. 4.

For a given efficiency at sine wave conditions, the derated efficiency of the DOL IM supplied with distorted voltage can be estimated using the results obtained in Eq. 7, Fig. 4 and solving Eq. 8

$$\eta_c = \frac{DF^2}{\eta^{-1} + DF^2 - 1} \tag{8}$$

For η_c the derated efficiency for a certain DF, DF the derating factor as function of the HVF and η the reference

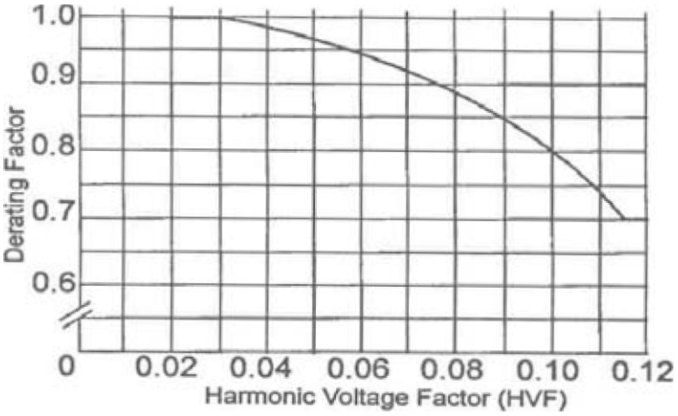

Fig. 4. Derating Factor as a Function of HVF

efficiency, which is the efficiency at sine wave conditions. By means of example the η_c for 10% fifth harmonic distortion is obtained by calcuating a HVF of 0.044, the corresponding DF is 0,975 and with the reference efficiency is 87,5% the calculted reduced efficiency is 86,9%.

V. MEASUREMENTS

A. Goal of the measurement

Measurements will be performed to analyze the influence of harmonic voltage distortion on the overall energy efficiency of both LSPMM and IM. These measurement results will then be compared and matched to existing derating methods.

In order to prevent interaction of different harmonics [Section III-E], only a single harmonic distortion will be added to the fundamental waveform. Higher order of harmonics have less influence on the magnetic field, therefore, the harmonic that has the most dominant influence on the rotating magnetic field is the fifth harmonic.

Within the measurements the efficiency of the machine is measured, and this is done according to the IEEE 112-B (2004). Testing the efficiency at steady state conditions of the machine is done by direct measurement of input - output power. When the direct method is used, the output torque and the speed of the machine are measured to determine the mechanical output power. The electrical input power is measured, and the efficiency is the ratio of the output/input active power.

At first the measurement is done at pure sine wave conditions, this is the reference efficiency. The fifth harmonic is added to the fundamental, the magnitude is raised from 8%,10% ,12% up to 15% and this is done for both in phase and in anti-phase. The measured efficiencies of both IM and LSPMM are then compared.

B. set-up

Fig. 5 shows the general test set up. The tested IM is a standard of-the-shelf 4kW 50Hz DOL IM EFF 2 with a rated speed of 1440 rpm and a rated output torque of 26.7 Nm. The LPSMM is one of the first of-the-shelf 4kW 50Hz DOL LSPMM with a rated speed of 1500 rpm and a rated output torque of 25 Nm. In order to load the machines a 22kW DC machine in closed loop torque control with speed limitation is used.

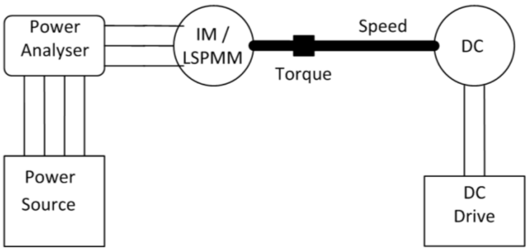

Fig. 5. General test setup

The voltage source is a free programmable power source with a rated power of 240kVA. For the measurement of the electrical input power a Voltech PM3000 power analyzer is used. Currents were measured directly over the internal shunt with a current range of 30Apeak. Speed is measured with the tachometer used in the closed loop of the DC machine. Torque is measured with external torque measurement equipment.

C. Measurements

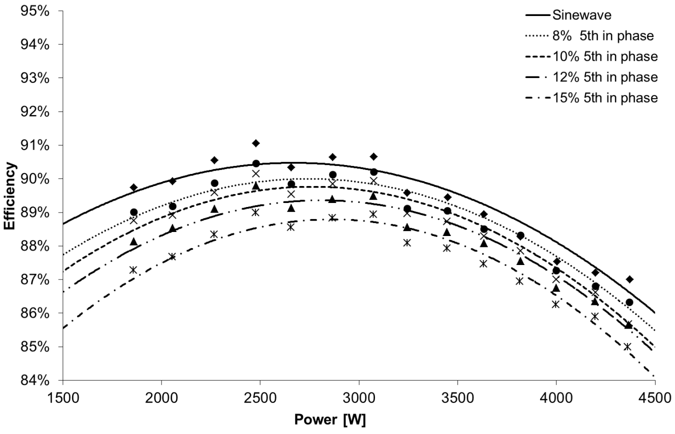

Fig. 6. Efficiency of IM when supplied with a distorted voltage

TABLE I
ABSOLUTE VALUES OF THE EFFICIENCY AT NOMINAL LOADING FOR IM

Phase angle	0	180
$8\%5^{th}$	87.30%	87.30%
$10\%5^{th}$	87.00%	87.00%
$12\%5^{th}$	86.8%	86.9%
$15\%5^{th}$	86.30%	86.30%

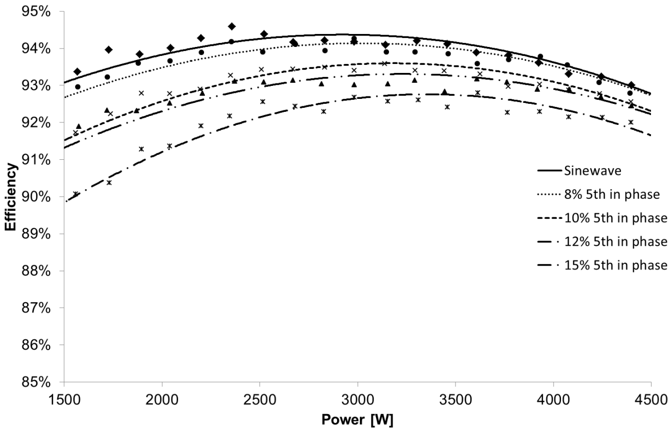

Fig. 7. Efficiency of LSPMM when supplied with a distorted voltage

TABLE II
ABSOLUTE VALUES OF THE EFFICIENCY AT NOMINAL LOADING FOR LSPMM

Phase angle	0	180		0	180
$8\%5^{th}$	93.78%	93.32%	$8\%7^{th}$	93.72%	93.86%
$10\%5^{th}$	93.03%	93.18%	$10\%7^{th}$	93.80%	93.74%
$12\%5^{th}$	92.90%	92.97%	$12\%7^{th}$	93.18%	93.37%
$15\%5^{th}$	92.29%	92.68%	$15\%7^{th}$	92.57%	93.02%

D. Evaluation of the measurements

Although the variation of absolute efficiency of both machines as function of the distorted voltage is of importance in this study, the absolute efficiency when supplied with a pure sine wave voltage is being used as a reference. Therefore absolute efficiency is measured and validated. The measured efficiency of the DOL IM at nominal load is 87,5% which complies to the EFF2 efficiency stated in [13]. In case of the DOL LSPMM at nominal load, measured efficiency is 93,8% corresponding to manufacturer data [10].

The measurements for IM, listed in Table.I, show that the efficiency reduces as the harmonic magnitude is increased. Shifting the phase angle of the fifth harmonic has little to no influence on the harmonic losses. This is due to the fact that magnetizing losses are minor losses in reference to stator joule losses at nominal loading. When regarding partial loading the magnetizing losses do become the dominant losses and the influence of the harmonic phase angle is measurable [Fig.6] as stated in [6]. For 15% fifth distortion the efficiency drops with 1.2%.

When the results for the LSPMM are evaluated from Table. II, the efficiency also decreases as the harmonic magnitude is increased. The harmonic phase angle has a noticeable influence on the overall efficiency. If the harmonic phase angle is in anti-phase the general trend is that the efficiency is higher than for the same harmonic content with a phase angle of 0°. For 15% fifth distortion the efficiency can be reduced with 1.5%.

A 15% fifth distortion ratio leads to a reduction of efficiency of 1.2% for IM and a maximum reduction of 1.5% for LSPMM. The previous evaluation confirms that LSPMM are more sensitive to harmonic voltages in reference to IM. However, if the absolute efficiency is evaluated, the LSPMM is still more efficient referred to IM.

For a LSPMM not only the harmonic magnitude is increased. Additional measurements were also performed for the seventh harmonic, results are listed in Table.V. Similar trends between fifth and seventh harmonic distortion are noticeable in Table.II, but as already stated the seventh harmonic content has a reduced influence in reference to the fifth. This is due to the damping of the stator leakage inductance.

E. Comparison to derating methods

The first objective within this paper was to evaluate the efficiency of the LSPMM when supplied with a distorted voltage. A second topic of interest is if normative derating methods for IM supplied with distorted voltage are also applicable to LSPMM. The reference efficiencies of both IM and LSPMM are used to estimate the reduction of efficiency as explained in section IV. The results of the calculations are compared to the measured efficiencies. The complete analysis is summarized in Table. I and Table. II.

TABLE III
DERATING OF A IM AT NOMINAL LOADING

Phase angle	0	180	HVF	DF	η_c
$8\%5^{th}$	87.30%	87.30%	0.036	99%	87.28%
$10\%5^{th}$	87.00%	87.00%	0.045	97.5%	86.95%
$12\%5^{th}$	86.8%	86.9%	0.054	96%	86.58%
$15\%5^{th}$	86.30%	86.30%	0.067	93%	85.82%

TABLE IV
DERATING FOR A FIFTH HARMONIC OF A LSPMM AT NOMINAL LOADING

Phase angle	0	180	HVF	DF	η_c
$8\%5^{th}$	93.78%	93.32%	0.036	99%	93.58%
$10\%5^{th}$	93.03%	93.18%	0.045	97.5%	93.39%
$12\%5^{th}$	92.9%	92.97%	0.054	96%	93.20%
$15\%5^{th}$	92.29%	92.68%	0.067	93%	92.79%

TABLE V
DERATING FOR A SEVENTH HARMONIC OF A LSPMM AT NOMINAL LOADING

Phase angle	0	180	HVF	DF	η_c
$8\%7^{th}$	93.72%	93.86%	0.03	100%	93.7%
$10\%7^{th}$	93.80%	93.74%	0.038	98%	93.46%
$12\%7^{th}$	93.18%	93.37%	0.045	97.5%	93.39%
$15\%7^{th}$	92.57%	93.02%	0.057	95%	93.07%

When the calculated derated efficiency is compared to the measured efficiency for IM (Table. III) the estimation of the losses is quite accurate for relative low distortion ratios(up to 10%). For high distortions the calculated efficiency is actually lower than the measured efficiency. A possible explanation could be the fact that the measured machine is a 4kW machine. Damping of harmonics due to the stator leakage induction can be expected be more dominant for small power ratings of motors. For larger motors the damping due to the stator leakage inductance will be less, and the overall reduction will be more pronounced. Since the derating method should be valid for different power ratings of machines, it does not include this damping effect of the stator leakage inductance. In general, the derating factors do give a fairly good estimation of the reduced efficiency.

If the estimated efficiency is compared with the measured efficiency for LSPMM, differences are noticeable. For the fifth harmonic distortion (Table. IV), the actual efficiency is always lower than the estimated efficiency. The fact that the phase angle has not been taken into account to calculate the reduced efficiency leads to a large error. If the seventh harmonic distortion is evaluated (Table. V), the differences are less noticeable.

Two possible reasons are given for errors.

1) For IM at nominal loading the stator joule losses are the dominant losses, however, for LSPMM the magnetizing losses are the dominant losses. The influence of the phase angle will be more pronounced for LSPMM as is explained in Section III

2) When fifth and seventh harmonic content is evaluated for LSPMM additional torques have to be taken in to account. In motor operation a fifth harmonic generates a inverse field and torque, further reducing efficiency. However, a seventh harmonic generates a direct field and thus a positive torque. This positive torque could lead to reduction of the overal losses and thus a slightly higher efficiency.

Both the effects lead to a different behavior of IM compared to LSPMM when supplied with a distorted voltage. As normative references are designed specifically for IM, the derating methods give less accurate estimation of reduction of efficiency for LSPMM.

VI. Conclusions

In this paper the influence of harmonic voltage distortion on the efficiency of IM and LSPMM is evaluated based on practical measurements. The measurements indicate that the reduction of the efficiency is more pronounced in case of a LSPMM in reference to a IM. The influence of the phase of the harmonic voltage is not very dominating in case of a IM, the contrary is so for a LSPMM. The harmonic phase angle has a significant impact on the resulting efficiency, if the harmonic phase angle is in phase the lowest efficiency is obtained. This is similar to the effect of the phase angle in case of a IM.

In order to explain these results, constructional differences between the machines have been emphasized. For IM a Fourier Transform can be used to estimate electrical quantities such as induced rotor currents, resulting rotor current or skin effect inside the rotor. Every harmonic induces a specific frequency due to the fact that the slip value (s) is never zero, therefore superposition of the losses is allowed.

In case of LPSMM, two problems occur that adds difficulty to analytical computation of different electrical quantities. First of all, induction cannot be linearized at the origin as there is no one-to-one relation between the stator current and the resulting induction. Therefore it is not possible to estimate additional losses, average torque and the reduction of efficiency on a pure theoretical basis for LSPMM. Secondly, for LSPMM the slip value (s) equals zero. It is shown that specific harmonic components will interact. Simple superposition of the losses per frequency component is not allowed in this case. Within this paper only a single harmonic is added to the stator voltage in order to compare a IM and a LSPMM.

VII. Further research

As the LSPMM is becoming a commercial product the previous research is of utmost importance. The research will be extended to a more detailed torque ripple analysis. Furthermore the machine will be modeled by means of Finite Element Modeling enabling a more profound loss evaluation. This approach will also be more convenient to evaluate the induction level, the interaction of harmonics on fundamental induction and resulting torque.

Further research will also include multiple harmonics superimposed on the voltage. The order of these harmonics will be chosen in such a way that these harmonics will interact. By shifting the harmonics the overall efficiency will be evaluated.

The LSPMM is also very suitable as a direct coupled generator for dispersed generation, for example in micro CHP and small wind turbines. For LSPMM generators directly coupled to the grid, the influence of harmonic voltages on the efficiency will be researched.

VIII. acknowledgement

The authors wish to thank the Flemish Hercules foundation for granting the programmable power source of 240kVA, which was an important analysis equipment in order to do the research work on machine efficiency.

References

[1] W. Deprez, “Energy efficiency of the induction machines: a critical assessment,” Ph.D. dissertation, KU Leuven University, 2008.

[2] K. Stockman, S. Dereyne, D. Vanhooydonck, W. Symens, J. Lemmens, and W. Deprez, “Iso Efficiency Contour Measurement Results for Variable Speed Drives,” in *Electrical Machines (ICEM), 2010 XIX International Conference on*, 2010, pp. 1–6.

[3] E. Quispe, G. Gonzalez, and J. Aguado, “Influence of Unbalanced and Waveform Voltage on the Performance Characteristics of Three-phase Induction Motors,” pp. 1–5.

[4] C. Debruyne, J. Desmet, and S. Derammelaere, “Derating Factors for Direct Online Induction Machines when supplied with voltage harmonics : a critical view,” *IEMDC*, pp. 1063–1067, 2011.

[5] "NEMA Standards Publication MG 1-2006 Revision 1-2007 Motors and Generators," *ReVision*, 2007.

[6] C. Debruyne, J. Desmet, B. Vervish, and S. Derammelaere, "Influence of Harmonic Voltage Distortion on Asynchronous Generators," *SDEMPED*, no. Im, pp. 159 –164, 2011.

[7] "IEC 60034-7 ed2.1 Consol. with am1 : Rotating electrical machines - Part 7: Classification of types of construction, mounting arrangements and terminal box position (IM Code)," p. 49, 2001.

[8] X. Feng, L. Liu, and Z. Y., "Super Premium Efficient Line Start-up Permanent Magnet Synchronous Motor," in *ICEM 2010*, 2010.

[9] F. D'Hulster, "Optimisation platform for torque control of 8/6 SRM," Ph.D. dissertation, KU Leuven, 2005.

[10] "WQuatro motordata -0.55-7.5 kW." [Online]. Available: http://catalogo.weg.com.br/TEC_CAT/tech_motor_tab_web.asp

[11] S. Bhattacharyya, "Power Quality Requirements and Responsibilities at the Point of Connection," Ph.D. dissertation, T.U. Eindhoven, 2011.

[12] "EN50160: Voltage Characteristics of electricity supplied by public electricity networks," 2010.

[13] A. Almeida, F. Ferreirra, J. Fong, and P. Fonseca, "Europea Ecodesign Deirective on Energy- Using Products (EUP's), Project LOT 11 Motors," Coimbra, p. 2008.