Harmonic effects on Induction and Line Start Permanent Magnet Machines

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Abstract

Power Electronics (PE) are implemented in a wide variety of appliances, either to increase its controllability or energy efficiency, or simply because a DC supply is needed. The massive integration of rectifiers has resulted in a decrease of the supply voltage quality. Although PE have enabled the end user to control electrical machines, the resulting distortion inversely affects Direct On-Line (DOL) machines. In this paper a review is presented of the influence of these supply anomalies on Induction Motors (IM). The suggested problems have already been subject of much study. However, as new DOL technologies are emerging, for example Line Start Permanent Magnet Machines or Induction Generator systems, the influence of supply distortion on these systems should also be considered. This paper will present a comprehensive overview of the loss mechanisms, the magnitude of the losses and the impact of these losses on operation of IM, LSPMM and IG.

1. Introduction

Both due to economic and ecological incentives, energy has become a scarce product. The electric consumption is a significant part of the total energy consumption and consequently the complete chain of generation, transportation and usage of electricity should be optimized. The usage of electrical energy is often optimized by controlling the output of electrical equipment towards the desired value. Advances in Power Electronic (PE) energy conversion have led to an optimization of electrical equipment. Practical examples of PE controlled energy conversion are dimmable halogen lighting, low and high pressurized discharge lights, variable speed drives (VSD) for Induction Machines (IM) etc. Additional to the advantages of PE in terms of energy optimization, a lot of PE is also used for DC supply in for example IT equipment, DC arcing or electrolysis.

AC/DC converters, cited as rectifiers, are generally build with passive components. Inherent to the operation of diodes, does the discretization of current imply a non-sinusoidal current demand. In combination with the present grid impedance this current distortion results into a distortion of the supply voltage. In Section 2 the nature and limits of the supply voltage at end user are presented.

If the electrical power consumption at industrial plants is regarded, more than 65% of all generated power is consumed for electromechanical conversion. IM have several advantages in respect to other electric motors and as a result a lot of effort has been done to increase the efficiency of these machines (Section 3). IM have one disadvantage, the fact that the mechanical speed of the machine is directly coupled to the frequency of the supply voltage, which limits its flexibility when supplied directly from the grid. Although the usage of VSD can adjust the supply frequency, only 25% of the newly installed machines are supplied from a VSD.

A lot of efforts are done to increase the efficiency of IM, however, distortion of the supply voltage does inversely affect the efficiency of IM. Although this effect is well known, it is often neglected or marginalized. If the actual limits of the supply distortion are taken into account, a reduction of efficiency of more than 1% is not uncommon. This one number also indicates that the influence of supply voltage distortion can undo a lot of efforts of motor efficiency enhancement. In Section 4 the influence of supply voltage distortion on IM is summarized and confirmed by measurements.

The efficiency of the standard IM is practically limited to IE3. This is due to the fact that the magnetizing power for the rotor has to be delivered through the stator. The integration of Permanent Magnets (PM) is one way to tackle the problem and still maintaining the DOL operation. If the motor would consist of only PM, the motor would be unable to start up at line frequency. The combination of PM with a standard IM rotor cage results in a machine which is able to start up as a standard IM and once near synchronism, the PM can synchronize with the magnetic field in the stator. This machine is commonly referred to as a LSPMM.

However, if the LSPMM is to become the next evolutionary step of IM the influence of supply voltage distortion on LSPMM should be addressed. Although attractive, in Section 5 it will be elucidated that straight forward comparison of the loss mechanisms for an LSPMM and a standard IM can result in serious miscalculations and/or estimations.

Electrical machines are responsible for 50% of the total electric consumption worldwide. For the industry the electrical machines consume up to 65% of the total electrical energy. Almost 90% of the installed power of machines that convert electrical energy to mechanical energy are IM. This essentially led to the machines being optimized for motor operation. Secondly, nearly all of the studies which examine the influence of distorted voltages are focused towards motor operation.

Both consumption as electrical generation should also be performed with the highest possible efficiency and overall yield. The rise of decentralized production such as small wind, hydro, Combined Heat Power (CHP) or Organic Rankine Cycle (ORC) power, resulted in an increased interest towards Induction Generators (IG). However, anomalies in the supply voltage also affect the operation and efficiency of IG systems. Although IM and IG are the same machine, in Section 6 it will be illustrated that the use of IM loss models, derating methods etc, are insufficient to estimate the effect of harmonic distortion on the energy efficiency of IG.

2. End user voltage distortion

Estimation of end user voltage quality has proven to be difficult, as it is function of many parameters such as the loads connected to the grid, the grid impedance and the background distortion. In order to give some reference to the voltage quality, studies generally refer to the normative reference EN50160, which defines the voltage quality at Point of Common Coupling (PCC). This approach however does not include the distortion generated at the internal low voltage grid. Consequently, the voltage quality is overestimated, as is the overall energy efficiency of electrical appliances. This chapter results in concrete values and estimation guidelines of the amount of distortion of the voltage supplied at loads, taking into account both background distortion and internally generated distortion. These results will be implemented to give more accurate estimations concerning energy efficiency of electrical loads such as DOL IM.

Most of the current distortion, and therefore the resulting voltage distortion, is generated by PE converters. The combination of the grid impedance and the nature of the current distortion, namely single or three phase loads, will determine the resulting voltage distortion. The background distortion is limited by standards such as the EN50160 to 8%. In order to have an idea of the actual background distortion, 42 measurements according to the EN50160 are presented for both large power industrial sites (35) and sites situated in urban areas (7) Fig. 1. If the generated distortion is superimposed on the already present background distortion, the resulting voltage distortion at end user can be simulated and the results are presented in Fig. 2. [3]

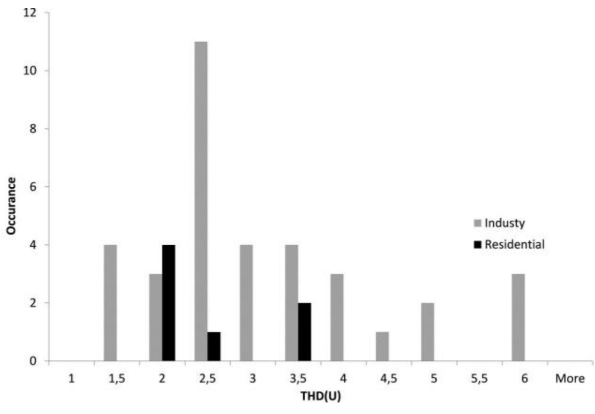

Fig. 1: 95% occurrence THD(U) values obtained by EN50160 analysis for 42 sites

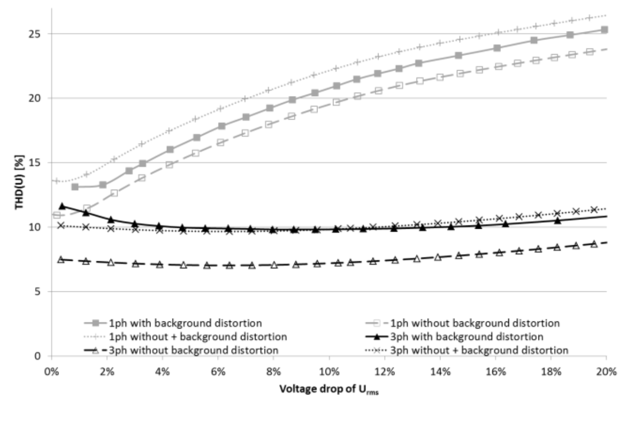

Fig. 2: Variation of THD(U) with shifting grid impedance for single and three phase rectifiers including background distortion

From Fig. 2 it is clearly illustrated that the limits of voltage distortion can well exceed the limits stated by the EN50160. A limit of 12% distortion can be calculated, while still complying to all the standards and design procedures. Harmonic mitigation equipment, such as active filters, can significantly reduce the current distortion ratio, consequently, this also suggests that active filters can have a positive effect on the resulting voltage distortion. The effect of harmonic filtering to both the resulting current and voltage distortion has been monitored for 2 separate industrial installations and the results are listed in Table 1.

Table 1: Measurements of 2 industrial sites of the reduction of THD (I) and THD (U) by active filtering

	THDU			THDI		
	L1	L2	L3	L1	L2	L3
Filter inactive (Company 1)	5.67	5.93	6.22	18.99	18.84	19.14
Filter active (Company 1)	1.99	2.00	2.06	2.42	2.91	2.34
	L1,L2,L3 (AVG Value)			L1,L2,L3 (AVG Value)		
Filter inactive (Company 2)	6.39			16.20		
Filter active (Company 2)	3.72			3.67		

The values of Table 1 are measured values, however, it is delicate to generalize or even predict the effect of filtering harmonic currents in relation to the present distortion. The influence of the filtering to the present voltage distortion is function of the filter settings, the physical location on site and the power relation between the installed filter and injected current distortion. Table 1 does indicate the positive effect of reducing current harmonics and the relation to the present voltage distortion.

3. Increasing the energy efficiency of IM

Currently, almost 70% of the world's electrical energy is consumed for electro-mechanical energy conversion and 90% of this power is converted by standard Squirrel Cage Induction Machines (SCIM). If the efficiency of IM's is to be increased this can be achieved at every design parameter of the machine. Fig. 3.

In order to uniform the efficiency of IM, the IEC has introduced a classification system (IEC 60034-30) which states the efficiency, from IE1 up to IE4 as listed in Table 2.

Table 2: Rated efficiency levels for commercial 50-Hz, 4-pole LSPMSMs up to 7,5 kW and IE2-, IE3- and IE4-class limits defined in IEC60034-30/31 [9].

	Frame	80	80	L90S	90L	100L	100L	112M	132S	132M
	Rated output (kW)	0,55	0,75	1,1	1,5	2,2	3,0	4,0	5,5	7,5
Efficiency	LSPMSM	84,2	87,5	87,6	88,3	90,2	90,4	91,7	92,4	92,8
	IEC IE4		85,6	87,4	88,1	89,7	90,3	90,9	92,1	92,6
	IEC IE3		82,5	84,1	85,3	86,7	87,7	88,6	89,6	90,4
	IEC IE2		79,6	81,4	82,8	84,3	85,5	86,6	87,7	88,7

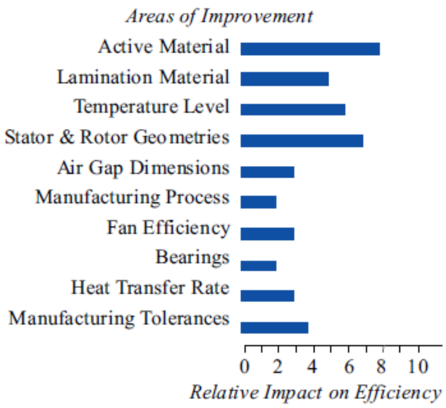

Fig. 3: Impact of the possible areas for improving the motor performance

A lot of research is performed in introducing better active materials, such as in Diecast Copper Rotors (DCR) or increasing the performance of the lamination steel. Because an energy efficient machine dissipates less power, this not only results in a reduced power consumption or operating cost, additionally this implies a direct decrease of the operating temperature in the different motor components [7].

From Table 2 it is observed that nearly every step of efficiency increase is varying approximately 3% points. However, these efficiency levels are valid for sine wave voltages. In the latter it will be pointed out that the efficiency reduction caused by voltage anomalies can significantly reduce the overall efficiency of an IM. If this reduction is within the same order of magnitude as the efficiency enhancement from for example IE3 to IE4 , this effect should be taken into account.

4. The effect of harmonic Voltage Distortion on IM

The effects distorted supply voltage are numerous as it affects almost every single operational parameter of the machine, such as output torque, torque ripple, motor temperature, vibrations, bearing stress etc. However, as this paper focuses on the additional losses due to harmonic voltages, some key effects are listed.

1. The higher frequencies force the current to flow on the outer rims of the conductor. This effect is known as the “skin effect”. However, for IM this effect is predominantly present in the rotor bars and is accordingly addressed to as the “deep bar effect”. This effect is far less pronounced in the stator, due to both the reduced section of the stator coil windings and the relatively low frequencies considered (<40 order of harmonic).

2. The deep bar effect results in a reduced active surface area, which results in an increased current density towards the outer radius. This results in an increase of the rotor bar resistance. Subsequently, the top of the rotor lamination begins to saturate, and results in a decrease of rotor reactance. In terms of total harmonic current, the RMS value of the current is dominated by the RMS harmonic voltage and the total reactance at harmonic frequency, the losses can be calculated by Joule’s law taken into account the skin effect.

3. The total averaged voltage is influenced by the phase of the harmonics, accordingly this influences the magnetizing current. However, this effect is only measureable for low power ratings of machines and at partial loading [10]. As the loading increased, the increased stator voltage drop results in a slight demagnetization of the machine. Accordingly a linear induction is assumed and the effect on the magnetizing current is often neglected [1][8].

4. Harmonics also result in electro-magnetic power and consequently mechanical torque. In motor operation, voltage harmonics of $h_{k>1}$=1-6k result in breaking torques. Because the magnitude of voltage distortion decreases with increasing order, and the damping of harmonics is increased with increasing harmonic order, all harmonic power is assumed to be additional loss.

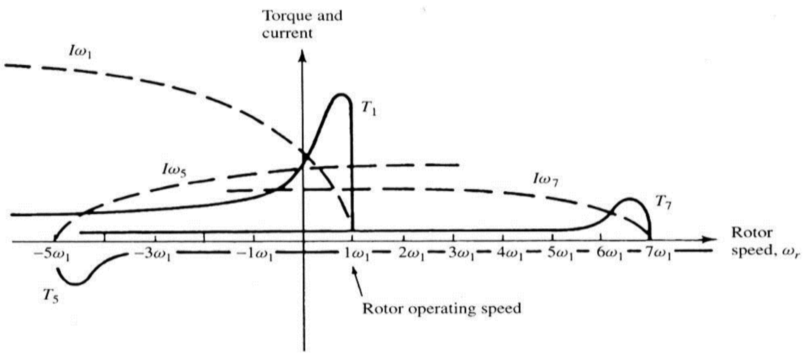

Fig. 4: Harmonic torques caused by supply voltage distortion

In order for an IM to cope with additional harmonic losses, the IM nominal power is reduced in case of severe distortion. Different derating methods for IMs when supplied with a distorted voltage have been suggested. If the derating is necessary from a technical perspective, generally excessive stator heating, Thermal Based Derating has been suggested. If the actual losses are of interest, Loss Based Derating (LBD) is more convenient. Due to both the increase in distortion of the supply voltage, and the increase of IM supplied from VSD’s, there was a demand for a relatively easy method of derating. Consequently, normative derating, such as the NEMA MG1 have been suggested which directly calculate the reduction of efficiency.

The goal within this paper is not to fully present the scientific details concerning the efficiency reduction caused by supply voltage distortion, but rather to present a comprehensive overview. As the influence of harmonic voltage distortion to the overall energy efficiency is inversely proportional to the harmonic order, it makes more sense to introduce a weighted voltage distortion ratio, rather than using the linear parameter Total Harmonic Distortion THD(U) [10].

Both the NEMA Standard MG1 as the IEC 60034-17 specify the "Harmonic Voltage Factor" HVF as:

$$HVF = \sqrt{\sum \frac{(V_n)^2}{n}} \qquad (1)$$

With n, the odd harmonics, excluding triple n harmonics and V_n the p.u. value of the n[th] harmonic. From the HVF, and using Fig. 5 the Derating Factor (DF) can be obtained, accordingly the resulting efficiency can be calculated according to Eq.(2).

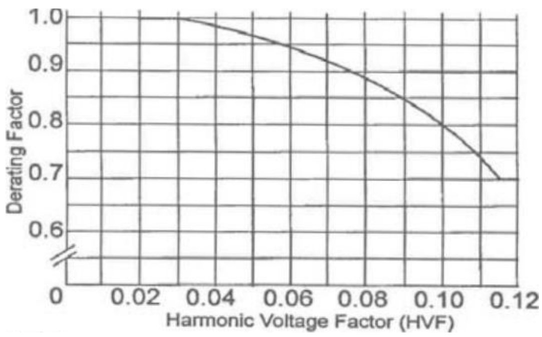

Fig. 5: DF as function of the HVF

With DF: the derating factor obtained from Fig. 5, η : de motor efficiency at sinewave condition and η_C the corrected motor efficiency in case of a distorted voltage.

$$\eta_c = \frac{DF^2}{\frac{1}{\eta} + DF^2 - 1} \qquad (2)$$

Studies have indicated that the normative derating methods present fairly good estimations concerning the reduction of motor efficiency. Subsequently, the absolute losses can be calculated, and combined with the correct knowledge of the thermal parameters of the motor, this can result in estimations concerning the temperature increase of the different motor parts. In Fig. 6 the temperature increase of different motor parts is presented for a 4kW IM IE2 at full load and supplied with a distorted voltage.

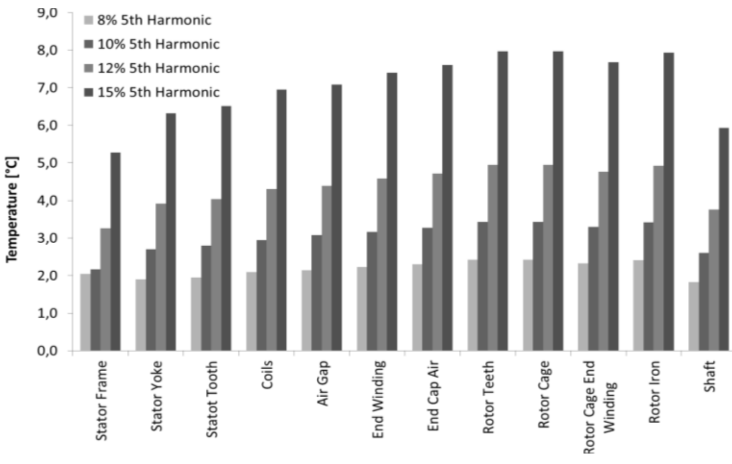

Fig. 6 Estimated temperature rise for a 4 pole 4kW IE 2 IM caused by harmonic distortion @ full load. Temperatures obtained by lumped thermal modeling

Based on Eq.(2) and Fig. 6 some important conclusions can be made. First of all, from Eq.(2) it can be deduced that for increased efficiency of the IM, the susceptibility of the IM towards supply voltage harmonics reduces. Consequently, the same amount of voltage distortion will result in a reduced loss in both actual power [W] as in pu, if an IE3 is compared to a IE2 of the same rated power. This also indicates that with increasing motor size, the harmonic losses in pu will reduce Fig. 7. However, in terms of actual active power [W], there is an increased loss for higher power ratings.

Secondly, harmonic modeling of IM assumes that the harmonic losses are nearly independent of the loading ratio. Measurements have indicated that the losses caused by harmonic voltage distortion slightly shift as function of the applied load. But harmonic losses are indeed present even at no load. This can have a significant cost if the motor is constantly unloaded. Fig. 7. The additional loss results in additional operating costs, but additional losses can also be evaluated from a technical perspective.

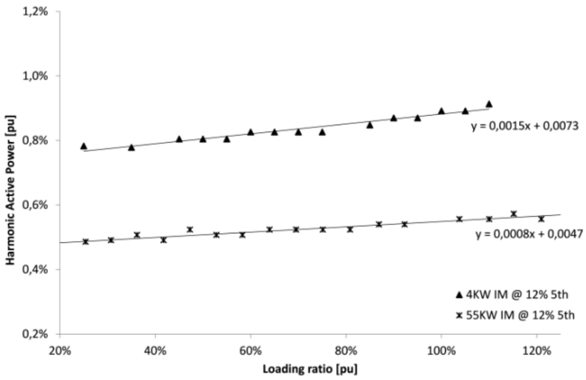

Fig. 7: harmonic loss [pu] for a 4pole 4kW IM and a 55kW IM for different loading ratio's and 12% 5th distortion

Additional losses imply additional heating and thus harmonic voltage distortion could result in premature failure, generally accelerated stator winding insulation breakdown. However, IM are usually over dimensioned as the general load ratio is only 60% [10]. Although according to Fig. 6 the additional losses increase, the operating temperature this effect is only to be taken into account at full load. At partial load stator winding temperature is significantly under the nominal temperature, even when supplied with a considerable distortion.

To conclude it can be stated that harmonic voltage results in additional losses and additional heating. Although the additional heating can cause problems, this effect is only important for small machines (which have an inherent large thermal resistance from stator coils to ambient) and at full load [1]. If the cost of harmonics is evaluated this is not negligible. It has to be stipulated that, according to Fig. 5 the losses are not linear to the applied distortion. This inversely implies that even a slight reduction of the distortion can result in significant energy savings.

5. The effect of harmonic Voltage Distortion on LSPMM [11]

The integration of Permanent Magnets (PM) in the rotor reduces both rotor and stator losses as the magnetizing power for the rotor is no longer supplied by the grid. If the rotor consists of both PM and rotor bars, the motor can start as a IM and once near synchronism the MagnetoMotive Force (MMF) of the PM can synchronize with the MMF induced in the stator. Consequently, these high efficient Line Start Permanent Magnet Machines (LSPMM) have been developed from the mid-eighties and recently became an off-the-shelf product. LSPMM are often suggested as one of the possibilities to achieve IE4 or even IE5.

Fig. 8: Rotor inserted PM, Courtesy of WEG ®

A state-of-the-art review of both practical advantages and limitations of these LSPMM's has been presented in [9]. If LSPMM are to become an actual substitute for standard IM, the influence of voltage distortion on its overall energy efficiency should be evaluated. Literature concerning the influence of harmonic distortion on the efficiency and operation of LSPMM is scarce. However, due to the similar configuration and operation to standard IM, it is tempting to straightforward adapt the loss mechanisms and models of IM.

A more profound analysis indicates that, in case of IM, the effect of slip combined with the additional voltage drop over the stator impedance allows superposition of losses obtained by harmonic modeling. Contradictory, for a LSPMM the use of superposition is prohibited, due to both the presence of PM and the synchronous operation. The supply voltage rarely holds one single harmonic imposed on the fundamental. If multiple harmonic distortions are superimposed on the supply voltage, certain harmonics will interact due to synchronous operation. Harmonic rotor currents, induced by stator harmonics of orders $h_{-\infty<k<+\infty}=1+6k$, and with equal value of |k| interact with one other resulting in either an amplification or reduction of the resulting rotor harmonic current.

If the phase angle of the different harmonics is shifted in reference to each other, the corresponding losses shift with a factor 4. A 4kW LSPMM machine has been subjected to both 10% fifth and seventh harmonic content. The losses were monitored as the phase angle from the seventh and the fifth shifted in reference to each other. The total power loss was averaged, and the variation of the losses is plotted in Fig. 9.

Fig. 9 does illustrate the interaction of individual harmonics and consequently discard superposition.

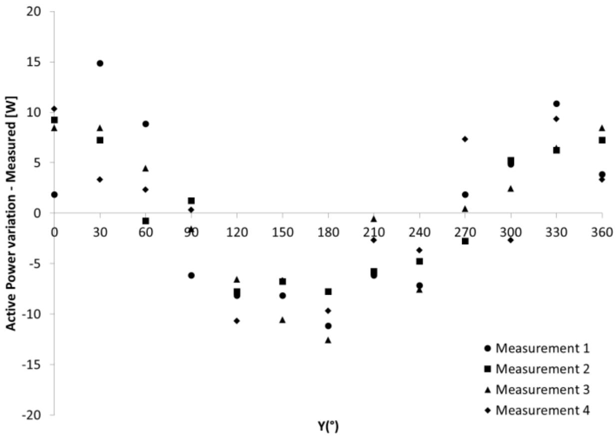

Fig. 9: Shifting the relative phase shift between Harmonic Five and Seven (Y) and its influence on the overall losses

The absence of rotor joule loss additionally reduces the stator joule loss. As the magnetizing losses become more dominant, the phase angle of the voltage distortion has significant influence on the overall efficiency of these machines Table 3.

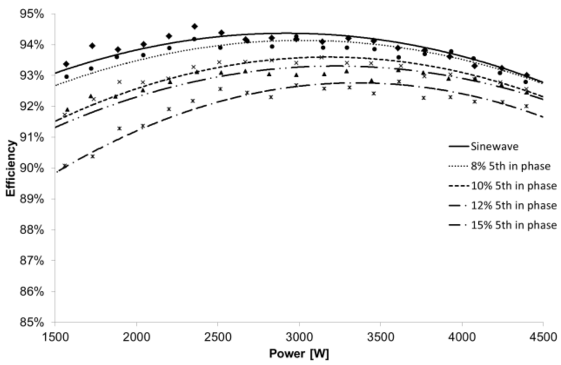

Fig. 10: Efficiency of LSPMM when supplied with a distorted voltage

Table 3: 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%

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 indicates 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.

6. The effect of harmonic Voltage Distortion on IG

Due to the high power to weight ratio, its robust construction and line start capabilities is the Induction Generator (IG) still the preferred choice of energy converter for certain types of CHP's, backup power or low cost Wind turbines. As the integration of IG continues to rise, the effect of supply voltage distortion on IG should be considered. The same effects occur in generator mode as in motor mode, however, similar to LSPMM, the use of harmonic motor models is prohibited. Additionally, there are several practical considerations which have to be taken into account in order to practically test an IG under distorted supply conditions.

First of all, when harmonic models of induction motors are build, a linear flux linkage is assumed. This is generally valid for motor operation, as the additional stator impedance voltage drop results in a decrease of the flux linkage. In case of IG the assumption of linear induction is no longer generally valid. If high efficient motors or specifically designed IG are used, these are specifically build with low stator resistance and a high amount of lamination steel in the stator to maintain an unsaturated operation. In these cases linear induction in generator mode can be justified, however, if standard motors are used as IG, the higher stator resistance combined with the reduced amount of lamination steel can result in saturated operation, and thus prohibiting linearization. (Fig. 11)

Furthermore, as the mechanical speed is above the synchronous speed for IG, the frequency of the injected harmonic rotor currents also varies. The frequency of the current harmonics of order $h_{k>1}$=1+6k will reduce in frequency in reference to motor operation. Contrary, in IG operation the frequency induced by harmonic orders of $h_{k>1}$=1-6k will increase. Skin effects are often derived by measurement in motor operation, however, the previous directly implies that neither skin coefficient for neither resistance and impedance are still valid in generator operation. In addition harmonics of $h_{k>1}$=1-6k do result in breaking torques in case of motor operation, however in generator operation this is a positive torque.

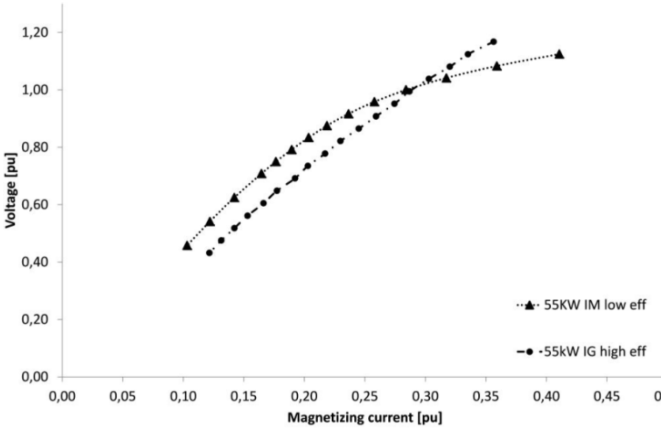

Fig. 11: magnetization curves for an IM used as a IG and a machine specifically designed for IG operation

From the previous it can be concluded that straightforward adaption of harmonic loss mechanisms for IM to IG can result in severe errors. Similar to the pitfalls of harmonic modeling, straight forward comparison between efficiency in motor and generator operation is equally delicate.

In Eq.(3) and Eq. (4) the definitions of the efficiency are given for motor and generator mode. When evaluating the efficiency of IM in case of voltage distortion, identical output power can be easily achieved by loading the test machine with a machine controlled towards constant output torque or constant output power. The increase in electrical input power is a measure for the additional losses in case of voltage distortion.

$$\eta_{\mathrm{motor}} = \frac{\mathrm{P_{mech}}}{\mathrm{P_{elk}}} = \frac{\mathrm{P_{elk}} - \mathrm{P_{loss}}}{\mathrm{P_{elk}}} \quad (3)$$

$$\eta_{\mathrm{generator}} = \frac{\mathrm{P_{elk}}}{\mathrm{P_{mech}}} = \frac{\mathrm{P_{elk}}}{\mathrm{P_{elk}} + \mathrm{P_{loss}}} \quad (4)$$

When motor and generator operation are compared, the following question arises. If a machine is designed particularly for motor operation, but used as a generator, what is the nominal IG operating condition and to which reference should efficiencies be compared? Both from a theoretical point of view, as from an design point of view, the general conclusion should be that machines are designed towards certain thermal limits. As the stator and rotor joule losses account for the majority of the total losses, it is logic to relate to maximum allowed current and therefore the nominal electric input power is often used as reference. If harmonics are imposed on the voltage, the mechanical power should be increased to obtain identical electrical power in reference to pure sine regime.

$$\eta_{generator} = \frac{P_{elk}}{P_{mech}} = \frac{P_{elk}}{P_{elk} + P_{loss} + P_{h\_mech}} = \frac{P_{elk} - P_{h\_elk}}{P_{elk} + P_{loss}} \quad (5)$$

$$P_{h\_mech} \neq P_{h\_elk} \quad (6)$$

The increase in mechanical input power $\mathrm{P_{h\_mech}}$ is a measure for the additional losses and not the reduction of electrical output power $\mathrm{P_{h\_elk}}$. Note that this effect is more dominant as the efficiency reduces, especially for low efficient or low power ratings of machines. The previous also imposes practical difficulties, because the measurement accuracy is now function of both electrical and mechanical sensors, as are the practical tests more time consuming.

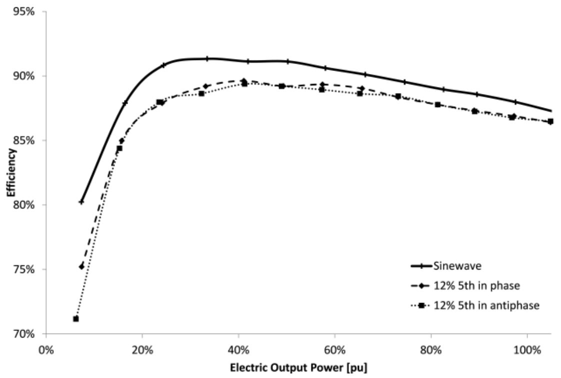

Fig. 12: a 4KW IM used as a IG, supplied with a distorted voltage and controlled to constant P_{mech}[WRONG]

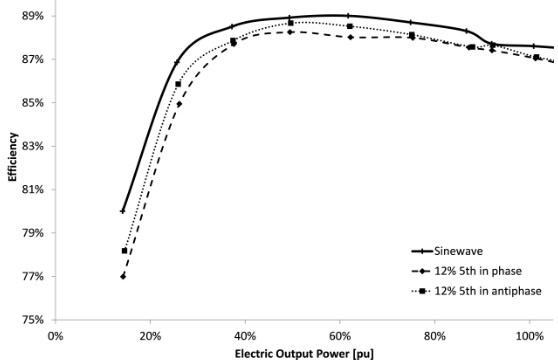

Fig. 13: a 4KW IM used as a IG, supplied with a distorted voltage and controlled to constant P_{elk}[Correct]

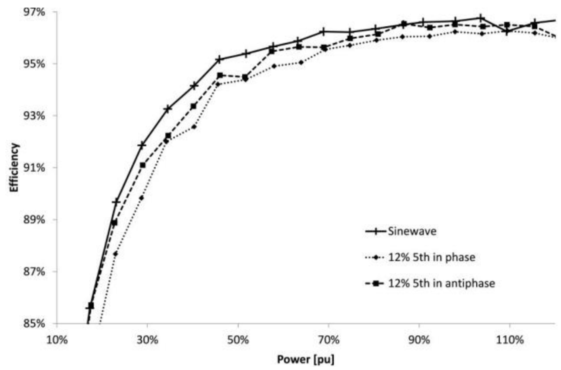

Fig. 14: influence of 12% fifth harmonic for a 55kW IG [6]

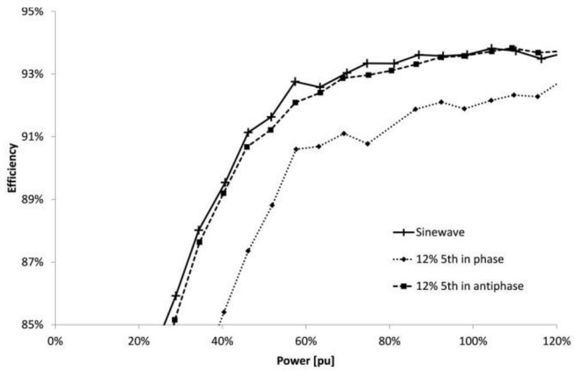

Fig. 15: influence of 12% fifth harmonic for a 55kW IM used as IG [6]

7. Conclusions

In this paper it is suggested that voltage distortion can have a significant influence on the overall energy efficiency of Induction Machines. In case of motor operation, this effect is well known, however in terms of energy efficiency the effect is often marginalized or even neglected.

This paper starts by proposing limits to end user voltage quality, and it indicates that the supply voltage distortion can reach up to 12% while still complying to all the design guidelines and normative references.

A supply voltage distortion of 12% fifth harmonic results in approximately a reduction of 1% efficiency. However, because the induction machine is a nonlinear system, even a small reduction of the supply voltage distortion can result in a significant energy reduction. Harmonic mitigation tools, such as filters or tuned capacitor banks could be mutually beneficial in both a reduction of the supply distortion and simultaneously the increase of energy efficiency of machines.

As energy efficient electromechanical energy conversion is of key importance, new types of high efficient machines are suggested, such as LSPMM. If LSPMM are to become an actual substitute for standard IM, the influence of voltage distortion on its overall energy efficiency should be evaluated. Within the presented research initial steps are made, additionally, it has been stressed that harmonic modeling of IM is not applicable for LSPMM. New models should be suggested and validated.

Induction machines can also be used as generator systems. As the integration of IG continues to rise, the effect of supply voltage distortion on IG should be considered. Literature concerning this subject is thin and obtaining measurement results has proven to be difficult. Similar to LSPMM is the use of harmonic models of IM prohibited for IG and more detailed loss modeling is needed.

To conclude, the LSPMM could also be used as an generator system. Due to its self-excitation, the high energy efficiency and its line start capability, LSPMM could be promising for “low cost” and “low maintenance” generator systems. Within this research no measurements are presented concerning the influence of supply voltage distortion on LSPMG, although this is subject for further research.

8. Biography

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