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A Control Strategy to Minimize Magnet Losses in Vehicle PMSM by Field-Weakening Operation

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Abstract

An applied control of PMSM is the flux weakening operation for extending the region over nominal speed on nominal voltage. This paper deals with these questions and its impacts. The proved method increases the torque angle and with this the *d* axis directed component of the stator current vector for reduce the main flux, but the loss developing in magnets became significant. These impacts and its reduction need several investigations. Our work indicates the possibilities and limits of flux-weakening for a given PMSM, and a usable control strategy.

Keywords: efficiency, field-weakening, HEV (hybrid electric vehicle)

1 Introduction

There are some sophistically elaborated control methods in the literature to achieve the needed points of operation increase in speed and power regarding the available torque [1],[3],[6],[7]. Vector control method provides adequate possibilities for realise the tasks mentioned in the PM synchronous motor. Nowadays to apply an electrical driven for vehicle demands a PMSM having extended speed range possibility with high efficiency and a good torque-ampere ratio. With Infolytica software we had developed a 110kW PMSM for a city bus of 12 tons driven by battery, see Fig. 1.

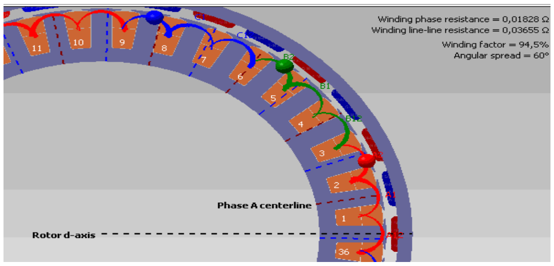


Figure 1: Detail from the stator, rotor and winding of our outer rotor and fractional slot per pole type motor

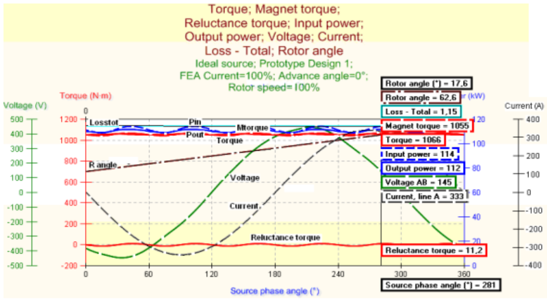


Figure 2: The main features of PMSM by near1 % reluctance torque

The nominal voltage, current, torque, speed are 650V, 240A, 1100 Nm and 1000 rpm respectively. The maximum torque is 2500 Nm under 900 rpm and the maximum speed is 2500 rpm with good features, it can be seen in Fig. 2-3-4-5.

The outer type rotor has surface-mounted NeFeB magnets. For achieve a lower cogging torque we chose a fractional number of slots per pole. We have some experiences in this area throughout building some PMSM by lower power.

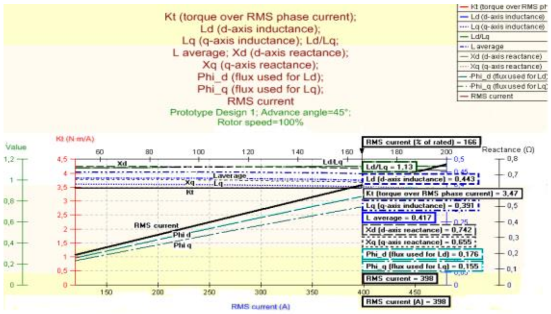


Figure 3: Electromagnetic features of PMSM

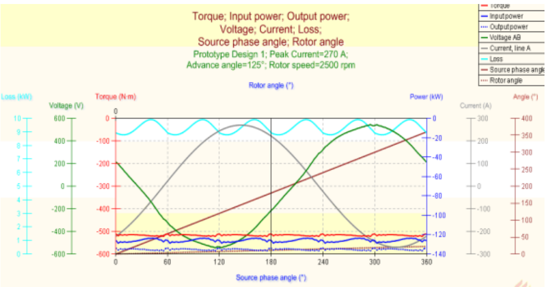


Figure 4: High speed regenerative braking. The braking torque (red line) is near constant

We were studying to achieve the possible most appropriate rate of pole and slot numbers, magnet shape and thickness, its remanence, the airgap length, stack length, winding type, and the shape and measure to all detail of the slot. The cogging torque is lower than 0.69 Nm, the maximum efficiency is higher than 95%, the active mass is of 71.1 kg, and the mass of magnet is of 4.9 kg only.

2 Investigations

For realize this results we suppose that the motor control has available flux-weakening operation. In Fig 5 can be seen these known current and voltage vectors, setting by υ torque angle.

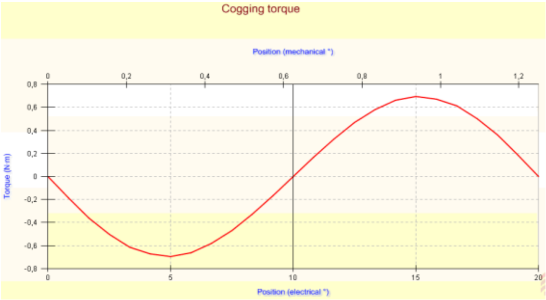


Figure 5: The cogging torque is 0.7 Nm, i.e. 0.07 % of nominal torque

We have done several simulations by Infolytica based FEA to investigate some main characteristics of this PMSM in this region namely the power factor, the loss of magnet eddy current, one of stator teeth hysteresis and other losses. The functions of results are fitted by MATLAB.

The eddy current loss induced in the permanent magnets of BLDC or BLAC machines were often neglected long ago but several researcher dealt with it in [4],[5],[6],[7].

They worked out very accurate analytical models for predicting losses in rotor magnets of machines have a fractional number of slots per pole too, and they validated it compared to their results by finite-element analysis (FEA). Eddy currents will be induced in magnets by rotating MMFs and due to the higher conductivity of rare-earth magnets the loss of magnets can be significant. The losses by analytical method [6] are:

$$J_m\,(r,\theta_r,t) = -\frac{1}{\rho}\frac{\partial A(r,\theta_r,t)}{\partial t} + C(t) \qquad (1)$$

$$P = 2P_r\,\frac{\omega_r}{2\pi}\int_0^{\frac{2\pi}{\omega_r}}\int_{R_r}^{R_m}\int_{-\frac{\alpha_p}{2}} \rho\, J_m^2\, r dr d\theta dt \qquad (2)$$

Here $\boldsymbol{J_m}$ eddy current, $\boldsymbol{A}$ vector magnetic potential, the $\boldsymbol{\rho}$ is resistivity, $\boldsymbol{p}$ the pair of pole, $\boldsymbol{r}$ radial, $\boldsymbol{\theta}$ angular coordinate, $\boldsymbol{t}$ time, $\boldsymbol{\omega}$ speed.

The power loss in magnet may cause high, non-permitted temperature rise and result in partial irreversible demagnetization of magnets especially with a high rotational speed and high pole number or under higher electric loading.

In this machines the induced eddy currents are usually resistance-limited and the associated loss in magnets can be derived from the armature reaction field [4],[7]. The eddy current loss rises significantly by the maximum current density or electric loading, and it varies approximately in proportion of the current density and rotor speed.

These features are remarkable in the results due our investigations from those we present one series when the value of speed were higher, 1500, 2000, 2500 and 3000 rpm and the values of power was held at 108kW of these speeds by the torque of 686, 517, 413 and 343.8 Nm

For each investigation one point of work was signed at the same speed and the settings were realized by different values of advance angle. The angle is measured in degrees and varies over the $\boldsymbol{q}$ axis in rotor coordinates and the torque or the power was set to the same value by tuned of the stator current.

Fig. 6 shows the magnet eddy current loss v. advance angle at P_{out} = 108kW. On the four curves the power is constant and at speeds of motor are as previously 1500, 2000, 2500 and 3000 rpm. The power, the torque and the value of speed on any curve are the same.

This magnet loss depends on current and speeds. This values are calculated by Infolytica with its FEA method.

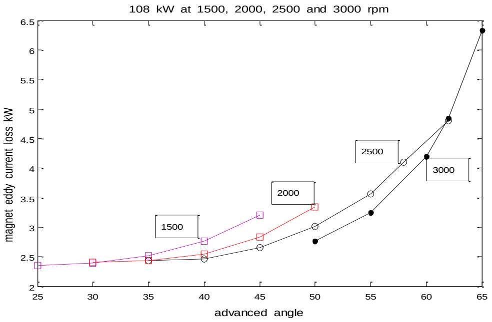


Figure 6: The magnet eddy current loss vs. advance angle at P=108kW and speeds are 1500, 2000, 2500 and 3000 rpm

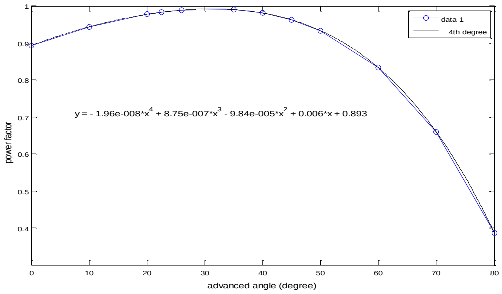


Figure 7: The power factor at speed 1000 rpm and motor current 280A

At speed of 1500 rpm and 45 degrees the loss in magnet is 3.2kW, at 2500 rpm and 62 degrees the loss is 4.8kW and at 3000 rpm and 65 degrees is 6.3kW. This last value is too large and a cooling system should be needed rather expensive for keeping the temperature of magnets on a permitted level.

The power factor was very sensitive to set of advance angle, as can be seen in Fig. 7. The high power factor demanded to reduce the losses of the inverter. We have been intended to achieve the higher power factor among entirely different circumstances.

It is observable that at constant speed 1000 rpm and current 280A the power factor versus the advance angle may be varied in a large domain. The maximum value of the function is 0.98 and there is at about 31 degrees of advance angle. At 2000 rpm and 280A and without any flux weakening the power factor is 0.9, but between 20 and 40 degrees advance angle by applied current vector rotation the power factor at least 0.97, and between 10 and 50 degrees these are at least 0.95 (this figure isn’t here).

Fig. 8 shows the loss of stator teeth hysteresis vs. advance angle at speed 2000 rpm and 280A motor current. Fig. 9 shows it by varied motor current at constant speed 1000 rpm and at 26 degrees. We can see that increasing the current the hysteresis losses are decreasing until we reach about 340A which is the maximum planned current in this motor. The losses in magnets increased fast depending on advance angle and by increase the stator current so it was needed to limit the increase of the advance angle.

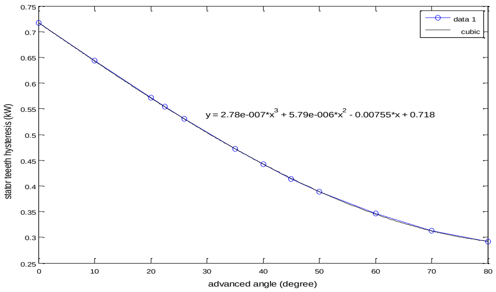


Figure 8: The loss of stator teeth hysteresis vs. advance angle. Speed 2000 rpm, I_{mot} 280A

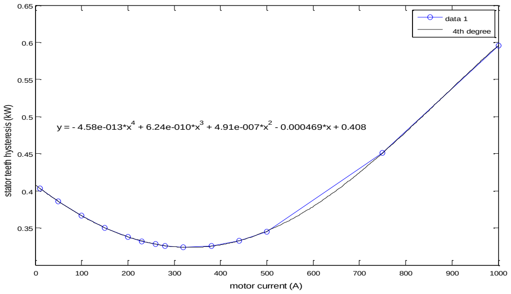


Figure 9: Loss of stator teeth hysteresis vs. motor current at speed 2000 rpm, at advance angle 26 degrees

In the flux-weakening process the impacts of increase the ***d***-direction component of the stator current is well known. From its positive side we can see that field weakening decreases hysteresis and eddy current losses in core of stator and of rotor and improves the power factor significantly. As a negative side it increases the magnet losses.

In the interest of giving a good survey about consequences of applied field weakening it will be worth to deal with its relationships. Fig. 10 shows the stator voltage functions vs. advance angle at power out P_{out}=108kW = const, and at speeds of motor 1500, 2000, 2500 and 3000 rpm. The power and the value of speeds are constant along any curve so the torque is the same also. To increase the advance angle at the same toque it needs to increase the motor current well. An increased value of current provides more effective flux weakening and with this decreases the MMF it will be sufficient a lower voltage of battery to supply the PMSM. This is the main aim of flux weakening. The 4 curves of the mantioned four speed parameters can be seen in Fig. 10.

In lowest curve it is shown at speed 1500 rpm that for achieving 108kW at 390V it is needed to set the current vector 29 degrees in advance, over ***q***-axis.

Here the actual DC voltage is 550V. If the advance angle is only 25 degrees the needed DC voltage is 575V. For this PMSM the planned maximum speed is 2500 rpm and achieving this by 550V DC the needed angle is 58.5 degrees, and by 700V DC the needed advance angle is 47.9 degrees.

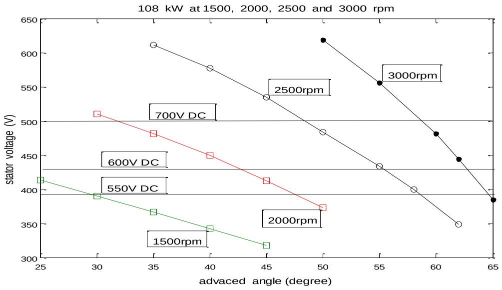


Figure 10: The stator voltage vs. advance angle at P=108kW and varied speeds

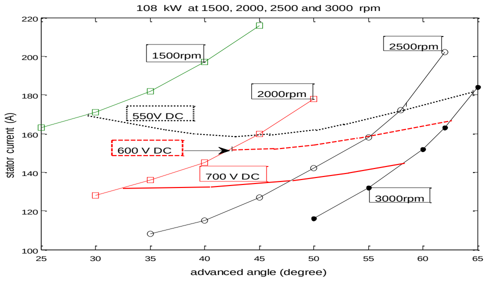


Figure 11: The current vs. advance angle by P= 108kW at varied speeds

In order to achieve the experimental speed 3000 rpm by 700V DC the needed advance angle is 58.5 degrees and by 550V DC the advance angle is 64.5 degrees. If the battery voltage is 800V than the needed advance angle is 53.5 degrees only.

Fig. 11 describes the motor current vs. advance angle at P_{out}=108kW. The power, the torque and the value of speed on one curve are the same. To decrease the required voltage and power at the same speed the advance angle and the motor current must be increased.

At speed 1500 rpm the need advance angle 25 degrees by the current 163A. To achieve speed 3000 rpm at 550V DC the needed angle is 64.3 degrees, and at 700V DC is 57.7 degrees. In Fig. 11 the curves of constant voltages of 550V DC, 600V DC and 700V DC show the actually achievable work points in the curves of constant speeds. These voltage curves have been constructed to this Figure from a previous one. In this figure may be read the possible region due to a current voltage of the battery.

If we draw from the previous figure's curves to Fig. 6 we can see in Fig. 12 and Fig. 13 that at 550V DC and speed of 3000 rpm the magnet loss is 6kW. At 2500 rpm the loss is 42kW in magnets as heat, so it needs to be transported away by a cooling system. At 700V battery voltage will be developped only 428kW and at 2500 rpm 3kW magnet losses that need much lower cooling power. Perhaps to limit the speed of the vehicle should be useful.

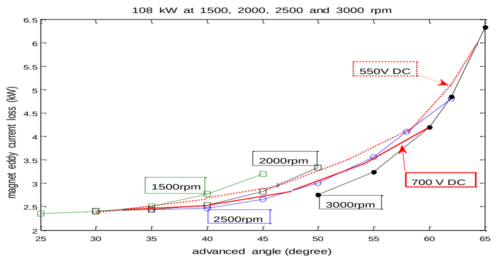


Figure 12: Magnet eddy current vs. advance angle at P_{out}=108kW by varied speeds and the constant battery voltages of 550V and 700V

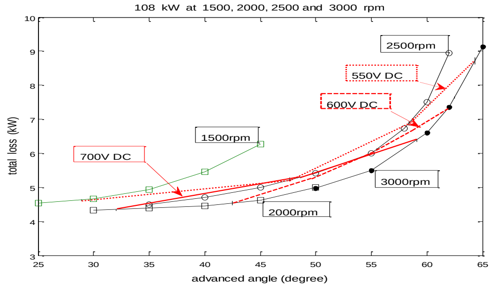


Figure 13: Total losses vs. advance angle at P=108kW by varied speeds and the constant battery voltages of 550V, 600V and 700V

In Fig. 13 shows the total losses v. advance angle at P_{out}= 108kW and at similar circumstances. The curves are very similar to ones of magnet loss because this is the main loss-component. The curves of total loss determine the efficiency curves. At 700V DC battery voltage the losses are the lowest and at 550V DC the losses are the highest. This difference may be 40%.

Efficiency vs. advance angle curves can be seen in Fig. 14 with 108kW output power and the speeds are as previously. We can observe that the points due to the actual maximum of efficiency are all above of 95%. Three curves go over the value of efficiency 96%.

The decrease of efficiency comes with the increase of current and advance angle to achieve reduction of MMF. The needed voltage of battery as 550V and 700V can be shown mainly on curves of 2500 and 3000 rpm. With a battery voltage of 550V at speed of 2500 and 3000 rpm 93.8 and 92.5% efficiency will be achieved but with 700V batttery voltage these values increased to 95.3 and 94.6%. We can draft that the voltage of battery may change the efficiency only by about 2% at 2500 and 3000 rpm and 108kW output power between 700V and 550V, but the developped heat in rotormagnets will be higher by 50% and that should be critical with its consequences. A cooling system for this task may be very complex and expensive and that should be critical with its consequences. A cooling system for this task may be very complex and expensive regarding to this is an outer rotor type PMSM.

In Fig. 15 the power factor vs. advance angle are visible by the same cases as previously with 1500, 2000, 2500 and 3000 rpm and by the output power P_{out}= 108kW. The value of these curves are the highest at speed of 1500, 2000 and 2250 rpm where the values of power factor are above 0.95. At speeds of 2500 and 3000 rpm begins to degrease to the lowest value of 0.89. At the same time we can see that at 3000 rpm and by a 65 degrees flux weakening the power factor increases again and achieves the value of 0.94.

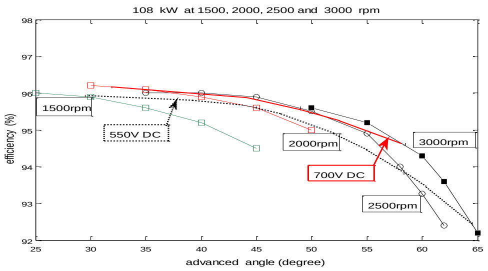


Figure 14: Motor efficiency vs. advance angle at P_{out}=108kW by varied speeds and the constant battery voltages of 550V and 700V

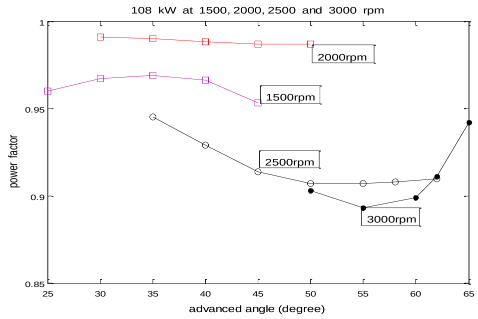


Figure 15: Power factor vs. advance angle at P=108kW by varied speeds

The distribution of induction for I_{mot} = 300% is for a strong overloading can be seen in Fig. 16. Even for this utilization the maximum induction is about from 1.9 to 2 Vs/m^2 in teeth.

The loss is decreased in ratio of the distribution of magnet-size. At the same time there are some disadvantages: the efficiency of magnet and the mutual inductance will be smaller a little, the cogging torque will be higher due the increase of the numbers of slots between magnets, and the cost of manufacturing will be increased definitely. The eddy current loss in each equally segmented piece may differ, which implies that the temperature distribution in the magnets will be uneven, investigated by a newer analytical method [4]. Our modified magnet-arrangement by two-slice type is shown in Fig. 17.

The losses in magnets can be decreased to make the magnet by narrower slices. We investigated this possibility, as it can be seen in Fig. 17. The main parameters here are P_{out} = 108kW, speed 3000 rpm, the torque is 344 Nm, the motor current is 186 A, the advance angle is 65 degree and the magnet loss here is $P_{lossmagn}$=2.58kW only. The power factor is 0.966, and the efficiency increased to 95.2%.

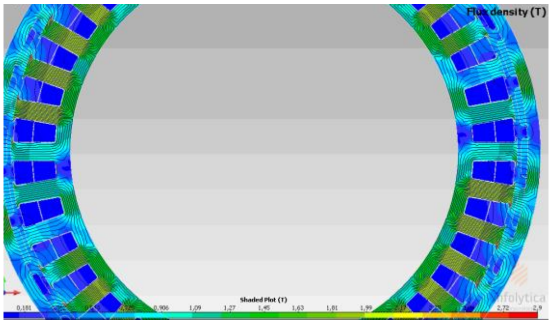
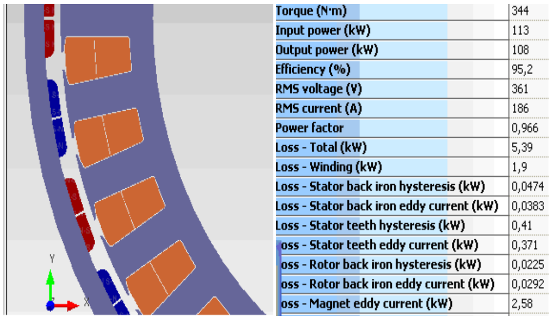


Figure16: The distribution of induction in the stator core at 300% overloading



Torque (N·m)	344
Input power (kW)	113
Output power (kW)	108
Efficiency (%)	95,2
RMS voltage (V)	361
RMS current (A)	186
Power factor	0,966
Loss - Total (kW)	5,39
Loss - Winding (kW)	1,9
Loss - Stator back iron hysteresis (kW)	0,0474
Loss - Stator back iron eddy current (kW)	0,0383
Loss - Stator teeth hysteresis (kW)	0,41
oss - Stator teeth eddy current (kW)	0,371
oss - Rotor back iron hysteresis (kW)	0,0225
oss - Rotor back iron eddy current (kW)	0,0292
oss - Magnet eddy current (kW)	2,58

Figure 17: The modified rotor with two-slice type magnets and the decreasing of loss in magnets

3 Results in the Fields of current vectors

A circle diagram is a well-known graphical device for determining the adequate field-weakening control strategy for synchronous motor drives [10]. These drives are usually current controlled and so it is convenient to define the operating point in terms of its location in the (I_d-I_q) plane. The current limit constraint $I_{qn}^2 + I_{dn}^2 \leq I_n^2$ forms a circle:

$$U_n^2 = \omega_n^2 \left[(\Phi_{mn} + L_n + I_{dn})^2 + \left(L_n + I_{qn} \right)^2 \right] \quad (3)$$

$$T_n = \Phi_{mn} * I_{qn} \quad (4)$$

From (3) it can be seen that voltage limit constraint if $V_n \leq 1$ defines a circle whose center is offset from the origin (see Fig 18). The size of this circle is inversely proportional to speed.

From (4) it can be seen that lines of constant torque form strait lines parallel to the d-axis in Fig. 18. The size of this circle is inversely proportional to speed. From (4) it can be seen that the lines of constant torque form strait lines parallel to the d-axis (see Fig. 18).

There are several method and strategy in literature to control a PMSM drive in different applications. Among these methods a maximum efficiency control is very important in several applications where energy saving may be critical, for example in hybrid electric and electric vehicle drives [3]. Unfortunately there is not a simple algorithm for implementing this strategy online. If the loss is computed for every operating point in advance we can give an efficient use.

Fig. 19 sums up the results of our studies and investigations for our outer-rotor type surface-mounted synchronous motor in its field-weakening region. The drawn work-points are the same as were previously: the power is P_{out} = 108kW, the four speeds are 1500, 2000, 2500 and 3000 rpm. The degree and the relative % of current vectors are described next to them.

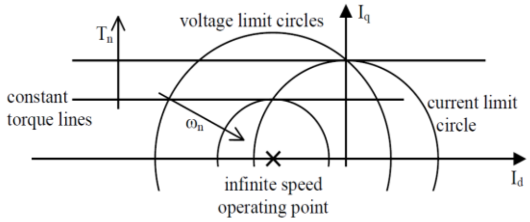


Figure 18: The (I_d-I_q) plane with the circle diagram for field-weakening control

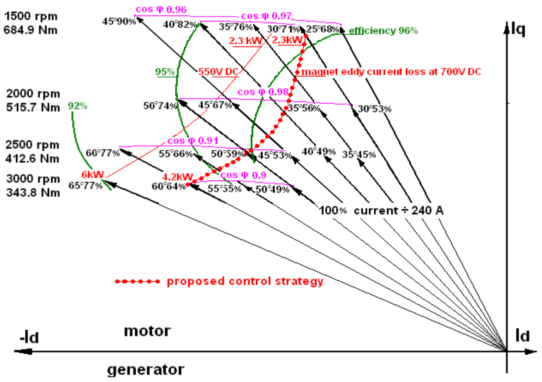


Figure 19: The field of current vectors at P_{out}=108kW. Curves of efficiency, power factor and magnet losses at 700 and 550V DC, in field-weakening

We drawn three curves of constant efficiency of 96, 95 and 92%, the five curves of power factor of 0.96, 0.97, 0.98, 0.91 and 0.9 values and the two curves of magnet losses due to 700V DC and 550V DC battery voltages.

There is a favour continuous line in Fig 19, which connects the speed curves of 1500 and 3000 rpm: these are just the magnet eddy current losses at 700 V, which across the field of current vectors are from 1500 to 3000 rpm. It touches the efficiencies nearby 96%, and later the 95 and 94% and at the same time across the highest values of power factor region. Practically this red-dotted curve seems to be the most adequate line of an optimal control strategy for this motor in field weakening region at case if P_{out}= 108 kW power is needed.

To realise this we determined the I_d and I_q functions (see Fig. 20) from Fig. 19 to calculate these currents from actual values of speed, fitted with 4th and 3th orded polynoms:

$$I_d = 1{,}9 * 10^{-11}x^4 - 1{,}7 * 10^{-7}x^3 + 0.00052x^2 - 0{,}71x + 2{,}5 * 10^2 \qquad (5)$$

$$I_q = -1{,}83 * 10^{-8}x^3 + 1{,}41 * 10^{-4}x^2 - 0.415x + 575 \qquad (6)$$

where x are the values of speed (rpm).

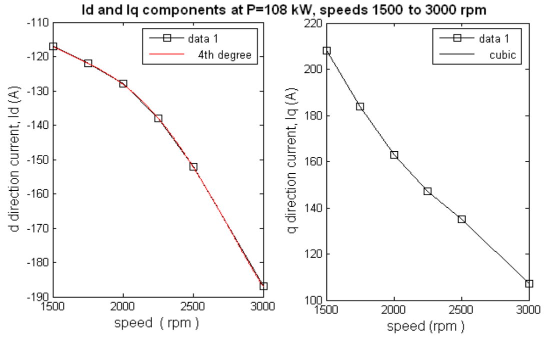


Figure 20: The function of I_d and I_q components vs. speed for proposed control strategy from Fig. 19 at 108kW and at speeds from 1500 to 3000rpm

4 Conclusions

The result of our work is a possible strategy in (I_d-I_q) plane. Computing and drawing the curves of magnet losses, efficiency and power factor, in the field of current vectors it could be find the adequate controlling line. From values of this line can be determined the (5) and (6) functions of I_d and I_q component v. speed, as actual reference current-signals for the control of PMSM in the field–weakening region, with approximately a possible best optimum of magnet losses, power factor and efficiency, in case at a constant DC voltage supplying. We continuously develop the dynamometer's control system to produce experimental results, but it seems that few months will be sufficient for validations with measurements.

Acknowledgment

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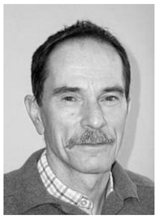

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