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(Article begins on next page)
Design tradeoffs between constant power speed range, uncontrolled generator operation and rated current of IPM motor drives

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Abstract -- A closed-form approximate formulation is proposed to establish a relationship between the uncontrolled generator operation of IPM motors at high speed and the constant power speed range and drive current capabilities. High saliency IPM motors of the PM-assisted synchronous reluctance type are mainly considered in the analysis, since they are proved to have the most favorable ratio between flux weakening capability and uncontrolled generator voltage. The results of the analysis show the tight relationship between the uncontrolled overvoltage and the constant power speed range of the drive. Moreover, where the uncontrolled voltage is higher, the relationship between the constant power speed range and the motor current amplitude becomes stiffer: for small current variations a large reduction of the speed range can occur. The analysis is validated experimentally on two motors of very different size (500 W and 1 MW).

Index Terms -- Permanent magnet machines, Variable Speed Drives, Synchronous Motor Drives, Traction Motor Drives, Electric Machine Design Methodology.

LIST OF SYMBOLS

- \( \lambda \)  
  stator flux linkage

- \( \lambda_{pm} \)  
  permanent magnet flux linkage

- \( \lambda_r \)  
  reluctance component of stator flux linkage

- \( \lambda_{rated} \)  
  rated flux linkage

- \( \lambda_{min} \)  
  flux linkage at maximum operating speed

- \( T \)  
  motor torque

- \( p \)  
  number of pole pairs

- \( i_0 \)  
  rated current of the drive

- \( i_s \)  
  minimum current with flat power profile

- \( i_{ch} \)  
  characteristic current of the IPM motor

- \( L_d, L_q \)  
  direct and quadrature inductances

- \( \xi \)  
  motor saliency

- \( \gamma \)  
  phase of current vector with respect to the \( d \) axis

- \( \delta \)  
  phase of flux vector with respect to the \( d \) axis

- \( \omega_{max} \)  
  maximum operating speed

- \( r \)  
  constant power speed range

- \( V_{rated} \)  
  rated phase voltage

- \( V_{UCG} \)  
  phase back-EMF at maximum speed

Subscripts

- \( \text{rated} \)  
  rated condition of the drive (flux, voltage)

- \( r \)  
  referring to the reluctance flux component

- \( MTPA \)  
  Maximum Torque per Ampere condition

- \( MTPV \)  
  Maximum Torque per Volt condition

I. INTRODUCTION

Interior Permanent Magnet (IPM) motors are attractive in many applications for their flux weakening capability, associated with good torque density and high efficiency [1-2]. With respect to induction motors, IPM motors show a better compactness [3], and a smaller inverter size when a large constant power speed range (CPSR) is required, since the pull-out torque limit [4] can be shifted at theoretically infinite speed with a proper motor design [5]. To achieve the willed CPSR the correct matching of permanent magnet (PM) flux and rotor magnetic saliency must be found [5]. In general, large speed ranges are possible either with non salient rotors with surface mounted PMs and concentrated windings [6], or with multi layer IPM rotors with a high saliency and inset PMs. In particular, the latter ones show a reduced PM flux (with respect to the machine rated flux) that is beneficial in terms of uncontrolled generator (UCG) operation, in case of inverter shutdown at high speed, when the motor back-emf can induce currents back to the dc link [7]. The UCG fault can be lethal for the inverter if the dc voltage rise is not properly limited.

The first goal of the paper is to establish a closed-form relationship between the CPSR capability and the UCG overvoltage of IPM motors. Although this relationship is valid for all IPM motors, in general, the attention will be devoted here to those ones with a high saliency ratio (\( \xi \)) and a reduced PM per-unit flux (\( \lambda_{pm}/\lambda_{rated} \)). Such motors are basically synchronous reluctance (SR) motors where a proper quantity of PMs is added into the rotor core. That is why they are preferably indicated as PM-assisted synchronous reluctance (PMA SR) motors [8-10]. As a first conclusion, it will be pointed out that PMA SR motors are more suited to applications requiring large CPSRs then PM motors with a
lower saliency or no saliency at all [11].

The second goal of the paper is to evaluate how sensitive the CPSR of an IPM motor is towards a change of the current amplitude. All PM motor drives can have an ideally flat power profile when their current equals the characteristic (short circuit) current of the motor (\(i_{dc} = \lambda_0/I_{dq}\)), but as soon as the current gets higher or lower than this specific value the power curve at constant current amplitude can drop quite suddenly with speed, depending on the motor design. It is then important to establish how it is possible to obtain a wide current range, centered around the characteristic value, where the power versus speed curve of the drive is still nearly flat. Having such flexibility towards the current amplitude might be important for two reasons. First: the same motor design can be associated to different nameplates, with the current rating referring to the various cooling setups (e.g. natural air or forced ventilation or liquid cooling) and load specifications. Second: a drive with flat power curves at the different current levels is advantageous where the duty time at high speed and reduced power is significant, like in traction. Otherwise, it means an extra current component is needed for flux-weakening, giving additional copper losses. For such very different reasons it is important to establish whether a current that is higher of lower than the rated one still leads to a power curve that is nearly flat or not. It will be shown that machines with a low UCG voltage are more flexible from this point of view, while machines with high UCG voltage may have a high CPSR but in a very limited current range.

The model is validated through experimental data over two PMASR machines of very different size, one designed for home appliance (500 W) and the other one for railway roller tests (1 MW), showing a good agreement with experimental data.

![Figure 1. Definition of dq synchronous frame according to PMASR conventions.](image)

### II. CONSTANT POWER SPEED RANGE AND UNCONTROLLED GENERATOR VOLTAGE

The relationship between CPSR and UCG voltage is investigated, in order to evaluate the required UCG overvoltage for a given CPSR or vice-versa. PMASR motors will be mainly considered, although the results have general validity for all IPM machines.

#### A. PM-assisted Synchronous Reluctance motor model

PMASR motors have a low per-unit PM flux: \(\lambda_0 << \lambda_{rated}\), where \(\lambda_{rated}\) is the rated amplitude of the stator flux linkage, corresponding to the maximum torque per Ampere condition at rated drive current \(i_0\). At low speed, when the flux vector and torque are the rated ones, the flux vector happens to be nearly in quadrature with the PM flux and roughly aligned to the direction of maximum permeance, called the \(d\) axis, as shown both in Figs. 1 and 2. For convenience, the \(dq\) synchronous frame defined in Fig. 1 has been aligned with the direction of maximum permeance, as usual for SR motors [8] and not with the direction of the magnets, as usual for PM motors.

The considerations in the following are based on the simplified magnetic model (1)-(2), where the machine linked flux vector (\(\lambda\)) is split into the PM flux vector (script \(m\)) and the reluctance flux vector (script \(r\)), that is the one of the basic SR machine, before the PMs are inserted into the rotor.

\[
\lambda = \lambda_m + \lambda_r \tag{1}
\]

\[
\lambda_{r,dq} = L_q \begin{bmatrix} \xi & 0 \\ 0 & 1 \end{bmatrix} i_{dq} ; \quad \lambda_{m,dq} = \begin{bmatrix} 0 \\ -\lambda_m \end{bmatrix} \tag{2}
\]

The saliency ratio \(\xi = L_q/I_{dq} (> 1)\) has been introduced in (2), and the PM flux is aligned with the negative \(q\) axis, as defined in Fig. 1. Magnetic saturation and cross saturation are not evidenced in the simplified model (2). Nevertheless, they will be properly taken into consideration in the following by setting case by case different \(\xi\) values for the different working points, for taking into account the real-world effects (saturation and cross-saturation), according to the experimental magnetic curves of the investigated motor. In the following \(\xi_{MTPV}, \xi_{MTPV}\) will be adopted, referring to Maximum Torque per Ampere operation and Maximum Torque per Volt operation respectively. Detailed remarks are given in section IV.

#### B. Definition of constant power speed range (CPSR)

In the example vector diagram reported in Fig. 2 the PM and reluctance flux components defined in (1) are evidenced at the drive rated current \(i_0\). This corresponds to the inverter current rating and is the current that will be referred to for the design of the PM flux linkage, as explained in the following. It is not necessarily the current corresponding to the continuous power of the motor which is lower than \(i_0\) in most cases. The so defined rated vector situation is represented in Fig. 2 that gives the rated torque from zero to base speed. The dashed elliptical trajectories represent the flux paths when the current vector is rotated for flux weakening over the base speed. The flux weakening capability of the drive is related to the matching between the characteristic
current of the motor $i_{ch} = \lambda_m / L_q$ and the drive current amplitude $i_0$. When the available current is close to $i_{ch}$ (larger or smaller) a high CPSR can be obtained, while with current values that are either much higher or much lower than $i_{ch}$, the CPSR tends to drop or even disappear.

When the available current is close to $i_{ch}$ (larger or smaller) a high CPSR can be obtained, while with current values that are either much higher or much lower than $i_{ch}$ the CPSR tends to drop or even disappear. When the available current is close to $i_{ch}$ (larger or smaller) a high CPSR can be obtained, while with current values that are either much higher or much lower than $i_{ch}$ the CPSR tends to drop or even disappear.

For those current values that are larger than $i_{ch}$ the maximum torque per voltage (MTPV) region is encountered at a certain speed [5] that has been indicated with a circle in Fig. 3b.

From that speed on, the power curves corresponding to $1.35 i_{ch}$ and $2.5 i_{ch}$ drop more or less suddenly depending on how larger is the current with respect to $i_{ch}$, while they are practically flat within the square to circle speed range. Therefore, if the rated current of the drive $i_0$ is such that $i_0 > i_{ch}$, the circled speed can be consistently considered as the end of the CPSR region, since the power curve drops from there on, while the squared speed (base speed) is the beginning of the CPSR.

This simplified definition of CPSR at fixed current amplitude will be adopted in the following for its simplicity and tight relation with the vector diagrams used for motor design. It will be also assumed that the drive is designed for having $i_0 > i_{ch}$. A criterion for expressing the CPSR when the current amplitude is lower than the characteristic one will be also defined, that is for power curves that do not meet the MTPV region, like the ones reported in Fig. 3b (0.35 $i_{ch}$ and 0.7 $i_{ch}$).

### C. Design of the appropriate $\lambda_m$

Following the design procedure presented in [12], the PM flux of a PMASR motor is designed for maximizing the motor torque at the target maximum speed and rated drive current $i_0$ and it is based on the assumption that the rated current is higher than the characteristic current ($i_0 > i_{ch}$). At that aim, starting from the characteristics of a preliminarily designed SR motor, the target PM flux is set such that the resulting IPM drive will reach the MTPV region exactly at the maximum operating speed, with the rated current amplitude $i_0$. The wanted PM flux is obtained by inserting proper quantity of PMs in each rotor layer, according to the geometry of the existing rotor and the adopted PM grade, as addressed in detail in [10]. Once the proper $\lambda_{min}$ has been obtained, the vector diagram at maximum speed, rated current must be the one of Fig. 4, where $L_q / i_0$ is representative of the characteristics of the basic SR motor ($L_q$) and of the current load $i_0$. The $\lambda_{min}$ circle refers to the maximum speed condition at rated phase voltage ($V_{rated}$), according to the relation (3), where resistive drops have been neglected:

$$V_{rated} = \omega_{max} \cdot \lambda_{min}$$  \hspace{1cm} (3)

It is worth to be noticed that the design process requires some iterations for having the condition of Fig. 4 exactly respected, since the MTPV path of the final IPM machine
also depends on $\lambda_{m}$, as it will be shown analytically in the following.

With this design criterion, based on the maximum speed working condition, the torque and power factor at base speed are not directly determined, but come out as a consequence of the choice of $\lambda_{m}$. The torque is the one of the SR motor plus a contribution that depends on how large the PM flux is, in per-unit of the rated machine flux. The power at base speed might be lower than that at maximum speed, due to a lower power factor, because of the need of magnetizing current, as it will be shown with practical examples in the experimental section. The base speed follows from the high speed design according to the motor saliency, as shown in the following.

$D. \text{Uncontrolled generator operation (UCG)}$

It is useful to define the $k_{UCG}$ factor (4):

$$k_{UCG} = \frac{\lambda_{m}}{\lambda_{min}} = \frac{\omega_{max} \cdot \lambda_{m}}{\omega_{min} \cdot \lambda_{min}} \geq \frac{V_{UCG}}{V_{rated}}$$

(4)

where $V_{UCG}$ is the motor back-emf at maximum speed. For motors with a significant saliency ($\xi > 2$) an overshoot factor should be also taken into account, for evaluating the peak UCG voltage amplitude correctly, because of the hysteretic behavior described in [7]. However, the general conclusions of this analysis are not affected from this behavior and it will be disregarded here.

Once the PM flux has been determined according to the maximum speed condition as just described, the UCG back-emf at maximum speed follows from (4). In the example of Fig. 4 the overvoltage factor is $k_{UCG} = 1$. The $\lambda_{m}$ design procedure introduced in subsection II.C will be now expressed analytically and the approximate relationship (18) between the UCG overvoltage factor $k_{UCG}$ and the CPSR will be formulated.

$E. \text{MTPV trajectory in the } dq \text{ flux plane [12]}$

First of all, the expression of electromagnetic torque is recalled (5), showing both the flux and current vectors:

$$T = \frac{1}{2} p \chi \times i$$

(5)

must be equal to the flux at maximum speed. $\delta_{max}$ is 27.4° according to (17) and $L_{d0} = 1.45 \lambda_{min}$.

For describing the maximum torque per voltage operation (that is practically equal to the maximum torque per flux operation, MTPF), it is convenient to express (5) in terms of the flux vector only, in amplitude and phase (6):

$$T_{dq} = \lambda_{m} \left[ \begin{array}{c} \cos \delta \\ \sin \delta \end{array} \right]$$

(6)

where the flux phase angle $\delta$ has been defined in Fig. 1. By substituting (2) and (6) into (5), the expression (7) is found:

$$T = \frac{3}{2} p \cdot \frac{1}{L_{q}} \left( \frac{\lambda_{m} - \lambda}{\xi} \cdot \frac{\sin 2\delta}{2} + \lambda_{m} \cdot \cos \delta \right)$$

(7)

The MTPV or MTPF trajectory in ($\lambda$, $\delta$) coordinates can then be expressed by setting to zero the partial derivative of (7) with respect to $\delta$. After some manipulation, (8) is found:

$$\frac{\partial T}{\partial \delta}_{\delta=\text{const}} = 0 \Rightarrow 2 \cdot \sin^{2} \delta + \alpha \cdot \sin \delta - 1 = 0$$

(8)

where the factor $\alpha$ has been introduced for simplifying the notation:

$$\alpha = \frac{\lambda_{m}}{\lambda} \cdot \frac{\xi}{\xi - 1}$$

(9)

The derivative of the term ($\xi - 1$) / $\xi$ in (7) has been neglected in (8) for simplicity. Its impact in terms of accuracy is negligible, in particular for motors with high saliency. Moreover, the accuracy of the model relies on the choice of the proper $\xi$ value, that is not known with precision until the motor is not designed and tested. The $\xi$ value to be adopted in (9) will be indicated as $\xi_{MTPV}$ in the following. The solution of (8) describes the MTPV flux trajectory in the $dq$ flux plane (10).

$$\sin \delta_{MTPV} = \frac{1}{2} \left( -\alpha + \sqrt{\alpha^{2} + 8} \right)$$

(10)

The example MTPV trajectory reported in Fig. 4 has been calculated according to (10).

$F. \text{Simplified expression of the CPSR (r)}$

As said in subsection II.B, we will consider the CPSR as the speed range between the rated flux (MTPA) situation at rated drive current $i_{0}$ and the crossing of the MTPF zone still at $i_{0}$, that is the maximum speed condition of our design. The definition (11) follows:

$$r = \frac{n_{max}}{n_{base}} \geq \frac{\lambda_{rated}}{\lambda_{min}}$$

(11)

The resistive drops have been neglected and $\lambda_{rated}$ is the rated flux defined in Fig. 2. The rated flux is related through (12) to its $d$-axis component $\lambda_{rated,d}$, that is also equal to the $d$-axis flux component of the basic SR machine $\lambda_{r,rad} = \lambda_{r,rad,d}$.

$$\lambda_{rated,d} = \lambda_{r,rad,d} \cdot \cos \delta_{rated}$$

(12)
written as $\lambda_{r, \text{rated}, d} = L_d i_{0, d} = L_q i_0 \sin \gamma_{\text{rated}}$. Then, multiplying and dividing (11) by $\lambda_{r, \text{rated}, q} / \lambda_{r, \text{rated}, d}$ the expression (13) is obtained:

$$r = \frac{\lambda_{r, \text{rated}, d}}{\lambda_{\text{min}}} = \frac{\lambda_{r, \text{rated}, d}}{\lambda_{r, \text{rated}, q}} \frac{\lambda_{r, \text{rated}, q}}{\lambda_{\text{min}}} L_q i_0 \sin \gamma_{\text{rated}}$$

(13)

The SR flux component ratio in (13), can be developed as:

$$\frac{\lambda_{r, \text{rated}, d}}{\lambda_{r, \text{rated}, q}} = \frac{L_d}{L_q} \frac{i_{0, d}}{i_0} = \frac{\xi_{\text{MTPA}}}{\tan \gamma_{\text{rated}}}$$

(14)

The MTPA saliency value $\xi_{\text{MTPA}}$ is used in (14). The substitution of (12) and (14) into (13) gives (15).

$$r \equiv \frac{\xi_{\text{MTPA}}}{\cos \gamma_{\text{rated}}} \frac{L_q i_0}{\cos \delta_{\text{rated}}}$$

(15)

In Fig. 4 the SR flux ellipse is well approximated by the horizontal line $\lambda_{r, q} = L_q i_0$. The relationship (16) then follows.

$$\lambda_m \equiv L_q i_0 - \lambda_{\text{min}} \sin \delta_{\text{max}}$$

(16)

Because of the design assumptions made in subsection II.C, the angle $\delta_{\text{max}}$ evidenced in the Fig. 4 is the maximum phase angle of the IPM motor flux in all operating conditions, and occurs at maximum speed, rated $i_0$ current. Its expression is obtained by substituting $\lambda = \lambda_{\text{min}}$ in (9) and (10).

$$\sin \delta_{\text{max}} = \frac{1}{4} \left( -\alpha_{\text{max}} + \sqrt{\alpha_{\text{max}}^2 + 8} \right); \alpha_{\text{max}} = \frac{k_{\text{UCC}} \xi_{\text{MTPA}}}{\xi_{\text{MTPA}}}$$

(17)

The angle $\delta_{\text{max}}$ shows a close relation with $k_{\text{UCC}}$ through the $\alpha_{\text{max}}$ factor (17). The procedure for the design of $\lambda_m$ is summarized by the two formulas (16) and (17), that must be applied iteratively until the obtained IPM motor fulfills the high speed specifications, i.e. a vector diagram like that of Fig. 4 is obtained. Anyway, the $\sin \delta_{\text{max}}$ value is typically lower than 0.5.

Back to the CPSR factor $r$, the term $L_q i_0$ in (15) is modified according to (16) and the expression (18) is finally found.

$$r = \frac{\xi_{\text{MTPA}} \cos \gamma_{\text{rated}} i_0}{\cos \delta_{\text{rated}}} \left( k_{\text{UCC}} + \sin \delta_{\text{max}} \right)$$

(18)

This is the relationship between the approximate CPSR and the UCG voltage factor (4). The angle $\gamma_{\text{rated}}$ is defined in Fig. 2 and represents the current phase angle at low speed, according to the MTPA condition. The term $\xi_{\text{MTPA}}$ represents the saliency of the motor at low speed and rated drive current.

The angle $\delta_{\text{rated}}$ is typically low for a PMASR machine, since the flux orientation is not too far from the $d$-axis, as said.

In practical designs the rated flux $\lambda_{\text{rated}}$ is limited by stator and rotor core saturation and the $\gamma_{\text{rated}}$ current angle depends on many factors (e.g. motor size and current load) but it is usually $\gamma_{\text{rated}} > 45^\circ$. Further indications about how to evaluate the saliency values $\xi_{\text{MTPA}}, \xi_{\text{MTPP}}$ are given in Section IV.

According to (18) it can be then concluded that:

- the CPSR is strictly related to the UCG overvoltage ($k_{\text{UCC}}$); the CPSR can be increased at the detriment of a large UCG voltage;

- a high saliency is always welcome, giving a more favorable CPSR to $k_{\text{UCC}}$ ratio.

III. RELATIONSHIP BETWEEN UCG VOLTAGE, CPSR AND DRIVE CURRENT

Once the PMASR motor has been designed for a given drive current $i_0$ and a given maximum speed and CPSR, a certain UCG voltage follows. It has been demonstrated that the UCG voltage and the CPSR at rated drive current are related by (18). The CPSR is now evaluated again at reduced current amplitude, for finding out which is the minimum current level $i_1$ that still guarantees a flat power curve up to the maximum speed.

As the rated drive current $i_0$ is higher than the characteristic motor current, the reduction of the current amplitude will initially lead to a power profile that is even flatter, as the characteristic value is approached, as discussed in Section I. This can be seen by inspecting the curves with current values $> i_{k1}$ in Fig. 3b. Instead, as the current amplitude is under $i_{k1}$ and is further reduced, the power profile tends progressively to curl, until the curve drops at rather limited speed values for very low current values (e.g. 0.35 $i_{k1}$ in Fig. 3b). In conclusion: given the CPSR at rated drive current $i_0$, what is the current level $i_1 < i_0$ that still guarantees a flat curve up to the same $\omega_{\text{max}}$ obtained by $i_0$? The lower such current value is, the lower will be the sensitivity of the CPSR to current amplitude variations.

A straightforward approach for determining $i_1$ is proposed in Fig. 5: the current $i_1$ is defined as the one that reproduces at maximum speed a flux vector (of amplitude $\lambda_{\text{min}}$) that is mirrored with respect to the one obtained with $i_0$ (that is $\lambda_{\text{min}} = + \delta_{\text{max}}$ with $i_0$ and $\lambda_{\text{min}} = - \delta_{\text{max}}$ with $i_1$). This definition guarantees a good power factor at maximum speed and a power curve that is still flat, despite of the current that is lower than the characteristic one.
The relationship (19) follows.
\[
L_qi_1 = \lambda_m - \lambda_{\text{min}} \sin \delta_{\text{max}} \quad (19)
\]

By manipulating (16) and (19) the current ratio (20) is found.
\[
\frac{i_1}{i_0} = \frac{\lambda_m - \lambda_{\text{min}} \sin \delta_{\text{max}}}{\lambda_m + \lambda_{\text{min}} \sin \delta_{\text{max}}} = \frac{k_{\text{UCG}} - \sin \delta_{\text{max}}}{k_{\text{UCG}} + \sin \delta_{\text{max}}} \quad (20)
\]

As said, \(\sin \delta_{\text{max}}\) is typically < 0.5, thus the current range (20) mainly depends on \(\lambda_{\text{UCG}}\). With a high UCG overvoltage (e.g., \(k_{\text{UCG}} > 2\)) the current range from (20) results quite narrow and the drive is stiff from this point of view, while for low UCG overvoltage values the current interval is definitely larger. This once more confirms that a large CPSR can be conveniently pursued by means of a high saliency, for keeping \(\lambda_{\text{UCG}}\) as low as possible (18) and have more flexibility towards current variations (20). This approximated approach makes it easy to express the current interval \(i_1/i_0\) analytically. Nevertheless, in most of PMASR motors current values lower than \(i_1\) might still lead to quite flat power curves, thus the ratio (20) can be considered as a safe estimate. More accurate approaches are of course possible but they would require complicated models and would not change the general conclusions of this analysis. Dealing with PM flux variations due to temperature effects, the \(\lambda_m\) value considered in the design (16) and in the definition of \(k_{\text{UCG}}\) (4) was the one at operating temperature (hot conditions). Dealing with the actual UCG voltage, some margin must be safely introduced, since the worst case scenario of inverter fault occurs when the motor is cold. The PM flux realistically varies by 15% for a temperature variation of 120°C.

IV. EXPERIMENTAL RESULTS

A. Motors under test

The approximated equations (18) and (20) are validated through measurements on two very different PMASR motor drives, whose specifications are reported in the Appendix.

- Motor 1, nameplate ratings are 470 W @ 3200 rpm, 18000 rpm maximum speed, designed for washing machines, shown in Figs. 6-7.
- Motor 2, nameplate ratings are 1 MW @ 250 rpm, 1350 rpm maximum speed, designed for a railway roller test bench, shown in Figs. 11-12.

B. Validation approach

To validate the proposed formulas (18) and (20) by means of already designed motors it is necessary to turn upside down the approach that has been followed so far. In sections II and III, the PM flux \((\lambda_m)\) has been designed with reference to a specified maximum speed (i.e. at given \(\lambda_{\text{min}}\)) and it resulted in an UCG overvoltage factor \((k_{\text{UCG}})\). The reversed approach adopted here with given machines is:

- decide first a \(k_{\text{UCG}}\) factor to be tested.
- then verify equations (18), (20) according to the experimental identification of the machine.

Having an existing motor means that the PM flux \((\lambda_m)\) is already determined and cannot be changed. Then, for any \(k_{\text{UCG}}\) a corresponding \(\lambda_{\text{min}}\) follows, according to (4). Given the rated motor voltage, this means that the maximum speed \(n_{\text{max}}\) is also determined by the choice of \(k_{\text{UCG}}\), according to (3). Independently of what are the actual current and maximum speed the motor under test has been designed for, in this validation exercise the “rated” drive current \(i_0\) will be also determined according to the chosen \(k_{\text{UCG}}\) and calculated, on the basis of the motor experimental data, as the current whose flux weakening trajectory encounters the MTPV curve exactly at \(\lambda_{\text{min}}\) , thus reproducing the vector diagram of Fig. 4. Once \(i_0\) is so determined, the rated flux vector \(\lambda_{\text{rated}}\) is calculated as the flux amplitude corresponding to \(i_0\), on the experimental MTPA curve. The base speed and then the CPSR also follow, from \(V_{\text{rated}}\) and \(\lambda_{\text{rated}}\) (3). The reduced current \(i_1\) is calculated as the current amplitude that produces the same \(\lambda_{\text{min}}\) with mirrored flux phase angle \(-\delta_{\text{max}}\), as in Fig. 5. Finally, the so obtained CPSR and \(i_0/i_1\), evaluated from the experimental data, are compared with the results from (18) and (20).

C. Results with Motor 1

The steady-state magnetic behavior of the motor has been identified in the current range \(i_d = 0\) to 5 A pk, \(i_q = 0\) to 5 A pk, following the measurement procedure described in [13].

![Figure 6. Motor 1.](image6.png)

![Figure 7. Rotor lamination of Motor 1. The PM bonded (ferrite) material is injected in the hollow flux barriers.](image7.png)
The resulting flux versus current experimental curves are reported in Fig. 8. Based on the experimental data, the MTPA, MTPV, constant current and constant flux trajectories can be plotted, both in the \((i_d, i_q)\) and \((\lambda_d, \lambda_q)\) planes, as in Fig. 9. Two different \(k_{UGC}\) factors (1.0 and 1.5) and their corresponding \(\lambda_{\text{min}}\) values are considered for the evaluation of \(r\) and \(i_d/i_q\). The PM flux is 0.06 Vs (Figs. 8, 9, \(i_d = i_q = 0\)), then \(\lambda_{\text{min}}\) is 0.06 Vs in the former case and 0.04 Vs in the latter. With the rated voltage specified in the Appendix, the respective maximum speeds are 12000 rpm \((k_{UGC} = 1)\) and 18000 rpm \((k_{UGC} = 1.5)\). The \(i_0\) current is calculated in the flux frame of Fig. 9b by determining which of the constant-current-amplitude curve (pseudo ellipse) intersects the MTPV trajectory in correspondence of the \(\lambda_{\text{min}}\) circle. The angles \(\delta_{\text{max}}\) follow in both cases. Finally, the current \(i_1\) is individuated from the intersection of its “ellipse” with the \(\lambda_{\text{min}}\) circle at \(\delta_{\text{max}}\). In the examples of Fig. 9b, \(k_{UGC} = 1\) leads to \(i_1 = 1.0\) A, \(i_0 = 3.2\) A and \(k_{UGC} = 1.5\) leads to \(i_1 = 1.4\) A, \(i_0 = 2.7\) A. The power profiles at all current amplitudes are calculated on the basis of the experimental model and reported in Fig. 10. The base and maximum speed points have been evidenced in Fig. 10 by means of square and circle tags, respectively, and the CPSR can be evaluated in the two cases. The same squares and circles have been reported also in Fig. 9 for better clarity. The power profiles of Fig. 10 point out that the lower the CPSR is the larger the \(i_d/i_q\) ratio is.

Dealing with the application of (18) and (20) for evaluating \(r\) and \(i_d/i_q\) respectively, the motor saliency and the \(\gamma_{\text{rated}}, \delta_{\text{rated}}\) angles are estimated again from the motor experimental curves. The saliency values \(\xi_{\text{MTPA}}\) and \(\xi_{\text{MTPV}}\) might be roughly evaluated from the flux curves of Fig. 8. For better clarity, the experimental data have been manipulated to obtain the saliency map in the \((i_d, i_q)\) plane reported in Fig. 9a: the saliency has been calculated from the chord inductances. Along the MTPA curve, for both 2.7 A and 3.2 A, the current phase angles and the saliency values are close to each other and shown in Table I. \(\gamma_{\text{rated}}\) is practically zero (Fig. 9b, squares at 2.7 and 3.2 A).
Along the MTPV curve $\xi_{MTPV} = 4.6$ will be used in equation (17) for determining $\delta_{\max}$ both at 2.7 A and 3.2 A. Anyway, the sensitivity of $\delta_{\max}$ to $\xi$ is very low (17), at least for the considered anisotropy values. The results coming from (18) and (20) are compared in Table I to the values coming from experiments, showing a fairly good correspondence.

D. Results with Motor 2

The steady-state magnetic model of the motor, identified in the current range $i_d = 0$ to 1130 A pk, $i_q = 0$ to 1700 A pk, is reported in Fig. 13. The corresponding MTPA, MTPV and other significant trajectories are plotted in the $(i_d, i_q)$ and $(\lambda_d, \lambda_q)$ planes in Fig. 14. The $r$ and $i_d/i_1$ formulas are verified here with reference to $k_{UCG} = 1.55$. This value has been chosen instead of 1.50 because this one would have required the knowledge of the experimental magnetic model over a current range larger than the available one. The PM flux is 2.0 Vs (Figs. 13, 14b, $i_d = i_q = 0$), then $\lambda_{\min}$ is 1.29 Vs. With the rated voltage specified in the Appendix, the maximum speed is 1270 rpm. The application of the procedure described in subsection IV.C leads to $i_1 = 860$ A, $i_0 = 1500$ A, from the experimental curves. The corresponding power profiles are the ones in Fig. 15. The application of the formulas follows the evaluation of $\gamma_{\text{rated}} = 58^\circ$, $\xi_{MTPA} = 6$, $\xi_{MTPV} = 8$ (all from Fig. 14a), $\delta_{\text{rated}} = 0^\circ$ (Fig. 14b).

![Figure 11. Motor 2.](image1)

![Figure 12. Motor 2: detail of the hollows housing the inset PMs, seen from the inspection windows of one of the flanges of the rotor stack.](image2)

![Figure 13. Magnetic curves of Motor 2, measured at steady state.](image3)

![Figure 14. Motor 2: MTPA, MTPV, constant current and constant flux curves of the motor for a railway roller test bench, based on the experimental data. a) dq current plane; b) dq flux plane.](image4)

![Figure 15. Motor 2. power profiles of the motor for a railway roller test bench, based on the experimental data.](image5)

The results of (18) and (20) are compared with the experimental values in Table II. As for Motor 1, the estimate of the current ratio $i_d/i_1$ is in the direction of safety (estimated...


Table II

| Motor 2 (1 MW): Comparison between the simplified equations (18, 20) and the experimental data |
|---------------------------------|--------|----------------|----------------|----------------|
|                                  | Fig. 15 | k_{UGG} | i_d (A) 1500 | i_s (A) 860 |
|                                  | Fig. 14 |      | γ_{rated} | 60° |
|                                  | Fig. 13 |      | n_{base} | 240 |
|                                  |      |      | n_{max} | 1270 |
|                                  |      |      | r | 5.3 |
| Proposed model                   | Eq. 12 | sin δ_max | 0.39 |
|                                  | Eq. 18 | r | 5.8 |
|                                  | Eq. 20 | i_d/i_0 | 0.60 |

V. CONCLUSIONS

Two simple formulas have been introduced, giving better evidence to the effects of some design choices, when a CPSR is required from an interior permanent magnet motor drive. These formulas, starting from the expected value of the rotor saliency, allow the preliminary calculation of the obtainable CPSR and current span of the related IPM drive, with no need of the complete design procedure. This gives evidence to some important conclusions about the expected drive performance. A first general conclusion is drawn that maximization of the motor anisotropy is welcome, for having a large CPSR with a low UCG voltage. Second, it has been shown that large current spans are compatible with large CPSRs and again this is possible with large rotor saliency values. As a practical consequence, general purpose drives of the PM-assisted synchronous reluctance type can be designed and built, provided that the rotor saliency is properly maximized.

APPENDIX

The ratings of the two motors under test are reported in Tables III and IV. The inductance values are not reported in the tables because they can be derived by inspection of the magnetic curves of Figs. 8 and 13 for motors 1 and 2 respectively. The power curves can be derived from Fig. 10 (Motor 1) and Fig. 15 (Motor 2), apart from iron and mechanical losses.

Table III - Nameplate Ratings of Motor 1

<table>
<thead>
<tr>
<th>Torque</th>
<th>1.4 Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line to line voltage</td>
<td>270 V pk</td>
</tr>
<tr>
<td>Phase current</td>
<td>2.8 A pk</td>
</tr>
<tr>
<td>Base speed</td>
<td>3200 rpm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>18000 rpm</td>
</tr>
<tr>
<td>Back-emf at base speed (line to line)</td>
<td>70 V pk</td>
</tr>
<tr>
<td>Characteristic current</td>
<td>2.0 A pk</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Stator diameter, stack length</td>
<td>55.2 - 35 mm</td>
</tr>
</tbody>
</table>

References


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