Abstract: Torque measurement/estimation in surface permanent magnet synchronous machines (SPMSMs) is needed in many applications. Torque measurement systems are expensive, require extra room, add weight, can introduce resonances into the system, and their performance can be compromised due to electromagnetic interference. Alternatively, torque can be estimated, accurate knowledge of machine parameters being critical in this case. Injection of a high frequency (HF) signal in the stator via inverter has been shown to be a viable option for online identification of machine parameters identification required by torque estimation methods for interior PMSMs (IPMSMs). However, the reported methods require the use of two pulsating HF currents, which introduces concerns both on the adverse effects on machine’s performance (additional noise, vibration, losses, …) as well as to the additional computational burden, as HF current controllers are required. This paper proposes a torque estimation method for SPMSMs using a single HF signal; furthermore, a HF voltage signal can be used, avoiding the use of HF current controllers, and therefore simplifying the implementation.

Keywords—Permanent magnet synchronous machines, torque estimation, high frequency signal injection.

I. Introduction

Permanent magnet synchronous machines (PMSMs) are widely used in a large variety of high performance applications such as automotive, robotics, servo drive, military, aerospace…, due to their high efficiency, high power density and good dynamic response compared to other types of electrical machines [1]-[8]. Due to their importance, design, control, diagnostics and monitoring of PMSMs have been the focus of significant research efforts during the last decades.

Many applications require precise knowledge of machine torque [9]-[15]. Torque measurement systems can be roughly classified into strain gauges based methods [9]-[14] and torsional displacement based methods [15], with the first being the most extended. Both type of methods require extra room and cables, and their cost can account for a significant portion of the overall drive cost. Additionally, gauges based methods could introduce resonances into the system and are highly sensitive to electromagnetic interference. Torque estimation is often preferred due to these reasons [16]-[27].

Torque estimation methods can be roughly classified into torque equation based methods [16]-[18] and indirect estimation methods [19]-[27]. All these methods [16]-[27] require previous knowledge of certain machine parameters (PM flux, resistances, inductances…) and/or machine-operating condition (e.g. temperature), parameter sensitivity is one of the main weaknesses of these methods. To overcome this limitation, injection of pulsating HF signals on top of the fundamental excitation has been proved to be a viable option to estimate the machine parameters involved in the torque equation, i.e. PM flux and dq-axis inductances [18].

This paper proposes a new online parameter estimation method for SPMSMs aimed to improve the accuracy of torque estimation. The proposed method uses a modified torque equation based of HF parameters of the machine [28]. The parameters involved in the modified torque equation are estimated from the response to a HF signal injected in the stator terminals. While the method has some similarities with the method proposed in [18], the last required the injection of two pulsating HF currents, to estimate $L_{dHF}$ ($d$-axis HF inductance), $\lambda_{pm}$ (permanent magnet flux) and $L_{qHF}$ ($q$-axis HF inductance) and implied therefore the use two HF current controllers. The method proposed in this paper requires the injection of only one HF signal, which can be either a voltage or current pulsating HF signal. This reduces the adverse effects of the HF signal on the performance of the machine and reduces the computational burden. A second difference with the method proposed in [18] is that this last used the conventional torque equation for torque estimation, while the method presented in this paper proposes a modification that will be shown to improve the torque estimation accuracy.

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The paper is organized as follows: fundamental model of a SPMSM is presented in section II, torque estimation using a HF signal is presented in section III, simulation and experimental results are presented in sections IV and V respectively, conclusions are finally provided in section VI.

II. Fundamental model of a PMSM

The general fundamental model of a PMSM in a reference frame synchronous with the rotor is given by (1) where \( R_d, R_q, L_d, \) and \( L_q \) are the \( d \) and \( q \)-axes resistances and inductances respectively, \( \omega_r \) is the rotor speed and \( \lambda_{pm} \) is the PM flux; \( d \)-axis being aligned with PMs. The output torque can be expressed as (2), where \( P \) is the number of poles, \( T_{syn} \) is the electromagnetic/synchronous torque and \( T_{rel} \) is the reluctance torque. In surface SPMSMs, due to their symmetric rotor structure, the differential inductance \( (L_d-L_q) \), i.e. saliency, is small [29]-[31] (\(~7.8\%\) for the test machine that will be used in this paper), meaning that \( T_{syn}>>T_{rel} \) (2) can be also expressed as (3). It can be concluded from (2)-(3), that \( T_{out} \) estimation in SPMSMs requires estimation of \( \lambda_{pm}, L_d, \) and \( L_q \). It will be shown in the next section that all these parameters can be estimated from the response to a HF signal injected into the stator terminals of a SPMSM.

\[
\begin{bmatrix}
\nu_d' \\
\nu_q'
\end{bmatrix} =
\begin{bmatrix}
R_d & 0 \\
0 & R_q
\end{bmatrix}
\begin{bmatrix}
\nu_d' \\
\nu_q'
\end{bmatrix} +
\frac{p}{2}
\begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix}
\begin{bmatrix}
\nu_d' \\
\nu_q'
\end{bmatrix}
\]

(1)

\[
T_{out} = \frac{3}{2} P \left( \lambda_{pm} \nu_q' + (L_d - L_q) \nu_d' \nu_q' \right) = T_{syn} + T_{rel}
\]

(2)

\[
T_{out} = \frac{3}{2} P \left( \lambda_{pm} + L_d \nu_d' \right) \nu_q' = \left( L_d \nu_d' \nu_q' \right)
\]

(3)

Flux observers reported in the literature for torque estimation, normally assume constant PM flux linkage \( \lambda_{pm} \) [32]-[33]. However, due to the temperature dependency of PMs’ properties and saturation effect on the soft-iron, \( \lambda_{pm} \) varies, a linear relationship between torque and \( q \)-axis current not existing anymore [34]-[35]. Improvement of torque equation to include the variation of saturation level with temperature and fundamental current is presented in the next section. The \( d \)-axis HF inductance has been shown to be a reliable metric of the machine saturation level [36], and will be used for this purpose.

III. Torque estimation in SPMSMs using HF machine parameters

This section presents the HF model of a SPMSM and the physical principles of torque estimation in SPMSMs using HF signal injection.

a) HF model of a SPMSM

If the stator of a SPMSM is fed with a HF voltage/current sufficiently higher than the rotor frequency, the HF model shown in (4) can be deducted from (1) by neglecting the magnet flux (because it does not contain any HF component) and rotor speed dependent terms (assumed that the frequency of the HF signal is sufficiently higher than the rotor frequency [36]-[38]), where \( \nu_{dHF} \) and \( \nu_{qHF} \) are the \( dq \)-axes HF voltages in the rotor reference frame, \( \nu_{dHF} \) and \( \nu_{qHF} \) are the \( dq \)-axes HF currents in the rotor reference frame, and \( L_{dHF} \) and \( L_{qHF} \) are the \( dq \)-axes HF inductances. Furthermore, if the frequency of the HF signal is high enough, the HF resistive term can be safely neglected compared to the inductive term.

In an stationary reference frame (i.e. stator reference frame), the HF model shown in (4), is expressed by (5), where \( \Sigma L \) and \( \Delta L \) are the mean and differential inductances respectively, (6) and (7), \( \theta_r \) is the rotor electrical position, \( \nu_{dHF} \) and \( \nu_{qHF} \) are the \( dq \)-axes HF voltages in the stator reference frame and \( \nu_{dHF} \) and \( \nu_{qHF} \) are the \( dq \)-axes HF currents in the stator reference frame.

\[
\begin{bmatrix}
\nu_{dHF} \\
\nu_{qHF}
\end{bmatrix} =
\begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix}
\begin{bmatrix}
\nu_{dHF} \\
\nu_{qHF}
\end{bmatrix}
\]

(4)

\[
\begin{bmatrix}
\nu_{dHF} \\
\nu_{qHF}
\end{bmatrix} =
\begin{bmatrix}
\lambda \left( \Sigma L - \Delta L \cos(2\theta_r) \right) & -\Delta L \sin(2\theta_r) \\
-\Delta L \sin(2\theta_r) & \lambda \left( \Sigma L + \Delta L \cos(2\theta_r) \right)
\end{bmatrix}
\begin{bmatrix}
\nu_{dHF} \\
\nu_{qHF}
\end{bmatrix}
\]

(5)

\[
\Sigma L = \frac{L_{dHF} + L_{qHF}}{2}
\]

(6)

\[
\Delta L = \frac{L_{dHF} - L_{qHF}}{2}
\]

(7)

b) Torque estimation in SPMSMs using HF signal injection

The modified torque equation obtained from (2)-(3) is shown in (8). It is observed from (8) that the estimated \( d \)-axis HF inductance is used to scale the nominal PM flux linkage, \( \lambda_{pm} \). The \( d \)-axis HF inductance is function of the \( d \)-axis reluctance variation, reflecting therefore saturation effect on \( d \)-axis. Fig. 1 shows a simplified representation of the equivalent magnetic circuit of a 2-pole 3-slot SPMSM; this machine configuration has been used for exemplification purposes due to its simple structure. The equivalent magnetic circuit is composed of: three phase coils, represented by abc flux source,
variable reluctance components on the soft-iron taking into account saturation effect and PM generate flux; the PM flux path being aligned with the $d$-axis. It can be concluded that, for an SPMSM, the saturation effect on $d$-axis HF inductance is function of the PM flux linkage operating point; a linear relationship between $d$-axis HF inductance and PM flux linkage operating point has been assumed in this case. This relationship was achieved on an empirical basis, development of a mathematical model is a subject of ongoing current research.

$$T_{\text{out}} = \frac{3}{2} P \left[ \frac{L_{\text{p unt}} L_{\text{HFFo}} + L_{\text{HFFo}} i_d}{L_{\text{HFFo}}} \right]$$

where $\lambda_{\text{pm0}}$ and $L_{\text{HFFo}}$ are the PM flux and $d$-axis HF inductance at the room temperature ($T_{\text{r0}}$) and when no $dq$-axes fundamental current is injected.

Fig. 2 shows schematically the implementation of the proposed method. The HF voltage is injected superimposed on top of the fundamental voltage. HF inductances are estimated from the commanded HF voltage and the resulting HF current. Finally, the estimated $d$-axis HF inductance is used for scaling the PM flux linkage to improve the real-time torque estimation. Since $d$ and $q$-axis HF inductances are estimated online, variations due to changes of PM temperature or $d$ and $q$-axis current levels [18] do not affect to the accuracy of the method.

c) HF inductance estimation in SPMSMs using HF signal injection

If a pulsating HF voltage is injected in the stator terminals of the machine (9), the resulting HF current is represented by (12), where $V_{HF}^*$ is the magnitude of the injected HF signal, $\theta_{HF}$ is the phase of the HF signal (10), $\omega_{HF}$ is the frequency of the HF signal, $\hat{\theta}_r$ is the injection angle of the pulsating HF voltage (11) and $\phi$ is an arbitrary angle; e.g. if $\phi=0$ the pulsating HF voltage will be injected in the $d$-axis of the machine, while if $\phi=\pi/2$ it will be injected in the $q$-axis. In the injection reference frame, (12) is transformed into (13).

$$\begin{bmatrix} V_{HF}^* \sin(\theta_{HF}) \\ V_{HF}^* \cos(\theta_{HF}) \end{bmatrix} = \begin{bmatrix} \cos(\hat{\theta}) & -\sin(\hat{\theta}) \\ \sin(\hat{\theta}) & \cos(\hat{\theta}) \end{bmatrix} \begin{bmatrix} i_{dHF}^* \\ i_{qHF}^* \end{bmatrix}$$

$$\theta_{HF} = \omega_{HF} t$$

(9)

$$\hat{\theta}_r = \theta_r + \phi$$

(10)

$$\begin{bmatrix} i_{dHF}^* \\ i_{qHF}^* \end{bmatrix} = \frac{V_{HF}^*}{\omega_{HF} (\Sigma L^2 - \Delta L^2)} \begin{bmatrix} \cos(\hat{\theta}) + \Delta L \cos(2\theta_r - \hat{\theta}_r) \\ \sin(\hat{\theta}) + \Delta L \sin(2\theta_r - \hat{\theta}_r) \end{bmatrix}$$

$$\begin{bmatrix} \hat{i}_{dHF}^* \\ \hat{i}_{qHF}^* \end{bmatrix} = \frac{V_{HF}^*}{\omega_{HF} (\Sigma L^2 - \Delta L^2)} \begin{bmatrix} \Sigma L + \Delta L \cos(2\theta_r - \hat{\theta}_r) \\ \Delta L \sin(2\theta_r - \hat{\theta}_r) \end{bmatrix}$$

(12)

(13)

IV. FEM results

Finite element analysis (FEA) simulation results are presented in this section to validate the proposed method. Fig. 3 shows a schematic representation of the SPMSM that will be used; Table 1 shows the parameters of the machine. Fig 4 shows simulations results changing both $I_d$ and $I_q$ currents from -15A (-1 pu) to 15A (1 pu), in steps of 1.5 A, half of the operating points in flux-weakening region ($\omega < 0$) and half in flux-strengthening region ($\omega > 0$). A HF voltage signal of 10V and 250Hz, injected between $d$ and $q$-axes (i.e. $\hat{\theta}_r = \theta_r + \pi/4$), is used for all FEA simulation results.

Fig. 4a and 4b shows the estimated $d$ and $q$-axes HF inductances. It is observed that the $d$-axis inductance is smaller than $q$-axis inductance due to saturation, which is an expected result. Also, it can be noticed that the $d$-axis inductance is more prone to the armature current since the $d$-axis flux path is biased with PM flux source; it is important to note that the armature current flux path in $d$-axis is shared with PM flux path. The saturation level of $d$-axis flux path is indirectly estimated in the form of $d$-axis HF inductance in real-time for dynamic torque estimation.

Fig. 4c-e show the measured torque ($T_{\text{meas}}$), the estimated torque using the general torque equation (3) ($T_{\text{est}}$) and the estimated torque using the proposed method (8) ($T_{\text{out com}}$), note that the HF inductances shown in Fig. 4a and 4b are used for torque estimation when using the proposed method, see (8).

Fig. 4f and 4g show the torque estimation error when using the general torque equation and when using the proposed method.

<table>
<thead>
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<th>Table 1. Machine parameters</th>
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<td>$P_{\text{rated}}$ [kW]</td>
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method respectively. It is observed that the torque estimation error when using the proposed method is <4Nm (0.05 pu), while it is <11Nm (0.137 pu) when using the general torque equation; the maximum of the torque estimation error when using (3) occurs in the heavily saturated region (e.g. $I_d$ and $|I_q|>0.8$ pu), the proposed technique improves the estimation in this region. This is because the general torque equation assumes constant PM flux linkage and $dq$-axis inductances (see (3)), while the
proposed method dynamically adapt these parameters from the response to the injected HF signal.

V. Experimental results

Experimental results are shown in this section. Fig. 5 shows the experimental setup. The test SPMSM is the same describe in Section IV. It is loaded with an axial PMSM (EMRAX 228 [40]) driven by a BAMOCAR-PG-D3 power converter [41]; the setup including an Interface T3 torque sensor [42]. A HF voltage signal of 10V and 250Hz, injected between \(d\) and \(q\)-axes (i.e. \(\dot{\Theta} = \Theta + \pi / 4\)), is used for all experimental results.

Fig. 6 shows the general control block diagram of the machine while Fig. 7 shows the signal processing required for the torque estimation. As already stated, the pulsating HF voltage, \(V_{\text{dHF}}^*\), is injected between \(d\) and \(q\)-axis, the resulting HF current, \(i_{\text{dHF}}^*\), containing information of the inductances of the machine. \(Dq\)-axis inductances are obtained using (15) and (16). The torque is finally estimated using (8). It can be observed from Fig. 6 that knowledge of rotor position is required. For the experimental results shown in the paper an encoder with 4096 ppr has been used. Simultaneous use of HF signal injection for rotor position estimation and torque estimation should be feasible, but has not been investigated yet.

Fig. 8a shows the \(d\) and \(q\)-axes fundamental currents when the test machine is operated with positive \(d\)-axis current, i.e. flux-intensifying current (10A). Fig. 8b shows the \(d\) and \(q\)-axes HF currents, see (14); a band pass filter of 100Hz being used to isolate the HF currents. Fig. 8c shows the estimated HF inductances using (15) and (16). It is observed from Fig. 8c that the \(d\)-axis HF inductance is smaller than the \(q\)-axis HF inductance due to saturation, which was an expected result.
since the machine is being operated in the flux-intensifying region. Fig. 8d shows the measured torque using the torque sensor [45] ($T_{meas}$), the estimated torque using the general torque equation (3) ($\hat{T}_{\text{gen,con}}$) and the estimated torque using the proposed method (8) ($\hat{T}_{\text{est, HF}}$).

Finally, Fig. 8e shows the torque estimation error using both, the general torque equation and the proposed method; the reduction of its mean value (continuous torque) for the second being evident.

Fig. 9 shows the response to a step-like $q$-axis current command. Fig. 9a shows the measured torque and the estimated torque using the proposed method (8), while Fig. 9b shows the torque estimation error. It is observed that the dynamic response of the estimation is in the range of milliseconds.

Fig 10 shows experimental results of the proposed method for different $I_d$-$I_q$ working conditions. Fig. 10a and b shows the estimated $d$ and $q$-axes HF inductances; it is noted that the results in Fig. 10a and 10b are in good agreement with the simulation results, see Fig. 4.

Fig. 10c-e show the measured and estimated torques using the general torque equation (3) and the proposed method (8) respectively, Fig. 10f and 10g showing the corresponding estimation errors. SPMSMs are typically operated with $I_d \leq 0$. Torque estimation error in this region is using the proposed method is reduced by $\approx$50% with respect to the conventional method. Maximum error using both the conventional and the proposed method occurs when the machine is heavily saturated ($I_d$ & $I_q >0.8$ pu); still there is a reduction of the error in the range of $\approx$50% using the proposed method. It must be noted that operation with large positives values of $I_q$ (flux intensifying region) is unusual in SPMSMs.

Finally, Fig. 11 shows experimental results using the proposed method vs. $I_d$&$I_q$ for three different speeds. It can be observed that the torque estimation error slightly increases as the speed decreases.

VI. Conclusions

This paper proposes a new online parameter estimation method for SPMSMs aimed to improve the accuracy of torque estimation. The proposed method uses a modified torque equation based of HF parameters of the machine. The parameters involved in the modified torque equation are estimated from the response to a HF signal injected in the stator terminals. The HF signal is superposed on top of the fundamental excitation, allowing therefore real time torque estimation without interfering with the normal operation of the machine. FEA simulation results and experimental results injecting a HF voltage signal have been provided to demonstrate the viability of the proposed method. It has been shown that the proposed method improves the torque estimation compared to the general torque equation method.

VII. References

Fig. 10.- Experimental results. a) Estimated $d$-axis HF inductance (15), b) estimated $q$-axis HF inductance (16), c) Measured torque, d) estimated torque using the general torque equation (3), e) estimated torque using proposed method (8), f) torque estimation error usign the general torque equation and g) torque estimation error usign the proposed method. $V_{HF}=10V$, $f_{HF}=250Hz$, $\omega_r=2\pi \cdot 66$ rad/s.
Fig. 11. – Experimental results. Torque estimation error vs. \( I_d \) & \( I_q \) using the proposed method for three different speeds. \( V_{dd}=10V, f_{saw}=250Hz \).


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