High Frequency Impedance Analysis for Sensorless Starting of Wound Rotor Synchronous Machines


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Abstract: In sensorless control for synchronous machines at low speed and standstill, the position estimation can be sensitive to the choice of the carrier frequency of the injection method. Moreover, electromagnetic saturation or temperature variation in the machine might also affect the estimation error. In order to better describe the high-frequency (HF) behaviour of the machine, the effective HF inductances and resistances are presented in this paper. Then, the analytical expression for the carrier frequency dependent error is explained using the calculated HF-equivalent model and is proposed to be integrated into the sensorless control scheme when a rotating HF voltage injection is employed. Numerical simulations highlight the frequency dependent error and prove the satisfactory operation of the compensation.

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1. INTRODUCTION

In the more electric aircraft, the Brushless Exciter Synchronous Starter/Generators (S/G) present a high interest for the traditional generation mode as well as for the starter mode due to their ability to provide high torque to their associated engine. Precise knowledge of the rotor position is essential for Field Oriented Control (FOC) of the main machine: a Wound Rotor Synchronous Machine with damping windings (WRSM). However, position sensors are hard to implement in difficult environment conditions (high temperature, humidity), and any failure while operating might present security problems.

Hence, the main advantage of the sensorless control is to avoid the above-mentioned problems, besides the cost and the complexity reductions. The difficulty to suppress position sensors is that the position is not observable at standstill nor at very low speed. For salient machines, the use of HF carrier injection methods to estimate the rotor position is possible because the injected stator or rotor currents provide the system’s observability, see Koteich et al. (2015). Implementation of sensorless control methods using rotating or pulsating HF carrier injection on a WRSM can be found in the works of Maalouf et al. (2011) and respectively Griffo et al. (2012); Rambetius and Piepenbreier (2014).

Recent methods proposed in the literature require a HF signal to be injected into the rotor winding, for example in: Koteich et al. (2015); Rambetius and Piepenbreier (2014); Choi et al. (2013). These methods cannot be directly applied to a S/G because the rotor current cannot be measured or mechanically approached due to the structure of the machine, Maalouf et al. (2011). An approach for this architecture is to use the exciter stator current harmonics as carrier signals to determine the rotor position, see Uzel et al. (2014).

The analysis presented in this paper treats rotating high frequency carrier injection applied on a WRSM. Last decades studies have shown that the integrity of the signal that contains the position dependent harmonics is essential for a proper estimation: all distortions are accumulated and reflected as a bias or an oscillation over the estimated signal. In this context, signal processing and phase delay compensation play an important role in the structure of the position observer. Factors that can introduce phase delays or distortions are:

- Architecture and characteristics of the machine: saliency ratio, presence of secondary saliencies, saturation and cross-saturation effects, see Rambetius et al. (2014); El-Serafi et al. (1988); El-Serafi and Abdallah (1992); Chedot et al. (2007); Raca et al. (2008); Reigosa et al. (2010)
• Signal processing delays, see Mansouri-Toudert et al. (2013), distortions caused by the control loop, see Ovrebø (2004); Garcia et al. (2006).
• Dead-time and non-ideal inverter characteristics, see Raca et al. (2008); Garcia et al. (2006).

This paper proposes a HF equivalent model for WRSM which allows to analyse the influence of the damper windings and the parameter variation on the HF-saliency of the machine. With this model, the estimation errors due to the excitation frequency and the parameter evolution can be predicted. A compensation scheme is proposed and its efficiency is supported by numerical simulations.

The paper is organised as follows: section 2 is dedicated to the electrical and mechanical equations of the machine taking into account the magnetic saturation and the WRSM HF model is further proposed; section 3 presents the principle of rotating HF carrier injection and analyses the influence of the saturation in the HF model; section 4 deals with the position estimation using a tracking observer and phase compensation; the paper is concluded with simulation results and final remarks.

2. MODEL OF THE WRSM

In this section, the main machine of the S/G is modelled as a WRSM with damper windings. The damper windings are modelled by two short-circuited windings on the d- and q-axis respectively. It has been shown that short-circuited windings contribute to the electromagnetic saliency and that they interact with the HF test-signal, see Graus and Hahn (2014). In order to better describe the HF-behaviour of the machine, the effective inductances and resistances, also known as subtransient, will be calculated in this section.

Under the classical assumptions, the Park transformation is used in order to obtain the electrical equations of the machine in the stator frame:

$$
\begin{align*}
\psi_d &= R_s i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q, \\
\psi_q &= R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d.
\end{align*}
$$

The rotor winding’s parameters are indicated by (f). The damper windings, in quadrature, are indicated by (D) on the d-axis and by (Q) on the q-axis. All the rotor parameters are referred to the stator and marked by a prime symbol (‘) for a complete description of the model and corresponding relationships to a model in the natural frame, see Barakat et al. (2010).

Under the assumption that the inductances on the d-axis are decoupled from those on q-axis (no cross-coupling terms are taken into account), the flux linkage relationship to currents is described by the matrix products in (2, 3):

$$
\begin{bmatrix}
\psi_d \\
\psi_q \\
\psi_D \\
\psi_Q
\end{bmatrix} =
\begin{bmatrix}
L_d & L_{ad} & L_{ld} & i_d \\
L_{ad} & L_{ld} & L_{ld} & i_q \\
L_{ad} & L_{ld} & L_{ld} & i_f \\
L_{ad} & L_{ld} & L_{ld} & L_{lq}
\end{bmatrix}
\begin{bmatrix}
\psi_d \\
\psi_q \\
\psi_D \\
\psi_Q
\end{bmatrix} =
\begin{bmatrix}
L_d & L_{ad} & L_{ld} & i_d \\
L_{ad} & L_{ld} & L_{ld} & i_q \\
L_{ad} & L_{ld} & L_{ld} & i_f \\
L_{ad} & L_{ld} & L_{ld} & L_{lq}
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q \\
i_f \\
i_Q
\end{bmatrix}.
$$

The above-mentioned inductances are decomposed in the main magnetising inductances ($L_{ad}$, $L_{aq}$) and leakage inductances ($L_{ls}$,$L_{lf}$,$L_{ld}$,$L_{lq}$) for each winding:

$$
\begin{align*}
L_d &= L_{ad} + L_{ls}, \\
L_q &= L_{aq} + L_{ls},
\end{align*}
$$

$$
\begin{align*}
L_D' &= L_{ad} + L_{lf}, \\
L_Q' &= L_{aq} + L_{lq},
\end{align*}
$$

$$
\begin{align*}
L_f &= L_{ad} + L_{lf}.
\end{align*}
$$

The mechanical equation is presented in 7 with: $p$, the number of pole pairs, $\Gamma_e$, the electromagnetic torque, $\Gamma_L$ the load torque, $J$, the total moment of inertia and $f$, the viscous friction coefficient.

$$
J \frac{d\omega_e}{dt} + f \omega_e = p(\Gamma_e - \Gamma_L), \quad \Gamma_e = \frac{3}{2} p(\psi_d i_q - \psi_q i_d).
$$

2.1 Magnetic saturation effect

Because of efficiency requirements, S/G designers are optimising the mass versus loss trade-off. Therefore, the integrated S/G are built to operate in high saturation mode resulting in a non-linear relation between the fluxes and currents, a complex phenomenon intensely studied for the last decades, see for example El-Serafi et al. (1988); El-Serafi and Abdallah (1992); Chedot et al. (2007).

The model presented at the beginning of this section is based on the hypothesis that all the inductances are constant. A saturated flux model is obtained from the linear model by considering the inductances dependent on the currents circulating in the machine, as in El-Serafi et al. (1988); El-Serafi and Abdallah (1992); Chedot et al. (2007). Therefore, the saturated d– and q– axis inductances are obtained by modifying their unsaturated values using a non-linear coefficient, $K_{sat}$, calculated on the basis of the equivalent magnetizing current $i_m$ as in Maalouf et al. (2011). For simplification reasons, the saturation factor is considered equal on both axis,

$$
K_{sat} = f(i_m(i_d, i_f, i_q)).
$$

In this kind of representation, the leakage inductances have their magnetic paths in the air, therefore they are not affected by saturation, see El-Serafi et al. (1988). The main inductances have their magnetic paths in the body of the machine and will be affected by saturation (the overline marks a saturated parameter):

$$
\begin{align*}
\overline{L}_{ad} &= L_{ad} K_{sat}, \\
\overline{L}_{aq} &= L_{aq} K_{sat}.
\end{align*}
$$

2.2 Simplified WRSM model at high frequency

In the perspective of a HF carrier injection, a simplified model in the rotor reference frame of the stator voltage model (1) is further presented. Under the hypothesis that $\frac{d}{dt}K_{sat} \approx 0$, after the expansion of the flux expressions using (2) and (3), the stator equations are written:

$$
\begin{bmatrix}
\dot{v}_d \\
\dot{v}_q
\end{bmatrix} =
\begin{bmatrix}
R_s + L_{ad} s & -\omega_e L_{ld} \\
\omega_e L_{ld} & R_s + L_{aq} s
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} +
\begin{bmatrix}
L_{ad} s & -\omega_e L_{aq} \\
\omega_e L_{aq} & L_{ad} s
\end{bmatrix}
\begin{bmatrix}
\dot{i}_d \\
\dot{i}_q
\end{bmatrix} +
\begin{bmatrix}
L_{ad} s & -\omega_e L_{aq} \\
\omega_e L_{aq} & L_{ad} s
\end{bmatrix}
\begin{bmatrix}
i_f \\
i_q
\end{bmatrix} +
\begin{bmatrix}
L_{ad} s & -\omega_e L_{aq} \\
\omega_e L_{aq} & L_{ad} s
\end{bmatrix}
\begin{bmatrix}
\dot{i}_f \\
\dot{i}_q
\end{bmatrix},
$$

where $s$ is the Laplace differential operator.

Knowing that the carrier frequency of the injected signal is higher than the actual rotor angular velocity, $\omega_e << \omega_h$, for a low speed analysis, we can consider $\omega_e \approx 0$. Therefore, the coupling terms dependent on the rotor speed can be neglected for the further HF-analysis:
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