ASYNCHRONOUS STARTING OF PERMANENT-MAGNET SYNCHRONOUS MOTOR. MODELLING AND SIMULATION

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The paper objective is the determination of dynamic characteristics of a permanent-magnet synchronous machine (PMSM). A dynamic d, q model of the PMSM elaborated in the circuit theory is used. On this basis, there is made a comparative detailed analysis of the dynamic processes for asynchronous starting of a PMSM and of a correspondent induction motor (IM). The study offers, with high precision, qualitative and quantitative information regarding electrical, magnetic and mechanical stresses, useful in the design stage of a PMSM, which are difficult or almost impossible to be obtained other way. The simulations can be also valorized for the pre-determination of the behaviour of a given PMSM, in a particular dynamic operation.

1. INTRODUCTION

PMSM is nowadays frequently used in different applications, from powers of kW and less (in medicine, domestic robots etc.) up to MW in industrial installations (cement and petroleum industry, pumping systems, marine propulsion) and is the object of a lot of large researches. [1–8]. This option is justified through its advantages over IM: relatively simple construction, high power factor, high power density, reasonable costs and, very important, high efficiency. The high power PMSM efficiency can reach values of 98% while the induction motors efficiency is limited to 94%–96% at full load [9]; the drawbacks regard the magnets costs and the demagnetization phenomenon.

The dynamic performances in the starting and synchronization process are generally more reduced in a PMSM. In the competition with IM, the starting characteristics of a PMSM are of primary importance. The main problem of PMSM regards the braking torque produced by the permanent magnet on asynchronous operation. Ensuring, in addition, some contradictory conditions (reasonable starting currents and torques), solving the transient synchronization, make the design specific and difficult, especially the rotor design and the PMSM overall design; the material quality and the geometry of arrangement in the rotor of the permanent magnet and of the squirrel-cage get a major importance [10–16]. The simulations carried out for establishing the parameters and the constructive solutions, become a compulsory stage of design; they have to take into account the specific operation conditions of the motor.

This paper is inscribed in the line of these preoccupations. The dynamic mathematical model of PMSM is explained; there are simulated, in details, and compared dynamic characteristics, for the asynchronous starting and synchronization of PMSM and IM.

2. GENERAL EQUATIONS OF PMSM

The general voltage equations with respect to the rotor reference frame, in restricted matrix representation have the form

\[
\begin{bmatrix}
\psi_d \\
\psi_q \\
\psi_{D} \\
\psi_{Q}
\end{bmatrix} = \begin{bmatrix}
R_s & R_d & 0 \\
R_d & R_d + R_Q & -\omega \\
0 & -\omega & 0
\end{bmatrix} \begin{bmatrix}
d \psi_d \\
d \psi_q \\
d \psi_{D} \\
d \psi_{Q}
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
d \psi_d \\
d \psi_q \\
d \psi_{D} \\
d \psi_{Q}
\end{bmatrix} + \begin{bmatrix}
u_d \\
u_q \\
v_D \\
v_Q
\end{bmatrix} \tag{1}
\]

In eq. (1) \(u_d, u_q\) are the stator voltages, \(\psi_d, \psi_q, \psi_{D}, \psi_{Q}\), \(i_d, i_q, i_D, i_Q\), are the flux linkages and currents of the stator and rotor respectively, \(R_s, R_d, R_Q\) are the stator and rotor resistances and \(\omega\) is the electrical speed of the rotor. The flux linkages from (1) have the form

\[
\begin{align*}
\psi_d &= L_d i_d + L_{md} i_D + \Psi_{Ed} \\
\psi_q &= L_q i_q + L_{mq} i_Q \\
\psi_D &= L_D i_D + L_{md} i_d + \Psi_{ED} \\
\psi_Q &= L_Q i_Q + L_{mq} i_q \\
\Psi_{Ed} &= L_{md} i_E = \Psi_p \\
\Psi_{ED} &= \Psi_p 
\end{align*} \tag{2}
\]

where \(L_d, L_q\) and \(L_{md}, L_{mq}\) are the stator and q axis cyclic synchronous inductances and magnetizing inductances, respectively; \(L_D, L_Q\) denote rotor inductances. Among the main and leakage inductances the following relations are valid

\[
\begin{align*}
L_d &= L_{md} + L_{dr} \\
L_q &= L_{mq} + L_{qr} \\
L_D &= L_{md} + L_{Dr} \\
L_Q &= L_{mq} + L_{Qr} \\
L_{dr} &= L_{qr} 
\end{align*} \tag{3}
\]

Index \(\sigma\) is attached to the leakage inductances; \(L_{s\sigma}\) is the stator leakage cyclic inductance.

According to (2), it is considered that the lines of the flux linkage \(\Psi_p\) of the permanent magnet, produced by the hypothetic rotor winding \(E\), crossed by the constant...
current \( i_E \), link all the rotor windings and the stator winding placed in the \( d \)-axis. All the rotor quantities are referred to the stator side. The following leakage coefficients are introduced

\[
\sigma_d = \frac{L_d}{L_d}, \quad \sigma_q = \frac{L_q}{L_q}, \quad \sigma_D = \frac{L_D}{L_D}, \quad \sigma_Q = \frac{L_Q}{L_Q}
\]

Amongst the leakage coefficients, we have the following recurrence relations

\[
\begin{align*}
(1 - \sigma_d)(1 - \sigma_D) &= 1 - \sigma_{dd} \\
(1 - \sigma_q)(1 - \sigma_Q) &= 1 - \sigma_{qq}.
\end{align*}
\]

Taking into account (3) and (4) we have

\[
\begin{align*}
L_{ld} &= L_d(1 - \sigma_d) = L_D(1 - \sigma_D) \\
L_{lq} &= L_q(1 - \sigma_q) = L_Q(1 - \sigma_Q).
\end{align*}
\]

When the leakage coefficients are considered, the flux linkages from (2) get the form

\[
\begin{align*}
\Psi_d &= L_d \sigma_d i_d + L_d(1 - \sigma_d)(i_d + i_D) + \Psi_p \\
\Psi_D &= L_d \frac{1 - \sigma_d}{1 - \sigma_D} \sigma_D i_D + L_d(1 - \sigma_d)(i_d + i_D) + \Psi_p \\
\Psi_q &= L_q \sigma_q q + L_q(1 - \sigma_q)(i_q + i_q) \\
\Psi_Q &= L_q \frac{1 - \sigma_q}{1 - \sigma_Q} \sigma_Q i_Q + L_q(1 - \sigma_q)(i_q + i_Q).
\end{align*}
\]

By replacing the currents \( i \) in (1), according to (7), there are obtained the voltage equations with flux linkages \( \psi \) as state variables in the mathematical model of PMSM; mutually, by eliminating the flux linkages \( \psi \), the currents \( i \) become state variables.

In (1)

\[
\begin{align*}
u_d &= \sqrt{2} U \cos(\omega t + \varphi_u - \beta), & u_q &= \sqrt{2} U \sin(\omega t + \varphi_u - \beta),
\end{align*}
\]

where

\[
\beta = \int_0^t \omega dt + \beta_0,
\]

\( \varphi_u, \beta_0 \) fix the value of the stator A-phase voltage and the rotor \( d \)-axis position relatively to the axis of the same phase, considered as reference at \( t = 0 \).

To the voltage equations (1) for the complete dynamic mathematical model of PMSM, the motion equation is added

\[
m = \frac{3}{2} p \left[ \psi_d i_q - \psi_q i_d \right] = \frac{3}{2} p \left[ L_{md} i_d + i q_L q - L_{mq} i_q + i Q L Q \right] - \psi_p.
\]

(8)

\[J
\]

is the inertia of the rotor and \( m, M_r \) are the electromagnetic and load torques.

The speed of the main magnetic field \( \psi_m \) during the dynamic processes will be

\[
\omega_\psi = \frac{d \varphi}{dt} + \omega,
\]

where

\[
\frac{d \varphi}{dt} = \frac{1}{\psi_m} \left( \frac{d \psi_m}{dt} \cos \varphi - \frac{d \psi_m}{dt} \sin \varphi \right).
\]

(9)

\( \varphi \) fixes the position of \( \psi_m \) in the \((d, q)\) reference.

Equations (1) defined considering (7) together with (8), (9) specify the dynamic behaviour of PMSM in general case.

3. SIMULATION RESULTS

In order to emphasize the functional particularities of a PMSM in dynamic regime in comparison with an IM, there is detailed the starting process at rated voltage \( U_n = 220 \) V, according to the mathematical model (1), with and without permanent magnet, respectively. The same parameters have been taken into account; in order not to occur the magnetic asymmetry in the characteristics comparison, the same two-axis synchronous inductances have been considered. The parameters of the machine analyzed are listed in Appendix. There have been plotted representative characteristics regarding currents, torques, flux linkages and electrical angular speeds of the main rotating magnetic field and of the rotor. It has been considered that \( \varphi_u = \beta_0 = 0 \). The figures affected by indexes ‘a’, ‘b’ refer to PMSM and IM, respectively.

In Fig. 1 there are plotted the currents \( i(t) \). The differences between the two characteristics are notable. The current shock at \( t = 0 \) is practically independent upon the presence or absence of the permanent magnet but in the next moments the oscillations remain higher in PMSM and are practically extended on the entire period of starting, sensitively increased; getting the synchronism, through the permanent magnet presence, is strongly oscillating.
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In Fig. 2 there are plotted the torques $m(t)$ and $m(\omega)$. The observations regarding the characteristics $m(t)$ (Figs. 2a1, 2b1) are of the same nature as those for $i_\ell(t)$. The conditions of the first moments of connecting to the supply network are clearly shown in the characteristics $m(\omega)$ (Figs. 2a2, 2b2); for PMSM there result values much increased of the electromagnetic torque, which remains strongly oscillating until the synchronization is reached and, over a significant period, with important negative values. The details from Figs. 2a3, 2b3 show associated oscillations in the rotor angular speed $\omega$ too. They are very pronounced in PMSM and are accompanied including by an important decrease of $\omega$ (Fig. 2a1 plotted for $t = 0 – 0.7$ s).
Figures 3–6 emphasize the magnetic stresses. The characteristics $\psi_{md}(t)$ are plotted in Figs. 3a, 3b and suggest sensitively higher magnetic stresses and oscillations of them over a range which is much more important in case of PMSM. The characteristics $\psi_{md}$, $\psi_{mq}$ present the flux linkage $\psi_m$ in $(d, q)$ coordinates. The entire starting process is emphasized in Figs. 4a, 4b. There results a representation which is more complicated and with more intense stresses in case of PMSM. For a more convenient analysis, the representations plotted before are detailed in Figs. 4a2, 4a3 for PMSM and 4b2 for IM. By 1, 2 there have been emphasized the initial and final moments of the starting process.
The same conclusions as before there are obtained by comparing the characteristics $\psi_D(t)$ (Figs. 5a, 5b) and $\psi_Q(t)$ (Figs. 6a, 6b). The representations $\psi_D(t)$, $\psi_Q(t)$ provide interesting qualitative and quantitative information about their evolution over the entire starting process.

Figures 7 present, in connection, the electrical transient speeds $\omega_\psi(t), \omega(t)$ of the main magnetic field and of the rotor. Figures 7a1 and 7b1 refer to the entire starting process. By comparison, in Fig. 7a1, the permanent magnet presence causes a more complicated variation of $\omega_\psi(t)$, with a lot of reversals over a longer period. The same thing is also found for the over-synchronous transient speeds; including getting the synchronism is accompanied by visible oscillations. The strong breaking effect over the starting period, of the electromagnetic torque component caused by the permanent magnet, is also noticed in the rotor oscillating speed $\omega(t)$ and finally in a sensitive increase of the starting time. Figures 7a2, 7a3, respectively 7b2 detail, for clarity, the speeds $\omega_\psi(t), \omega(t)$ over significant time intervals.
the speeds \( \omega_p \) are different at \( t = 0 \) (in PMSM, \( \omega_p(0) = 0 \) (Fig. 7a), and in IM \( \omega_p(0) = 0.5 \omega_0 \) (Fig. 7b)); a low number of reversals of \( \omega_p \) (in this case two reversals) and, consequently, lower oscillations of \( \omega(t) \) are noticed in IM.

4. CONCLUSIONS

In this paper there is specified the dynamic mathematical model of PMSM; for generality, there are considered different windings by two axes and magnetic asymmetry.

The model capitalization is carried out by direct simulation of the dynamic asynchronous starting process. In order to emphasize the effects caused by the permanent magnet, there have been plotted comparatively representative characteristics, for a given machine, in the presence and in the absence of it, respectively.

Overall, the permanent magnet is the origin of some unfavourable asynchronous dynamic characteristics, with an increase of the electromagnetic and mechanical stresses and of the starting time.

Several other curves obtained, but which are not plotted, allow adjacent important conclusions.

The damping winding must be carefully dimensioned for satisfying conditions, some of them contradictory: to ensure reasonable values in the first moments of starting for the electromagnetic torque and the input current; to compensate the breaking effect of the permanent magnet over the entire starting period and to contribute to getting the synchronism; to protect the permanent magnet against the demagnetizing effect in asynchronous operation as well as against the load shocks in case of synchronous operation.

The electrical angles \( \varphi_p \) and \( \beta_0 \) influence in an important extent the amplitude of the electromagnetic and mechanical stresses which are immediately subsequent to coupling to the supply network.

PMSM will really find a wide use in industrial applications, in the extent in which the asynchronous and synchronizing transients are solved in a convenient way for practice.

APPENDIX

The PMSM parameters used for simulation are \( R_s = 2 \Omega \), \( R_D = R_D^C = 4.5 \Omega \), \( L_{sd} = L_{sd}^C = 0.21 \text{ H} \), \( L_{qd} = L_{qd}^C = 0.034 \text{ H} \), \( L_{sQ} = 0.032 \text{ H} \), \( p = 2 \), \( J = 0.048 \text{ kg m}^2 \), \( \psi_p = 0.98 \text{ Wb} \).

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