Common approaches in vector control design of induction motor and permanent-magnet synchronous motor

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Abstract. The article describes a way to generalize current control loop structure for AC drives, by implementing general PI gains calculation block. Article contains block diagram of generalized current control loop for smooth-air-gap and salient-pole machines. Electromagnetic torque estimator is represented, whose design based on stator voltage and current measurements. Results of simulation modeling of electromagnetic torque estimator in pair with field-oriented control are represented.

1. Introduction

Permanent-magnet synchronous motors (PMSMs) and induction motors (IMs) are the dominant type of motors used in manufacturing processes. From a stand point of control theory there is no so much difference between these AC machines, the main one lies in necessity of IM in rotor flux linkage estimation. Thinking this way the possibility to broaden application range of individual controller appears.

2. Description of equations in space-phasor form

One of the ways to describe voltage equations of AC motors in stationary reference frame is to represent them in the space-phasor form, in this case, equations will take the following form [1, 2]:

\[
\begin{align*}
\vec{u}_s &= \vec{i}_s R_s + \frac{d\vec{\psi}_s}{dt}; \\
\vec{u}_r' &= \vec{i}_r' R_r + \frac{d\vec{\psi}_r'}{dt} - j\omega_r \vec{\psi}_r',
\end{align*}
\]

where \(\vec{u}\) - voltage phasor, \(R\) - resistance of winding, \(\vec{\psi}\) - flux linkage, subscripts \(s\) and \(r\) define phasors belonging to stator and rotor respectively, superscript \(\prime\) defines rotor’s phasor in the stationary reference frame.
For induction machines with squirrel-cage rotor, rotor voltage phasor is considered to be zero, also as in the case of permanent-magnet synchronous motor. For the convenience of further design of control system, it is customary to change a stationary basis to rotating, which will allow us to look at controlled currents as direct currents. This way, new reference frame rotates with synchronous speed of stator flux linkage and describes any phasor in terms of real and imaginary part, which traditionally denoted as $d$ and $q$ axes.

Space-phasor of PMSM stator flux linkage determined as follows:

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r e^{j \theta_r} = L_s \vec{i}_s + \Psi_F e^{j \theta_r}, \quad (2)$$

where $L_s$- stator winding inductance; $L_m$- rotor winding inductance; $\Psi_F$- rotor flux linkage with stator windings; $\theta_r$- angle between stationary reference frame and rotating rotor reference frame.

PMSMs can be distinguished in terms of rotor saliency as follows: smooth-air-gap and salient-pole motors. Feature of smooth-air-gap machines lies in equality of direct- and quadrature-axes inductances, as at the same time salient-pole machines have different values of inductances and they ratio can vary in some range which adjusted by manufacturer. It should be noted here, that we will make an assumption of approximately equal inductances of salient-pole PMSMs and further consider them as ($L_{sd} = L_{sq} = L_s$).

There are several types of IM models, for further consideration, we will use reduced version of T-model, which combines simplicity of parameter calculation and still describes key dynamics of IM with high precision [3].

Parameters of equivalent circuit are defined as:

$$L_M = \frac{L_m^2}{L_r}, \quad R_R = R_r, \quad L_\sigma = L_s - L_M. \quad (3)$$

After substitution of these parameters and transformation perform, flux linkage equation will take the following form:

$$\vec{\psi}_s = (L_M + L_\sigma) \vec{i}_s + L_M \vec{i}_r e^{j \theta_r} = L_s \vec{i}_s + \vec{\psi}_R, \quad (4)$$

$$\vec{\psi}_R = L_M \vec{i}_s + L_M \vec{i}_r e^{j \theta_r}. \quad (5)$$

After expressing flux linkages (3) and (5), we substitute them in system of equations (1) and then we perform transformation to $d$-$q$ reference frame, by assuming that transform of phasor in stationary reference frame defined by next expression:

$$\vec{X}_g = \vec{X}_e^{-j \theta_g}, \quad (6)$$

where $\vec{X}_g$ is general phasor in $d$-$q$ reference frame, $\theta_g$- angle between stationary reference frame and $d$-$q$ reference frame.

As a result, we have general equation of PMSM in $d$-$q$ reference frame:

$$L_s \frac{d\vec{i}_s}{dt} = \vec{u}_s - (R_s + j \omega_g L_s) \vec{i}_s - j \omega_g \vec{\psi}_F, \quad (7)$$

and system of equations of IM in $d$-$q$ reference frame:

$$L_s \frac{d\vec{i}_s}{dt} = \vec{u}_s - (R_s + R_R + j \omega_g L_s) \vec{i}_s - (j \omega_r - \frac{R_R}{L_M}) \vec{\psi}_R, \quad (8)$$

$$\frac{d\vec{\psi}_R}{dt} = R_R \vec{i}_s - (\frac{R_R}{L_M} + j (\omega_g - \omega_r)) \vec{\psi}_R. \quad (9)$$
Figure 1. Current control loop general PMSM structure

3. Synthesis of general current control loop
To get linear relationship between current and voltage phasors in equations (7) and (8) we should compensate EMF phasor: $-j\omega_r\Psi_F$ in case of PMSM and $-(j\omega_r - \frac{R}{L_M})\vec{\psi}_{Rg}$ in case of IM. Besides EMF, one more term should be eliminated: $-j\omega_r L_s i_{sg}$, whose existance causes cross coupling between real and imaginary axis of regulated phasor.

It can be seen, that the PMSM and the IM equations have constant terms related to dynamical state, we can use this observation for the current regulator synthesis, which can be applied to both motors by using general block of PI gains calculation. We generalize those constants by terms $R'$ and $L'$, which will take following form for PMSM and IM respectively:

$$R' = R_s + R_a, \quad L' = L_s.$$  \hspace{1cm} (10)

$$R' = R_s + R_R + R_a, \quad L' = L_s - L_M.$$  \hspace{1cm} (11)

Thus, it becomes possible to design current control loop with generalized PI gain block, whose structure is shown for PMSM in Fig. 1.

At the initialization stage of a microcontroller, we enter the parameters $R'$ and $L'$. The next step is PI regulator gains calculation, which will be done with a use of next expressions:

$$K_{PC} = \alpha_c L', \quad K_{IC} = \alpha_c R', \quad R_a = \alpha_c L' - R' ,$$  \hspace{1cm} (12)

where $\alpha_c$ - cutoff frequency of desired closed loop system.

Some of the applications of vector control, in practice, require electromagnetic torque estimation with use of only stator voltage and current measurements. Electromagnetic torque of both PMSM and IM can be defined in stationary reference frame [4] through stator flux linkages and currents as follows:

$$T_e = \frac{3n_p}{2}(\psi_{s\alpha}i_{s\beta} - \psi_{s\beta}i_{s\alpha}).$$  \hspace{1cm} (13)

We can get flux linkage from system of equations (1) by considering phasors in stationary reference frame.
To estimate electromagnetic torque we use two measured states: stator voltages and currents. In practice, we get measurements with corresponding amount of noise, which will cause systematic error calculation at the integrator output. To avoid this, instead of integrator we will use first-order transfer function with time constant $\tau_c$ [5]. Thus, the expression of torque estimator in s-domain can be derived as:

$$T_e = \frac{3n_p}{2} \left( \frac{u_s\alpha - R_s i_{s\alpha}}{\tau_c s + 1} i_{s\beta} - \frac{u_s\beta - R_s i_{s\beta}}{\tau_c s + 1} i_{s\alpha} \right),$$

(14)

where $n_p$ is the number of pole pairs.

This estimator is convenient in realization and permits possibility of torque assessment with high enough precision in steady-state conditions.

Introduced estimator was implemented together with field-oriented control system of PMSM in simulation modeling environment Simulink. In a process of simulation, motor was affected by on-shaft load torques in a form of step input. Change of load conditions was implemented at times of 0.4 sec and 0.55 sec, values of load increase was 3 N*m and 10 N*m respectively. Results of torque estimation implemented in figures 2 and 3 below at speeds of 1500 rpm and 3000 rpm correspondingly.

Figure 2. Step responses to a given load at reference speed of 1500 rpm

Figure 3. Step responses to a given load at reference speed of 3000 rpm
4. Summary
The article presents methodological extensions to design algorithms of PI gains calculator, which is generalized across AC motors and broaden applicability of individual controller. In a pair with torque estimator controller structure of electric drive gets valid over a big range of manufacturing purposes. Torque estimator has room for improvements, and first one can be made is introduction of adaptive Kalman filter, which will cancel out most of the noise and estimation errors that arise at transition states.

In the near future it is planed to upgrate vector control system by introducing adaptive speed estimator which will cancel the need of actuator parameters monitoring sensors.

It is assumed that the results of the work will be included in the training course of the new master’s program “Conceptual Design and Engineering of Improving Energy Efficiency” for the training of engineering skills, scientific personnel and management personnel in the power industry, grid companies and related sectors [6].

Acknowledgments Research is also supported by educational and research grant 573879-EPP-1-2016-1-FR-EPPKA2-CBHE-JP by European program Erasmus+ (Project INSPIRE).

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