Control of anisotropic IPM machines

(Internal Permanent Magnet Machines)

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1 Control of anisotropic machines

In anisotropic machines, magnetic circuit does not have the same properties in all directions. For that reason, inductance in d-axis (Ld) is different than inductance in q-axis (Lq). In cases where the inductances do not change a great deal with current, the torque is equal to

Torque = K1 * Iq + 2*K2 * Id * Iq.

Parameter K1 depends on the flux created by permanent magnets. Parameter K2 depends on the difference between Ld and Lq. With Is being the current amplitude and "angle" being the angle between the flux and current, stator currents in d-axis and q-axis are Id = Is * cos(angle) and Iq = Is * sin(angle). The expression for the torque assumes the form

Torque = K1 * Is * sin(angle) + K2*Is*Is*sin(2*angle)

The first part of the expression is so called “electromagnetic torque”, while the second part is “reluctance torque”. There are also synchronous machines which do not have any magnets. Their torque is based on K2 and the difference between Ld and Lq. Such machines are called “reluctance” machines, as they rely on the difference between magnetic resistance (i.e. reluctance) in d-axis and q-axis.

Given the stator current Is, electromagnetic torque reaches its maximum for angle = 90 degrees. On the other hand, reluctance torque is maximal for angle = 45 degrees. When the machine has both torque components, the maximal torque Tem for the given current Is is obtained for an angle which remains between 90 degrees and 45 degrees. The exact value is function of K1, K2 and Is, angle = f(K1, K2, Is). In our drives, in order to facilitate the implementation, we simplify the expressions through piece-wise-linear approximation.

2 Machines with considerable magnetic saturation

In electrical machine application such as electric propulsion and renewable sources, it is of interest to reduce the weight and size of motors and generators. Design of such machines includes high flux-density and high torque-density. The operation at rated conditions includes considerable saturation of magnetic circuit. For that reason, inductances Ld and Lq exhibit considerable change with the current, and they cannot be considered constant. Namely, Ld exhibit considerable changes with Id, while Lq exhibits considerable changes with Iq.

In addition, the flux in one axis (say d-axis) changes the magnetic resistance (i.e. reluctance) in parts of magnetic circuit that are shared with the flux in orthogonal axis (say q-axis). For that reason, the inductance Ld/Lq also depends on the current in the other axis (q/d). Thus, Ld = f1(Id, Iq) and Lq = f2(Id, Iq), where f1 and f2 are nonlinear functions.

3 Maximizing torque-per-Amp

When considering electrical machines with permanent magnets, with considerable saturation of the magnetic circuit, with pronounced anisotropy and with cross-saturation, both flux linkages are nonlinear functions of corresponding currents,

$\Psi d = fd(Id, Iq)$, $\Psi q = fd(Is, Iq)$,

where fd and fq are nonlinear functions. Thus, the electromagnetic torque is obtained as

$Tem(Id, Iq) = \Psi d\ Iq - \Psi q\ Id = fd(Id, Iq) * Iq - fd(Id, Iq) * Id$.

Considering

$Id = Is * \cos(angle)$ and $Iq = Is * \sin(angle)$,

The torque is obtained as

$Tem = f_{em}(Is, angle)$

Most frequently, the goal is to obtain the desired torque Tem with the minimum indispensable current Is, that is, to maximize the Nm-per-Ampere ratio. Practical way of implementing this rule is to generate a 3-column Table where, for each Is, and “angle” is found that provides the maximum value of the function f_{em} (Is, angle). Then, the values of Is, angle and Tem are written in the table. In practical implementation, the reference torque points to the Table row where the corresponding values of Is and “angle” can be found.

It is important to notice that the function f_{em} (Is, angle) can be rarely found in analytical form. Most frequently, it comes out of FEM simulations of the electrical machine. Due to a relatively low number of feasible FEM simulations, said Table is bound to have limited number of cells which calls for interpolation.

4 Consideration of power losses

As explained previously, by considering the torque expression

$Tem = f_{em}(Is, angle)$,

the “angle” can be chosen which reduces the required stator current Is for the given torque reference. In operation with relatively low operating frequencies and relatively low iron losses, reduction of Is reduces at the same time the copper losses as well as the losses within the power converter.

In traction drives, it is often required to provide prolonged service at high speeds with elevated power. It often happens that the considerable part of losses takes place in iron. In such cases, it is not suitable to select “angle” that would minimize Tem/Is ratio. Instead, it is beneficial to establish

$[optimum\_angle, Is] = f(T_{em}, \Omega_m)$

which provides the desired torque/power, while at the same time minimizing the sum of copper and iron losses within the motor (or, the sum of copper, iron and converter power losses). Practical approach is, more or less, similar to the one adopted in (3).

5 The voltage margin and the operation in field weakening

All the previous considerations consider a saturable and anisotropic IPM supplied from PWM inverter with digital current controller, wherein the back-EMF does not reach the limit values of the supply voltage. In other words, previous considerations assume that the current controller has sufficient voltage margin. At higher speeds, when the back-EMF reaches the limit values of the supply voltage, it is necessary to resort to field weakening, namely, to reduce the flux and, therefore, the back-EMF so as to maintain the required voltage margin. In these operating conditions, the flux is lower than the value that would be optimal in the absence of a voltage limit.

The field-weakening strategy which preserves a certain amount of voltage margin reduces the flux and the back-EMF below levels that could otherwise be reached. For a voltage margin of 10%, the flux has to be reduced to 90% of the level that could otherwise be maintained. With 10% lower flux, the current required for the same torque would be 10% higher, while the copper losses and the converter losses would be some 20% larger. At the same time, the peak torque capability of the drive will be 10% lower than usual.

With the flux in field-weakening being already lower than the value that would be optimal in the absence of a voltage limit, the presence of additional voltage margin worsens the situation. So, in order to get the most out of the drive in the field-weakening region, it is necessary to use the maximum available voltage, leaving no margin at all. In the absence of margin, it is not possible to run the digital current controller. Thus, the high-speed control strategy has to change. It is necessary to maintain the maximum voltage amplitude (Us = Umax = const). The only control variable that remains available for the purposes of controlling the torque/power is the voltage orientation, that is, the angle between the voltage vector and the flux vector.

6 Integration and automation of saturable-anisotropic-IPM controls

The abovementioned control features require a set of manual adjustments suited for each specific IPM. It is possible to envisage automated procedures that would run the IPM and identify-and-approximate all the relevant nonlinear functions. In this manner, although quite specific and complex, the above listed control functions can be organized and implemented automatically, without the need for manual actions and adjustments performed by the operator.