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The cascade induction machine: a reliable and controllable motor or generator

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Abstract

This paper discusses and analyses a set of two induction machines, with $2p$ and $2q$ pole-pairs, respectively, connected in cascade. It highlights the design and development principles of a single unit version of a system consisting of two wire-wound rotor induction machines with their rotors connected in cascade. Presented performance analysis shows the described cascade machine, which is brushless and with no slip rings or commutators, as a reliable, efficient and practical machine that could replace the induction machine, which has a wire-wound rotor. An example of the conversion of a standard squirrel cage six pole induction machine into a $(6+2)$ pole induction machine, without rewinding the stator, is also presented together with simulation and measurements for asynchronous and synchronous modes of operation.

Keywords: Wire-wound rotor; Commutators; Squirrel cage induction machine

1. Introduction

The cascade machine consists of two wire-wound rotor induction machines with their rotors connected in cascade. If the two machines have a different number of pole-pairs, then they can be constructed as a single unit version with a single stator and a squirrel cage rotor. Otherwise, if the two machines have the same number of pole-pairs, the single unit version is not possible [1–9]. To date, reported work on the development of the cascade induction machine [1–9] has shown that the two machines making the cascade can be of the same size or different sizes, and can run in the same direction or in opposite directions. It has also been shown that the difference in the number of poles between the two machines is not the only parameter that affects the characteristic of the cascade unit.

Several parameters are involved in the construction of a cascade machine in order to be useful and adaptable for a specific application. This may explain why such a machine is yet to be made commercially available as ‘off-the-shelf’ product. This paper analyses two sets of induction machines connected in cascade and highlights the parameters affecting the cascade operational efficiency. Knowing these parameters and understanding well the operating and design principles will result in the development of an efficient practical machine. An example on the conversion of an ordinary squirrel cage induction machine into a cascade machine is also presented.

2. The equivalent circuit of a multipole machine

The transformation $\alpha = p\theta$ transforms a ‘p’ pole-pair machine into a single pole-pair machine. Here, α and θ represent the electrical and mechanical angles, respectively, of a ‘p’ pole-pair machine. According to this transformation, the ‘p’ pole-pair are ‘folded’ together and the input current of a ‘p’ pole-pair machine is equal to p times the input current of a single pole-pair machine for the same air gap flux. The input impedance of the ‘p’ pole machine is therefore equal to the voltage per pole divided by the total current, or $1/p$ times the impedance of a single pole-pair machine. The slip of the ‘p’ pole-pair machine is therefore equal to $(\omega - p\Omega)/\omega$, where Ω is the machine’s mechanical speed, ω is its line frequency and ‘$p\Omega$’ is its ‘folded’ speed or the electrical speed.

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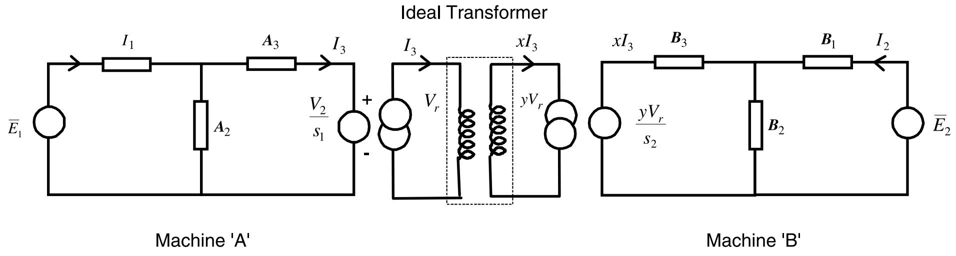

Fig. 1. Cascade machine equivalent circuit with reference to their stators.

3. The equivalent circuit of a cascade electrical machine

For a symmetrical grid, symmetrical polyphase machine, the equivalent electrical circuit per phase for a set of two wire-wound induction machines connected in cascade through their rotor's terminals with reference to their stators, is shown in Fig. 1. One machine is assumed to have 'p' pole-pair and the other 'q' pole-pair. In this equivalent circuit, the two machines are shown to be coupled through a transformer with voltage ratio y and current ratio x. In practice, $x = y = 1$ and therefore the two machines are coupled directly without a transformer.

Referring to Fig. 1, the circuits components of a 'p' pole-pair machine can be expressed, in terms of those of the resulting single pole-pair machine, as follows:

$$\boldsymbol{A}_1 = \frac{[R_\mathrm{f} + \mathrm{j}\omega_1(L_\mathrm{f} - M)]}{p} \overset{\Delta}{=} R_{\mathrm{f}1} + \mathrm{j}\omega_1(L_{\mathrm{f}1} - M_1)$$

$$\boldsymbol{A}_2 = \frac{\mathrm{j}\omega_1 M//R_\mathrm{i}}{p} \overset{\Delta}{=} \mathrm{j}\omega_1 M_1//R_{\mathrm{i}1}$$

$$\boldsymbol{A}_3 = \frac{[R_\mathrm{a}/s_1 + \mathrm{j}\omega_1(L_\mathrm{a} - M)]}{p} \overset{\Delta}{=} \frac{R_{\mathrm{a}1}}{s_1} + \mathrm{j}\omega_1(L_{\mathrm{a}1} - M_1)$$

Similarly for the 'q' pole-pair:

$$\boldsymbol{B}_1 = \frac{[R_\mathrm{f} + \mathrm{j}\omega_2(L_\mathrm{f} - M)]}{q} \overset{\Delta}{=} R_{\mathrm{f}2} + \mathrm{j}\omega_2(L_{\mathrm{f}2} - M_2)$$

$$\boldsymbol{B}_2 = \frac{[\mathrm{j}\omega_2 M//R_\mathrm{i}]}{q} \overset{\Delta}{=} \mathrm{j}\omega_2 M_2//R_{\mathrm{i}2}$$

$$\boldsymbol{B}_3 = \frac{[R_\mathrm{a}/s_2 + \mathrm{j}\omega_2(L_\mathrm{a} - M)]}{q} \overset{\Delta}{=} \frac{R_{\mathrm{a}2}}{s_2} + \mathrm{j}\omega_2(L_{\mathrm{a}2} - M_2)$$

where ω_1 is the frequency of the stator of the p pole-pair machine, which is assumed to be a constant grid frequency and ω_2 is the frequency of the q pole-pair machine which therefore is a dependent variable and function of the speed.

In general, the machine has two ports which can be used as inputs or outputs similar to the wire wound machine. For asynchronous operation, $\bar{E}_2 = 0$. For synchronous operation, $\bar{E}_2$ can be a voltage with a fixed frequency such as a dc voltage for constant speed operation or a variable frequency voltage for a variable speed application.

If the frequency of the voltage $\bar{E}_1$ is ω_1 and the frequency of the voltage $\bar{E}_2$ is ω_2, then power can flow between the two machines as shown in Fig. 1, if and only if, the frequencies of the two rotor voltages or currents are equal, thus,

$$|\omega_1 - p\Omega| = |\omega_2 + q\Omega| \tag{3.1}$$

Eq. (3.1) assumes the two machines are connected mechanically back to back, they are rotating in opposite directions. For synchronous operation, ω_1 and ω_2 are independent variables and the machine speed Ω becomes a dependent variable which depends on the phase between $\bar{E}_1$ and $\bar{E}_2$ with reference to rotating frames of references ω_1 and ω_2, respectively. On the other hand, in asynchronous operation, ω_2 is a dependent variable. In that case, $E_2 = 0$.

4. The isosynchronous machine

For the case $p = q$ and $\omega_2 = \omega_1$, the speed Ω is an independent variable in the Eq. (3.1). For this special particular case, the machine is called an isosynchronous machine. In practical application, two machines are coupled back to back and produce zero net torque for the case $\bar{E}_1 = \bar{E}_2$. Torque is produced only when a phase difference between $|E_1|$ and $|E_2|$ exists. Normally, the torque is controlled by a phase shifter or by adjusting mechanically one stator relative to the other as shown in Fig. 3. The torque/speed characteristic is shown in Fig. 5. Maximum torque is produced from the set if the angle of the electrical phase difference between the two machine stators is equal to 180°. The two machines can also be coupled front to back if double axis is available. It is worth emphasising, that this type of operation of the set is unique since both inputs accept voltage at the same frequency. However, the set works in the asynchronous mode contrary to the cascade set with$p \neq q$. The latter can operate only in the synchronous mode if two input voltages are present. This is the reason why the $p = q$ set is called an isosynchronous machine. Unfortunately, the set cannot be constructed in a single frame.

5. The cascade machine analysis

Analysis of the cascade machine equivalent electrical circuit shown in Fig. 1 is given in Appendix B for asynchronous and synchronous modes of operation. The two machines