Modeling and Control of an Induction Machine based Electric Variable Transmission

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***Abstract*—An electric variable transmission (EVT) is an electromagnetic device with multiple rotors. In hybrid electric vehicles it is used to split the power to the wheels in a part coming from the combustion engine and a part exchanged with the battery. This paper summarizes how an induction machine based EVT can be modeled and controlled using field oriented control.**

***Index Terms*—Electric variable transmission, field oriented control, modeling**

I. Introduction

The problems with today's traffic concerning fuel prices and air pollution are meanwhile a well-known fact to every engineer and scientist. Although a lot of research is being performed, a good alternative for the petrol fueled car is not immediate. Electric cars are limited by the unsatisfactory performance of battery technologies and the high cost of fuel cells. Hybrid electric vehicles have been considered as the best intermediate choice to bridge the current situation with a clean and energy-efficient future. These cars are powered both by an internal combustion engine and an electric motor. A power split device is needed to split the power to the wheels in a part directly coming from the combustion engine and a part exchanged with the battery. This task is nowadays performed through a mechanical planetary gear. Two electric motor/generators are needed, each connected to a different shaft of the gear. The remaining shaft is connected to the combustion engine. The power split makes it possible to drive the engine in an energy-efficient region of the torque-speed map over a wide range of torques and speeds delivered to the wheels. An additional advantage is that some of the braking energy can be recuperated and stored in the battery.

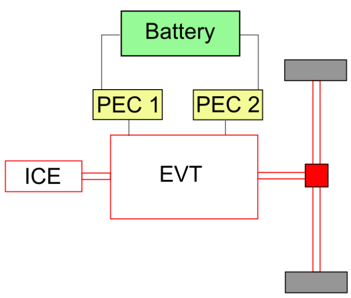

Fig. 1: Principle of a hybrid electric vehicle with electric variable transmission (EVT). The EVT is mechanically coupled to the internal combustion engine (ICE), and electrically coupled to the battery through two power electronic converters (PEC's).

The electromagnetic equivalent of this system, as proposed in [1] and [2], combines the power split and the two electrical motors into one electromagnetic device called an electric variable transmission (EVT) as can be seen in figure 1. This equivalent can have a comparable power density, as shown in [3]. Moreover, it has the advantage of high efficiency, absence of mechanical friction and wear, lower maintenance and inherent overload protection. There exist basically two types of EVT's, depending on whether or not permanent magnets are used. The induction machine based EVT of [2] has the advantage that no expensive (rare earth) magnets need to be provided, and that the irreversible demagnetization risk of magnets is avoided. Furthermore, the magnetic field can easily be weakened at high speeds in contrast to EVT's with permanent magnets. The disadvantage of this type of EVT are the higher losses due to on the one hand the inherent slip between the short-circuited rotor and the field and on the other hand due to the magnetization current.

Although articles can be found on EVT's, less is published about the flux and torque control on this types of machines. In this article it is shown how field oriented control (FOC) can be extended to control the torque and flux on an induction machine based EVT.

II. The Electric Variable Transmission

An induction machine based EVT can be seen as a conventional induction machine with two concentric rotors. The stator is coupled through a power electronic converter (PEC) to the battery. The middle rotor is called the interrotor and is a squirrel-cage rotor. The most inner rotor finally is connected through slip rings and a power electronic converter to the battery. The stator and the two rotors are electromagnetically coupled. A schematic overview can be seen in figure 2.

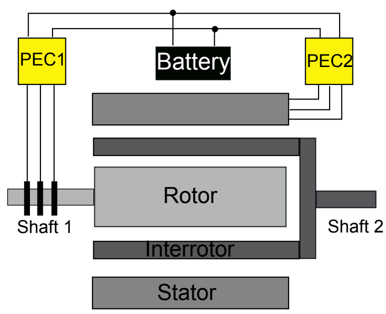

Fig. 2: Induction machine based electric variable transmission.

A. Replacement scheme

Electromagnetically, the considered EVT can be seen as three coupled windings. When the magnetic material is considered linear, and only the fundamental components of the magnetic field are considered, the relation between induced voltages and currents can be expressed in the matrix equation:

$$\begin{bmatrix} E_s \\ E_i \\ E_r \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} L_s & M_{si} & M_{sr} \\ M_{si} & L_i & M_{ir} \\ M_{sr} & M_{ir} & L_r \end{bmatrix} \begin{bmatrix} I_s \\ I_i \\ I_r \end{bmatrix}$$

The self inductances and mutual inductances can be written as a weighted sum of contributions of the main field and different leakage fields. The weighting factors are a function of the winding ratio's. As three windings are present, two winding ratio's are needed to describe the machine. It can be shown that the winding ratio's can be chosen is such a way that all leakage inductances representing the field coupled between two windings but not with the third one become zero. Since the final results do not depend on the chosen winding ratio, this specific ratio can be chosen to simplify the replacement scheme of the EVT. With the interrotor short circuited, this results in the scheme of figure 3.

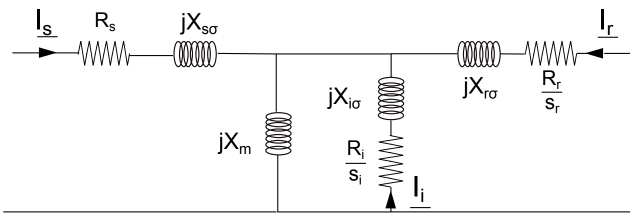

Fig. 3: Replacement scheme to model the fundamental behaviour of an induction machine based electric variable transmission. s = stator, i = interrotor, r = rotor.

B. Electromagnetic Torque

The electromagnetic torque on the different rotors can be calculated using Lorentz's law. To this end only the fundamental harmonics of the magnetic field and current layer are considered. It follows that

$$T_j = \frac{3}{s_j \Omega_{sy}} E_j I_j cos(\Psi_j) \tag{1}$$

where T_j is the torque on the j^{th} rotor. s_j is the slip of that rotor with respect to the main field rotating with speed Ω_{sy}. E_j is the induced emf in the rotor by the magnetic field and makes an angle Ψ_j with the corresponding current. Ψ_j is also the angle between the magnetic field and the current layer in the considered rotor.

III. Field Oriented Control

In order to control the torque on both rotors, the currents to the stator and inner rotor can be controlled using a current regulated voltage source inverter (CRVSI). Field Oriented Control (FOC) controls the current in an instantaneous synchronous reference frame with the interrotorflux along the negative d-axis. In this reference frame the torque on the interrotor (subscript i) and rotor (subscript r) can be rewritten as:

$$T_i = -\frac{3}{2} N_p \frac{L_m^2}{L_i} (I_{s,d} + I_{r,d})(I_{s,q} + I_{r,q}) \tag{2}$$

$$T_r = \frac{3}{2} N_p L_m ||\underline{I}_s + \underline{I}_i||.||\underline{I}_r|| \tag{3}$$

and is valid when $(\underline{I}_s + \underline{I}_i) \perp \underline{I}_r$. Together with the setpoint value of the interrotorflux

$$\Psi_{i,d} = L_m (I_{s,d} + I_{r,d}) \tag{4}$$

this forms a system of equations with the stator ($\underline{I}_s$) and rotor ($\underline{I}_r$) currents as unknowns. A possible vector diagram is shown in figure 4 where $I_{\tau i} = I_{s,q} + I_{r,q}$ is the torque forming current and $I_{\phi i} = I_{s,d} + I_{r,d}$ the flux forming current component of the interrotor. Analogous notations are used for the rotor. The orthogonality constraint is for certain torque and flux set points too strict for the system of equations to be resolvable, so in some cases a suboptimal solution will have to be found.

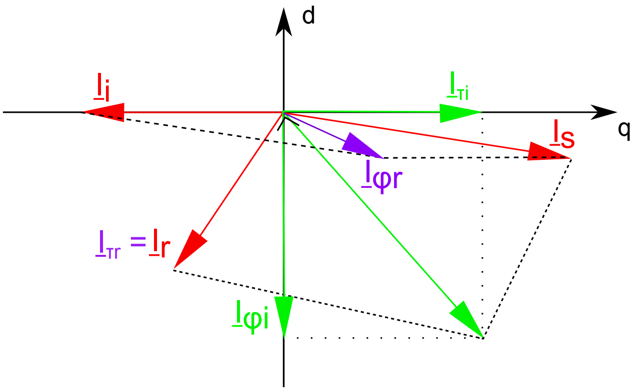

Fig. 4: Vector diagram field oriented EVT.

IV. Conclusion

An equivalent scheme of an induction motor based EVT can be derived using Faraday's law, and can be simplified using an appropriate winding ratio. By controlling both the stator current and the rotor current in a reference frame connected to the interrotor flux, the torques on both rotors can be controlled.

Acknowledgments

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