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Overview of flux-controllable machines: Electrically excited machines, hybrid excited machines and memory machines☆

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ABSTRACT

Flux-controllable machines have attracted much attention in modern industry, especially in electric vehicle propulsion and wind power generation, as they can ensure a wide constant power speed range when working at motoring mode, while maintain constant induced voltage when working at generating mode. This paper reviews the current research work about flux-controllable machines, mainly focused on electrically excited machines, hybrid excited machines and memory machines. The latest novel machine concepts with the potential of good flux controllability are particularly investigated. The working principle, advantages and drawbacks, and future trends of different flux-controllable machines are discussed, compared and summarized in detail.

1. Introduction

Electric machines have attracted more and more attention in recent years with the increasing concerns on energy crisis and environmental pollution. Many clean energy applications have been investigated by researchers to reduce the fuel energy consumptions, among which the electric vehicles (EVs)/hybrid electric vehicles (HEVs) and wind power generators are two prominent representatives.

Actually the EV was first invented as early as 1834, but almost varnished from the scene since 1930 due to the limitations associated with the batteries and the rapid advancement of internal combustion engine vehicles (ICEVs) [1]. As the growing concerns on fuel energy shortage and environmental pollution as well as global warming, the research on EVs has shifted dramatically since 1990s. Many major automotive manufacturers like GM, Nissan and BMW have launched aggressive programs to develop EVs for commercialization [2]. HEVs are also good candidates to reduce gasoline consumptions as well as increase engine efficiency. One successful commercial HEV is the Toyota Prius, many research works on this car have been conducted [3–5]. No matter the EVs which merely use electric energy for propulsion, or HEVs driven by gasoline combined with electricity, the driving motors are key components to ensure good performances of EVs/HEVs. Generally, there are two typical working stages for driving motors in EVs/HEVs, namely constant torque start-up stage and constant power high speed cruise stage. In order to meet the high speed requirements of EVs/HEVs, the driving motors should have good flux controllability to ensure wide constant power operating range.

On the other hand, the use of wind power is increasing rapidly as more technical breakthroughs have been achieved. Fig. 1 shows of the global wind capacity from 2015 to 2020, one can see that the wind power systems are growing fast and enjoy good potential for further sustained development [6]. Since the wind speed varies with the time, the induced voltage will also change while the wind speed varies, which would bring shock to power converters. To maintain a constant induced voltage, the wind turbines need to weaken or strengthen the air-gap flux when the wind speed increases or decreases. Therefore, the wind power generators should also have good flux regulating capability to meet the changes of wind speeds.

The purpose of this paper is to give an overview of the flux-controllable machines, especially focusing on the current research works including machine topologies, operating principles and features, and especially the latest emerged novel machine concepts with good flux.

2. Mathematical model and classification

2.1. Mathematical model

The mathematical model is the theoretical basis to understand the working principle of the flux-controllable machines. Through the research about the mathematical model, the accurate mathematical expressions of the back EMF and the electromagnetic torque can be obtained. For three-phase synchronous machines, the voltage equation can be expressed as:

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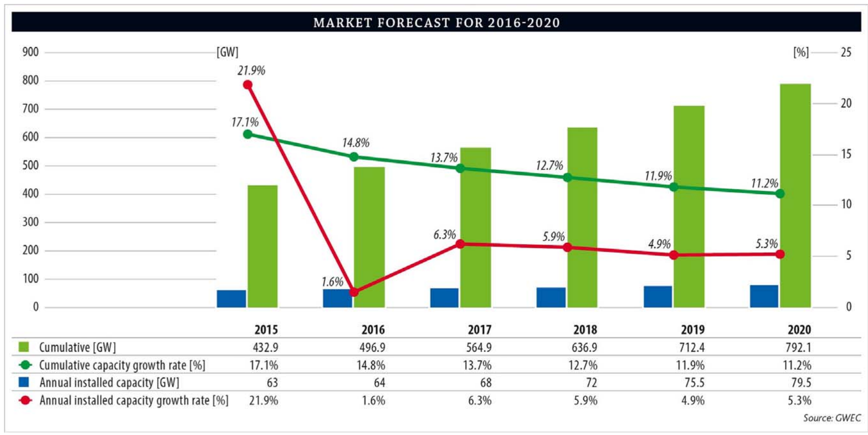

Fig. 1. Global wind power capacity [6].

$$\vec{u} = Rs\vec{i} + \frac{d\vec{\psi}}{dt} \tag{1}$$

where Rs is the resistance of each phase windings, $\vec{u} = [ua, ub, uc]^T$, $\vec{i} = [ia, ib, ic]^T$ and $\vec{\psi} = [\psi a, \psi b, \psi c]^T$ are the phase voltage, current and flux linkage vector, respectively. The flux linkage of each phase windings contains three parts, namely, the self inductance flux linkage, the mutual inductance flux linkage and the excitation flux linkage, which can be expressed as:

$$\vec{\psi} = \vec{L}\vec{i} + \vec{\psi}f \tag{2}$$

where $\vec{L}$ is the inductance matrix, $\vec{\psi}f$ is the excitation flux linkage vector.

$$\vec{L} = \begin{bmatrix} LAA & MAB & MAC \\ MAB & LBB & MBC \\ MAC & MBC & LCC \end{bmatrix} \tag{3}$$

$$\vec{\psi}f = \psi f \begin{bmatrix} \cos(\theta) \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix} \tag{4}$$

in which LAA, BB, CC are the self inductance of each phase, MAB, AC, BC are the mutual inductance, ψf and θ are the excitation flux linkage and the rotor position. By substituting Eq. (2) into Eq. (1), the voltage equation can be re-written as:

$$\vec{u} = Rs\vec{i} + \frac{d\vec{\psi}}{dt} = Rs\vec{i} + \frac{d\vec{L}}{dt}\vec{i} + \vec{L}\frac{d\vec{i}}{dt} + \frac{d\vec{\psi}f}{dt} \tag{5}$$

where $Rs\vec{i}$ is the voltage drop due to the winding resistance, $\frac{d\vec{L}}{dt}\vec{i}$ is known as rotational EMF due to the variation of inductance, $\vec{L}\frac{d\vec{i}}{dt}$ is known as the transformer EMF due to the variation of armature current, $\frac{d\vec{\psi}f}{dt}$ is known as the back EMF due to the relative motion of excitation flux and windings. The back EMF vector can be obtained by differentiate the flux linkage vector:

$$\vec{e} = -\frac{d\vec{\psi}f}{dt} = \omega\psi f \begin{bmatrix} \sin(\theta) \\ \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{bmatrix} \tag{6}$$

where ω is the angular frequency. The electromagnetic torque is resulted by the rotational EMF and back EMF, and can be expressed as:

$$T = \frac{1}{\omega}\vec{i}^T\left(\frac{d\vec{L}}{dt}\vec{i} + \frac{d\vec{\psi}f}{dt}\right)$$
$$= \frac{1}{\omega}\vec{i}^T\frac{d\vec{L}}{dt}\vec{i} - \vec{i}^T\psi f \begin{bmatrix} \sin(\theta) \\ \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{bmatrix} \tag{7}$$

where the first item is the reluctance torque component due to the variations of inductances, which is zero in machines with symmetrical air-gap. One can find that the excitation flux ψf can act as a regulator for both the back EMF and the electromagnetic torque. Therefore, by controlling the excitation flux, the back EMF and the terminal voltage as well as the electromagnetic torque can be regulated effectively. This feature is very useful to expand the constant power operating range when the machines work at motoring mode, and maintain constant output voltages when the machines work at generating mode.

2.2. Classification

According to the types of excitation sources and flux controlling methods, the flux-controllable machines can be divided into three categories, namely, electrically excited machines (EEMs), hybrid excited machines (HEMs) and memory machines (MMs). EEMs are only excited by field windings, continuous excitation currents are needed during the whole operating range, the flux regulating is achieved by directly controlling the excitation currents. HEMs are excited by both the field windings and PMs with high coercivity, continuous excitation currents are needed during flux regulating. MMs are excited by PMs with low coercivity and nonlinear hysteresis loops, the flux regulating can be achieved by applying current pulses. The equivalent circuit model of EEMs, HEMs and MMs in *d-q* frame is shown in Fig. 2. The steady-state voltage equations can be expressed as:

$$\begin{bmatrix} ud \\ uq \end{bmatrix} = Rs\begin{bmatrix} id \\ iq \end{bmatrix} + \omega\begin{bmatrix} 0 & -Lq \\ Ld & 0 \end{bmatrix}\begin{bmatrix} id \\ iq \end{bmatrix} + \omega\begin{bmatrix} 0 \\ \psi f \end{bmatrix} \tag{8}$$

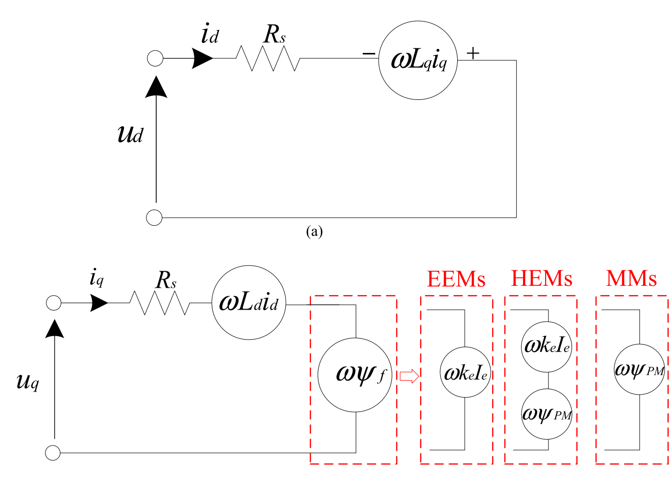

Fig. 2. Equivalent circuit model. (a) D-axis equivalent circuit. (b) q-axis equivalent circuit.