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An Energy Distribution Strategy for PMSM Drive Based on Cascaded Multilevel Converters with Energy Feedback Device

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Abstract

The cascaded H-bridge (CHB) multilevel converter with energy feedback device has been proved beneficial in a motor drive system to improve system dynamic performance and efficiency. This paper presents a power distribution strategy in energy source, cascaded multilevel converters, transformer and electric motor based on CHB-transformer configuration in different motor drive operation modes. In this strategy, a design trajectory for energy flow distribution is proposed. This power management strategy not only giving a trace for each part to fellow in operation modes, but also show the energy flow working, An energy flow control method is developed to perform power transition smoothly between different operation modes and make sure to the whole system working steady. Simulation results are provided to demonstrate the effectiveness of the proposed motor drive system.

Keywords: *CHB, energy feedback, distribution strategy, PMSM*

1. Introduction

TODAY, Cascaded multilevel inverters with applicable energy distribution technology are beneficial in a motor drive system since they can improve system dynamic performance and efficiency [1-8], These CHB multilevel converter systems have higher efficiency because the devices can be switched at minimum frequency and the energy regenerative system can feed the energy flow back to the converter. With a special topology and switching strategies, the converter can work with only one DC supply, which has advantage in industrial applications widely. They are suitable for medium or high-voltage motor drives, especially in all-electrical vehicle and hybrid power vehicle [9-15].

Figure 1 proposes a novel system configuration of a PMSM drives using CHB-transformer configuration. The whole system can be considered as four parts: energy source, energy storage (UCs), energy feedback transformer, and electric motor, whereby the closed-loop control of energy transmission in the system is achieved. Therefore the whole system could have all the advantages of a closed-loop control system, including stability, split-second control, and working in miniaturized condition. This paper presents an energy distribution strategy in four parts of the power system under different motor drive operation modes. Using this strategy, the whole system will reduce the adverse effect of power transients on energy sources, recover the regenerative power from the motor, and improve the system dynamic performance and power quality.

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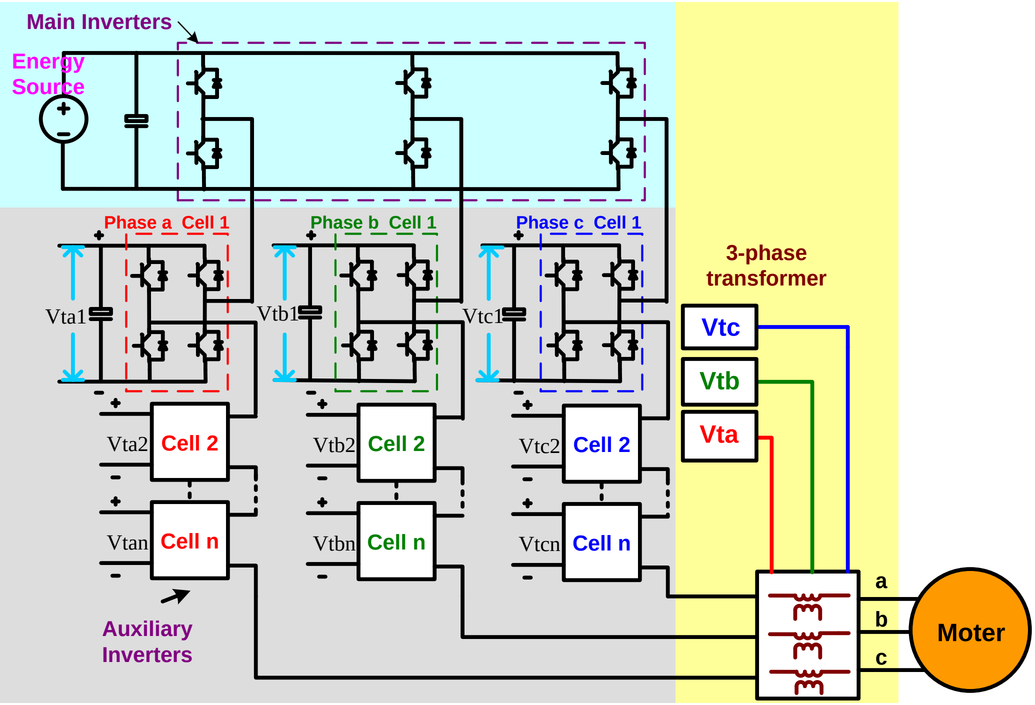

Figure 1. PMSM Drive System based on CHB-transformer Configuration

2. Operation Modes Analysis and Energy Distribution Strategy

The corresponding energy distribution strategy includes energy flow distribution control and energy trajectory control among energy source, energy storage, energy feedback transformer, and electric motor. A typical driving cycle of PMSM has 5 different working modes; they are startup mode, acceleration mode, navigation mode, deceleration mode, and standstill mode [1-3].

The proposed energy flow among four parts of the PMSM drive system is illustrated in Figure 2. It shows that the energy source provides power to the electric motor in startup mode, acceleration mode, navigation mode, and absorbing power form the electric motor in deceleration mode. The thickness of the transmission route means the degree of the support energy. When the motor is working in the startup mode, the energy source provides a small value of energy to the electric motor to start it at a low speed by the main inverters, meanwhile charges the storage quickly with the transformer or in ordinary charging mode. In the acceleration mode, both the main inverters and the energy feedback-storage provide energy to the electric motor, so the speed can rise rapidly, at the same time, the transformer can be used to control the energy distribution. In a navigation period, the energy source provides all required energy to the electric motor, and the energy feedback-storage receives a small amount of power from the energy source by transformer to maintain the voltage at a desire value. In the deceleration mode, the energy feedback-storage recovers all the regenerative energy by the main inverter from the motor. In the standstill mode, the energy source can provide a little energy to maintain the energy feedback-storage voltage.

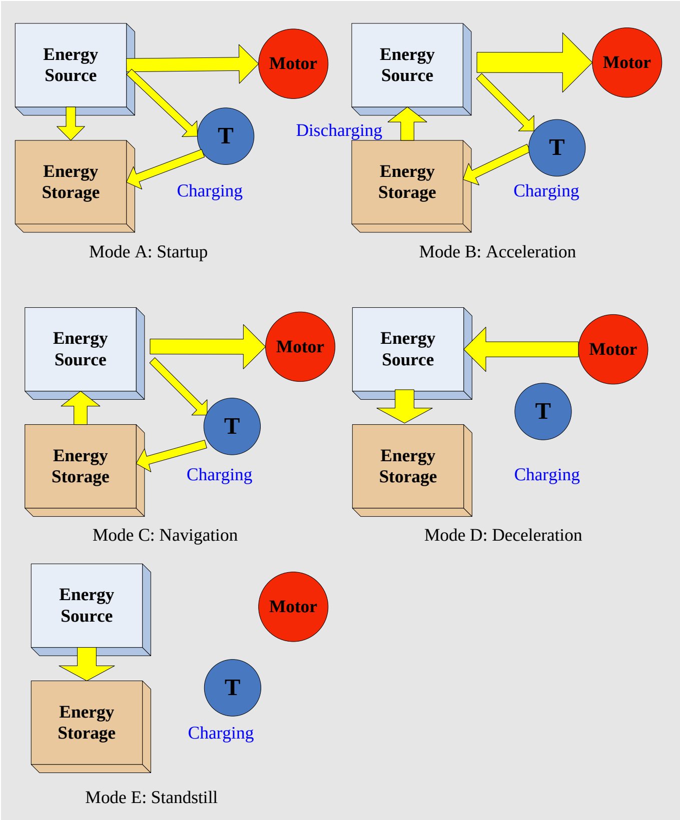

Figure 2. Energy Flow Transmission in the System

The corresponding energy distribution strategy during a typical driving cycle is presented in Figure 3.

Define the energy flow get in or out of the electric motor, the energy sources, and the energy feedback-storage are P_{motor}, P_{source} and $P_{storage}$, respectively, so:

$$\begin{cases} P_{motor} + P_{storage} = P_{source} & \text{opeation in startup mode} \\ P_{source} + P_{storage} = P_{motor} & \text{opeation in acceleration mode} \\ P_{source} + P_{storage} = P_{motor} & \text{opeation in navigation mode} \\ P_{motor} + P_{storage} = 0 & \text{opeation in deceleration mode} \\ P_{source} = P_{storage};\ P_{motor} = 0 & \text{opeation in standstill mode} \end{cases} \tag{1}$$

P_{source} is designed to follow the trajectory by the red line. Because the energy source has unidirectional character to discharge all the driving cycle, so this trajectory is a unipolarity track. In order to eliminate adverse power/current stress on an energy source, this trajectory has smooth increase/decrease slope. The energy is desired to be designed not to absorb regenerative energy and not to suffer fast power/current change with the energy feedback-storage. The energy trajectory of the energy feedback-storage is shown as a blue line. This trajectory is a bipolar track, since the energy feedback-storage supplies peak power to achieve high speed in acceleration mode, and absorb regenerative energy by the VSR in the deceleration mode. The energy transferred shown in the shadow region results from coordination control between the energy source and the energy feedback-storage.

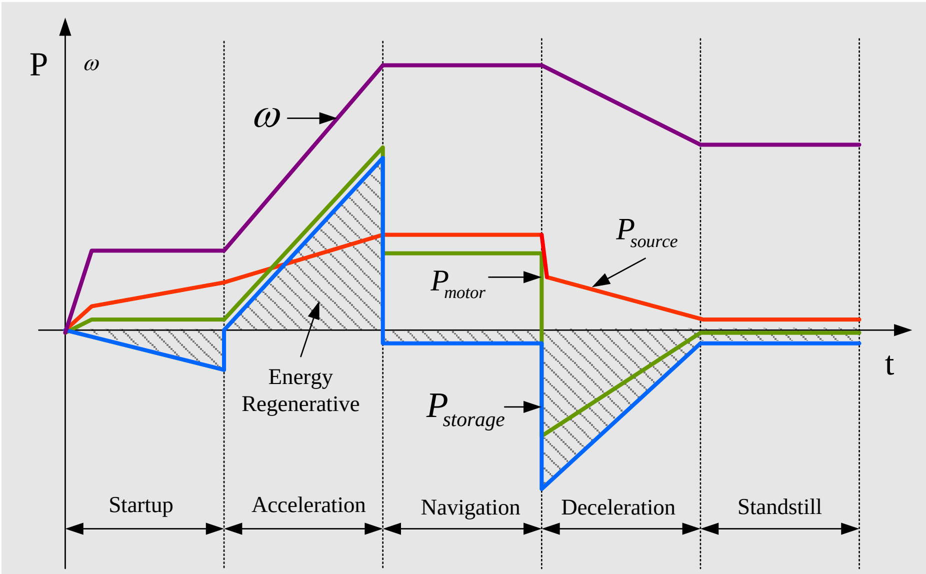

Figure 3. Energy Distribution Strategy in Different Modes

3. Energy Flow Control Analysis

The fundamental switching angle $\theta_i(\mathrm{i}=\mathrm{a,b,c})$ of the main inverter will decide P_{source} to follow the desired energy trajectory. In this paper n = 2 is selected for the drive system, it can be extended to any number. The main-inverter output voltage is defined as $\mathrm{V}_{1i}(\mathrm{i}=\mathrm{a,b,c})$, and the auxiliary-inverter output voltages are defined as V_{2i} and V_{3i}, respectively. V_{1i} is produced by controlling the main inverter switching at fundamental frequency. In order to obtain θ_i, P_{source} is first expressed as follows.

$$p_{source}=\frac{3}{2}V_{1i\_F}i_{sq},(\mathrm{i}=\mathrm{a,b,c}) \tag{2}$$

where V_{1i_F} is the magnitude of the fundamental component of V_{1i}, and i_{sq} is the q-axis stator current in the synchronous reference $d-q$ frame rotating at the rotor electrical speed ω. According to 5 drive modes of the PMSM shown in Fig. 3, P_{source} can be calculated as

$$p_{source}=\begin{cases} p_1=\dfrac{2}{p}(\mathrm{k}_t\mathrm{i}_{sq1}\,\omega_1),0\le \mathrm{t}\le \mathrm{t}_1 \\ p_2=\dfrac{2}{p}(\mathrm{k}_t\mathrm{i}_{sq2}\,\omega_2),\mathrm{t}_2\le \mathrm{t}\le \mathrm{t}_3 \\ p_2=\dfrac{2}{p}(\mathrm{k}_t\mathrm{i}_{sq3}\,\omega_3),\mathrm{t}_4\le \mathrm{t} \\ p_1+\dfrac{t-t_1}{t_2-t_1}(\mathrm{p}_2-\mathrm{p}_1),\mathrm{t}_1\le \mathrm{t}\le \mathrm{t}_2 \\ p_2-\dfrac{t-t_3}{t_4-t_3}(\mathrm{p}_3-\mathrm{p}_2),\mathrm{t}_3\le \mathrm{t}\le \mathrm{t}_4 \end{cases} \tag{3}$$

Where p is number of poles; k_t is the torque constant, and i_{sq1}, i_{sq2} i_{sq3} are the i_{sq} value at ω_1, ω_2 and ω_3, respectively. The Fourier series expansion of v_{1i} is given by:

$$\begin{cases} v_{1i} = \sum_{n=1,3,5...}^{\infty} \frac{4v_{dci}}{n\pi} \cos(n\,\theta_i)\sin(n\,\omega_r\, t) \\ v_{1i\_F} = \frac{4v_{dci}}{\pi} \cos(\theta_i)\sin(\omega_r\, t) \qquad (i = a, b, c) \\ v_{1i\_h} = \sum_{n=3,5...}^{\infty} \frac{4v_{dci}}{n\pi} \cos(n\,\theta_i)\sin(n\,\omega_r\, t) \end{cases} \tag{4}$$

Angle θ_i can be derived from the fundamental component of v_{1i} and can be written as

$$\theta_i = \cos^{-1}\left(\frac{\pi}{4} \times \frac{v_{1i\_F}}{v_{dci}}\right), i = a, b, c \tag{5}$$

4. Simulation

In order to evaluate the performance of the proposed motor drive system, simulation tests has also developed with the simulation platform of MATLAB/Simulink. Figure 5 shows simulation results in a typical driving cycle including startup, acceleration, navigation, and deceleration modes.

Figure 4(a) shows the speed response character, and the result shows the actual speed response meet the command fast and smoothly. Figure 4 (b) shows energy feedback-storage voltage of each auxiliary converter. In the acceleration period, the energy feedback-storages are discharged to provide required peak power; thus, the voltages decrease from 50to 10 V. In deceleration period, the energy feedback-storages recover regenerative energy from PMSM.

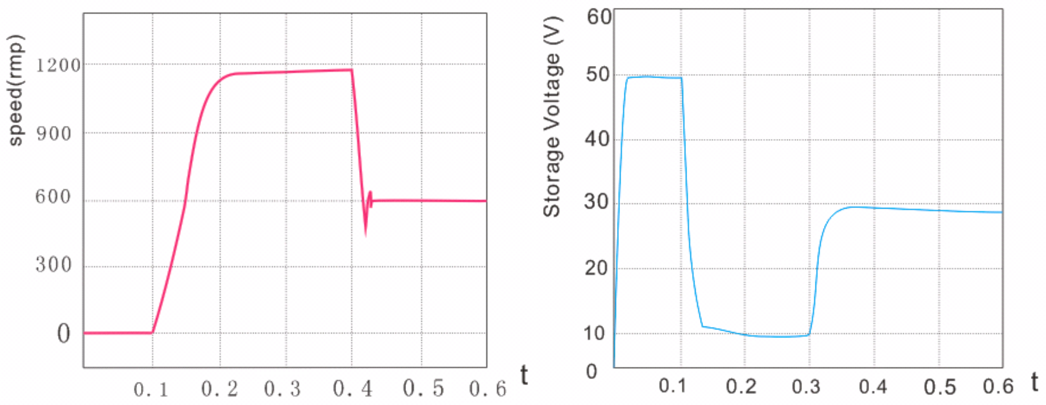

Figure 4. Simulation Result for PMSM Drives (a) Speed Response (b) Energy Feedback-storage Voltage

Figure 5 shows the output of the phase voltage under the seven-level converter working with VSR device. Figure 6 shows the output of the phase voltage of v_{1a} under the seven-level converter working with VSR device

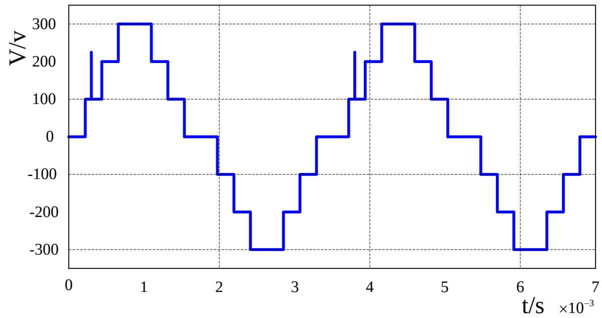

Figure 5. Output Phase Voltage

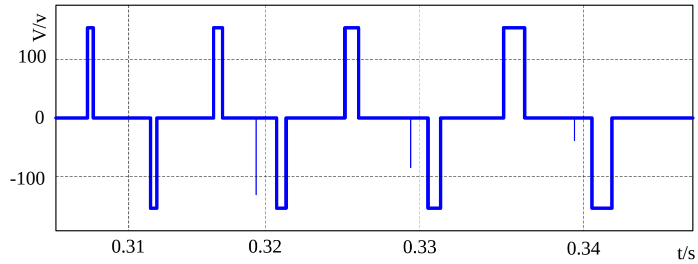

Figure 6. Output Phase Voltage of v_{1a}

5. Conclusions

This paper has proposed an energy distribution strategy for cascaded multilevel converter based motor drive system with energy regenerative device. The corresponding energy distribution strategy includes energy flow distribution control and energy trajectory control among Energy source, energy feedback-storage, and electric motor. In order to make sure the energy feedback-storage providing harmonic compensation and discharging/recovering regenerative energy, an energy feedback transformer is used in the system. The simulation results have shown the dynamics, and harmonic charter of the proposed motor drive system.

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