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Muhammad Ali Masood Cheema ·
John Edward Fletcher

Advanced Direct Thrust Force Control of Linear Permanent Magnet Synchronous Motor

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To

"My Old Man"

Muhammad Masood Cheema
"Baba! we did it together. It is your immense love and spiritual bond I have with you that enabled me to accomplish this great achievement."

To

Dr. Farrukh Humayun Cheema
"For your selfless love that always gave me strength."

Dr. Muhammad Ali Masood Cheema

To

"To those who walked before me for making this research possible, and for those who will follow for their dedication and pursuit of understanding."

Dr. John Edward Fletcher

Preface

The application areas for linear permanent magnet synchronous motors (linear PMSMs) include, but not limited to, servo-mechanisms, automation of manufacturing processes, transportation, renewable energy devices and pumping machinery. The broadening scope of the linear PMSMs implies the importance of developing robust, simple and fast control mechanisms for the linear drives to suit the essential needs of these emerging industries.

This book is focused on the direct thrust force control (DTFC) of tubular surface-mount linear PMSMs. The concept of DTFC is derived from direct torque control scheme which was first introduced in the 1980s initially for rotational induction machines, and in later studies this scheme was also applied to rotational permanent magnet synchronous motors (PMSMs). The simple structure of the direct torque control scheme provides it with inherent robustness to parameter variation and a fast transient response. These attributes make this control scheme a prime candidate when robustness and fast transient response are of vital significance. In recent years, direct torque control scheme has also been extended to linear PMSMs as DTFC; however, a little is published so far in this regard.

The DTFC scheme is analogous to direct torque control and has a similar switching table-based control structure in conjunction with two multilevel hysteresis comparators to regulate stator flux and thrust force. These hysteresis comparators are simplest form of a scaled relay controller with unity gain and are robust to parameter variation; therefore, DTFC is variable structure control scheme in nature. However, the main disadvantage of DTFC, due to the variable structure nature of the control scheme, is the presence of ripple in the stator flux and thrust force and a variable switching frequency.

The implementation of DTFC for linear PMSMs is substantially challenging compared to direct torque control of rotational PMSMs. In general, most of the linear PMSMs have a low value of stator inductance due to their larger air gap compared to rotational PMSMs. Also, due to the linear motion, the pole pitch of the linear PMSMs also affects the thrust force regulation. Therefore, classical switching table-based DTFC-controlled linear PMSMs with low inductance and short pole pitch exhibit large thrust force ripple which is typically beyond acceptable limits.

This book aims at in-depth formulation of nonlinear dynamic models for linear permanent magnet synchronous motors from a control system perspective and subsequently utilizes these models to develop several advanced DTFC schemes based on optimal control and sliding mode control approaches. A detailed chapter is also dedicated to formulation of sliding mode stator flux observer for sensorless speed estimation of linear PMSM. It is worth mentioning that extensive experimental results based on a laboratory prototype for validation of the presented control schemes along with exhaustive discussions are included in the text as well.

Chapters 1 and 2 of the book are based on a detailed literature review and comprehensive mathematical modelling of linear PMSMs in various reference frames. The conventional switching table-based DTFC is analysed at length in Chap. 3. In order to reduce the ripple and steady-state error in the stator flux and thrust force response of the linear PMSM, a duty ratio control-based control is proposed and studied to adapt switching table-based DTFC as provided in Chap. 3 of the book.

Another approach to effectively reduce steady-state thrust force ripple is to use space vector pulse-width modulation approach. In Chaps. 4–7, several advanced DTFC schemes utilizing space vector pulse-width modulation are proposed and analysed. Finally, a stator flux observer for sensorless speed estimation comprising a linear state observer and an improved sliding mode component is also proposed in Chap. 7.

The key feature of this book is formulation of a nonlinear second-order state-space model of the linear PMSM in a synchronously rotating stator flux vector *xy*-reference frame for combined dynamics of speed and thrust force as system states. The proposed nonlinear model is used to formulate the sliding mode control law with space vector pulse-width modulation for combined control of speed and thrust force.

In view of this fact that this text is written in way that the development of advanced concepts stems from a detailed mathematical foundation of the subject matter, this book is a suitable choice to be used as textbook or reference for undergraduate/graduate students for the subject of advanced electrical drives.

It is important to note that, although this book is set in the context of linear PMSMs, however the concepts and mathematical formulations presented here can conveniently be adapted or generalized for direct torque control for rotational multiphase PMSMs with or without saliency. This can be of great help for graduate research students and professional engineers in the field of electrical drives to expand their understanding of advanced nonlinear dynamics and control schemes for linear/rotational PMSMs.

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Dr. Muhammad Ali Masood Cheema

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