A Modular Linear Permanent-Magnet Machine with an FPGA-Based Controller

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***Abstract*– This paper details the design and testing of a high dynamic performance, modular linear permanent magnet (PM) machine and drive system with an FPGA based controller. Advantages of the modular design and the impacts of this arrangement on the drive and control systems are discussed. A complete description of the prototype machine is given, including the major design choices and construction. The necessary functions of the power electronic drive are explained, as are the tasks and architecture of the system control. Finally, results from extensive testing of the entire system are presented.**

I. Introduction

Linear electromagnetic machines are increasingly being used to replace existing rotary to linear motion systems. Currently, the primary market sectors of application are machining and fabrication environments as well as the transportation industry. In addition, both the U.S. Navy and NASA have expressed interest in development of a linear machine which can operate as a launching platform for military planes and space shuttles, respectively. The prototype machine investigated in this paper stems from the design of such an electromagnetic aircraft launch system that was carried out by Patterson, et al. [1].

The most innovative aspect of this linear PM machine is its modularity. The armature of the machine is divided into three electrically isolated segments such that each section, or module, can be operated independently of the others. The purposes for incorporating a degree of modularity into the design of a machine typically have to do with improving ease of construction and (or) fault tolerance. However, the armature of this prototype machine is sectioned with the goal of improving the dynamic performance of the machine by limiting the armature winding inductance [1].

This particular machine has three stator modules; however, the concepts presented here are easily extended to a machine with any number of sections. In addition to improving dynamic response, the track sectioning offers other advantages, particularly with respect to a relatively long machine [2]. First, the length of the track can easily be adjusted for various applications by simply adding or removing modules. Also, operation of the machine can continue with one or more damaged sections and only those damaged sections need be removed for repair. Another positive aspect, which has already been utilized by the transportation industry, is that the overall efficiency of the machine is improved because only those armature modules which can actively contribute to force production are energized at any time. In addition to its many benefits, the modular nature of this machine offers some interesting technical challenges in the design of the power electronic and control systems employed in driving the machine.

The use of field programmable gate array (FPGA) versus processor based control has become of significant interest in the last decade. The benefits of using an FPGA include increased dependability with dedicated hardware, the versatility of parallel execution and faster possible loop speeds. The scheme used to control the prototype machine consists of a current hysteresis loop implemented using an FPGA.

II. Prototype Machine Description

The prototype machine for this project is a three-phase linear PM machine. The design of this machine is a laboratory scale version of the electromagnetic aircraft launch system (EMALS) developed by Patterson, et al. [1], and therefore its purpose is to deliver high electromagnetic shear stress (force per unit area) to accelerate a large load to a high speed in a relatively short distance [3]-[5]. The final design for the structure of the machine is a blade configuration where the armature, containing the current-carrying windings, is double-sided and vertically oriented, while the moving component, termed the shuttle, houses the permanent magnets (Fig. 1). A linear motor with this arrangement is commonly termed a long armature-short field machine [6].

The shuttle has an active area on each side of 40mm by 150mm with a total mass of approximately 1.7kg. The field is provided by three pole pairs of nickel-coated NdFeB (N35) permanent magnets with a supporting structure composed of aluminum. Openings for the magnets were machined from both sides of the shuttle, with a 1mm web of aluminum remaining in the center, around the edge of the window. Magnets of opposite polarities were then introduced from either side of the shuttle and their attraction to one another holds them in place (Fig. 1). While four pairs of linear bearings are attached to the shuttle for horizontal localization, the force of attraction between the magnets and the steel stator is relied upon for vertical placement.