Research Article

Controlling Permanent Magnet Polysolenoid Linear Motor Based On the Nature of Voltage Source Inverter
Part 1: Two-Phase Voltage Source Inverter in Polysolenoid Motor Control Structure

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Abstract: Linear motor produces direct linear motion without intermediate mechanisms. It is usually fed by solid-state power supply. In this paper, a two-level voltage source inverter is designed to supply the Polysolenoid linear motor. Hardware solution and control rules of set of solid-state switches are proposed in order to implement voltage vector modulation technique of the inverter. The results are necessary for closed loop control of Polysolenoid linear motor.

Key words: Linear Motor, Polysolenoid Linear Motor, Permanent Magnet Linear Synchronous Motors, SVM, FOC.

1. Introduction

Polysolenoid linear motor (PLM) is a type of tubular permanent magnet linear synchronous motors, its working principle is mentioned in [1-14]. PLM is widely used in industry [15-20], it plays an important role in applications of parallel robots. PLM structure is shown in Fig. 1.

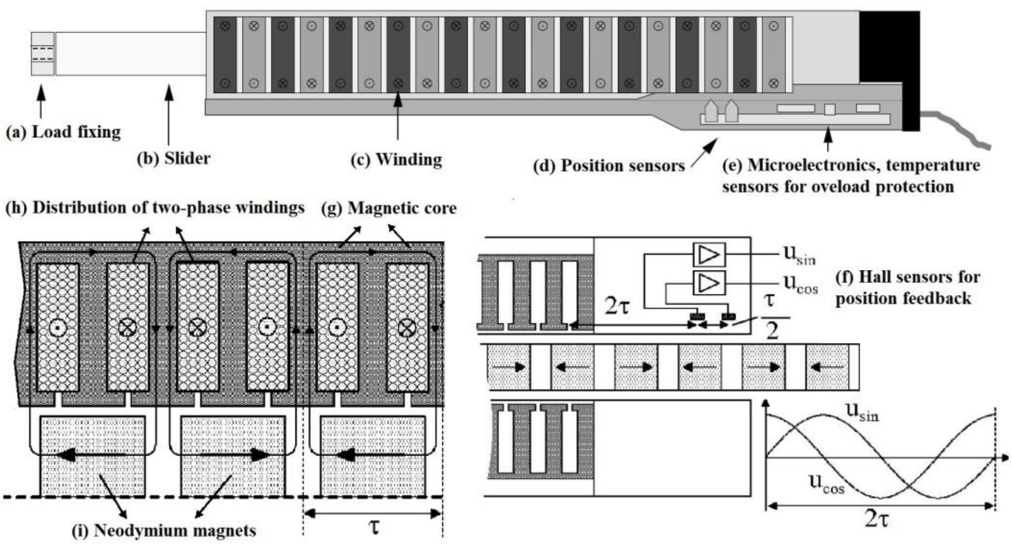

Figure 1: Polysolenoidlinear Motor [1-2].

The PLM analyzed here has a distinctive feature compared to the other types of linear motor that is 2-phase power supply. The motor stator consists of two windings and the windings are arranged so that the voltages of the two phases will differ by 90° electrical degrees. To implement closed-loop control technique based on FOC principle, the inverter used to power the motor will be different from the inverter used for three-phase motors. This is the content that is focused on clarifying in this study.

2. FOC-Based Closed-Loop Control of PLM

PLM has working principle inherited from the rotary motor, so most of the researches on this motor are derived from the content done for the rotary motor because of the similarity in structureof the two groups of motor. Similar to the control methods applied for rotary motors, there are two main directions in control methods for PLM, vector control principle and scalar control principle.

The studies applying the principle of scalar control are mentioned in [21-28]. These control methods aim at maintaining a constant flux in the air-gap to control torque, slip, etc. However, these methods encounter obstacles, when the load changes leading to the stator voltage drop due to the change of the stator current. Control methods based on the principle of scalar control have the advantage of being easy to apply to industrial equipment due to simple control rules, but they face difficulties in improving the quality of motion, especially in low speedregions.

The studies on vector control principles mentioned in [5,6,29-35]. In this group of methods, an explicit model of the quantities of current, voltage, and flux represented in vector form need to be built.

Similar to the control scheme of permanent magnet rotary motor in [29], the structure of closed-loop control of PLM is shown in Fig. 2.

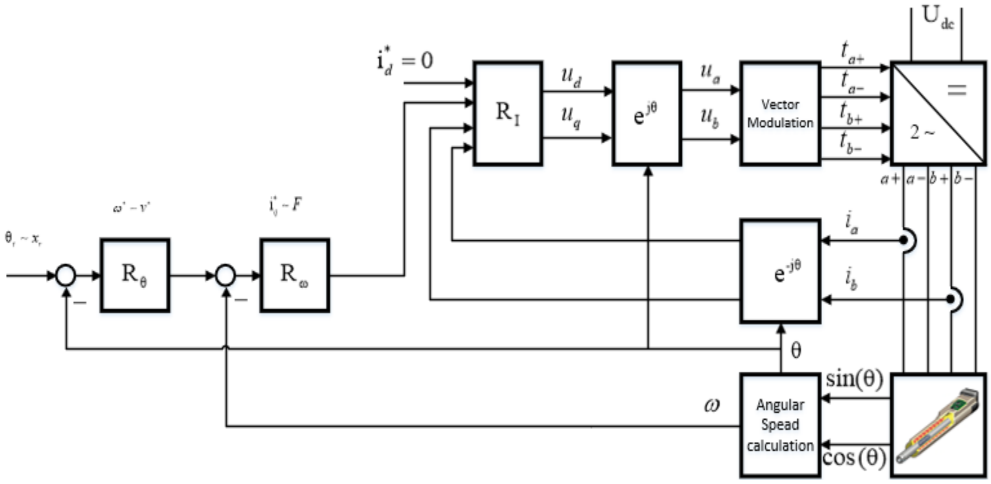

Figure 2: FOC Control Structure for 2-Phase Linear Motor, The Windings are Powered Independently.

In the implemented multi-loop control structure, the current controller R_I is designed decoupling in order to make the current dynamic linear, after that PI controllers designed by traditional methods are used.The speed controller R_ω also uses PI controller with integral anti-windup scheme. In order to eliminate the steady state error, a PD controller is chosen for the position controller R_θ since its control object is integral form (speed is equal to the derivative of position).

3. Space Vector Modulation Control for 2-Phase Inverter

As analyzed above, to perform motor control, we need to find the set of voltage vectors that can be generated by the converter or in other words find the modulation limit. The motor is powered by two independent voltage source converters as shown in Fig. 3.

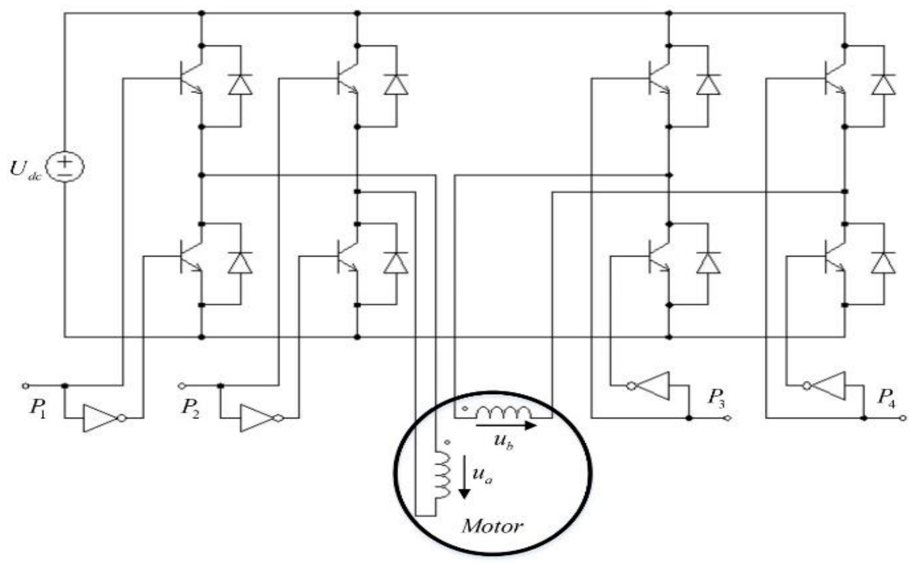

Figure 3: PLM is Fed by 2 Single Phase Unipolar PWM Voltage Source Inverter Independently.

With the given hardware structure, analysis of the combination of switching rules of an inverter leg supplying a motor winding is implemented. The logical state of two points A and B (two ends of the motor winding) is defined as: 0, if the winding is connected to the negative potential, or as 1, if the winding is connected to the positive potential. Then, a single inverter with 2 legs of switching device can create 2^2=4 logical states as illustrated in Fig. 4.

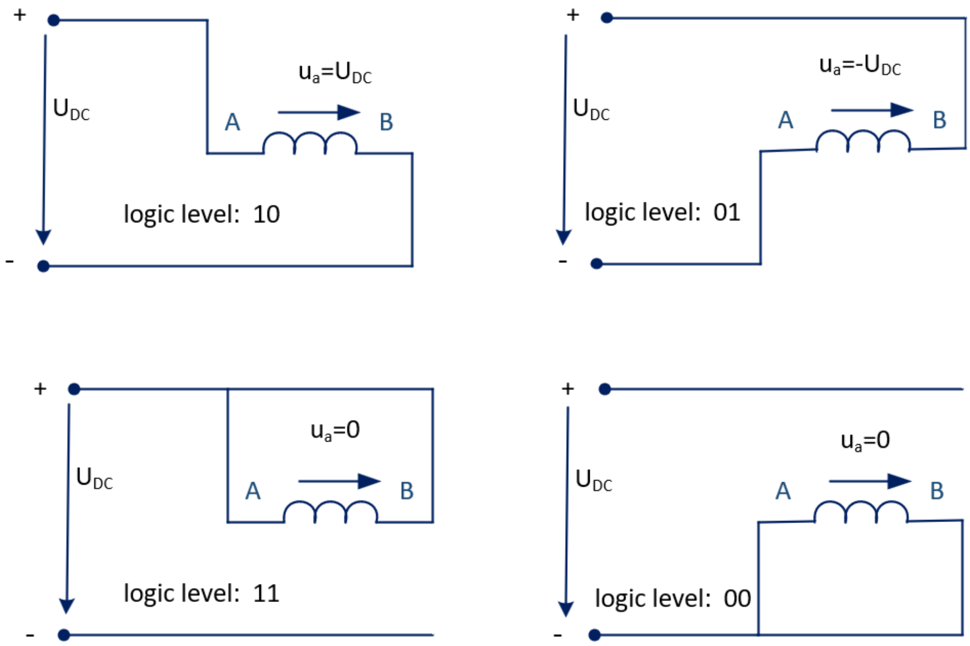

Figure 4: Logical States of a Motor Winding.

From analyzing the switching states for a winding, a set of switching states for both two windings is obtained. From the switching devices configuration, a finite set of switching states corresponding to the voltage value provided in Table 1.

Table 1: Switching State of the Converter

"1": On, "0": Off.						
Voltage Vector	**P_1**	**P_2**	**P_3**	**P_4**	**u_a**	**u_b**
	1	0	1	0	$+U_{dc}$	$+U_{dc}$
	1	0	0	1	$+U_{dc}$	$-U_{dc}$
	1	0	0	0	$+U_{dc}$	0
S_1	1	0	1	1	$+U_{dc}$	0
	0	1	1	0	$-U_{dc}$	$+U_{dc}$
	0	1	0	1	$-U_{dc}$	$-U_{dc}$
S_3	0	1	0	0	$-U_{dc}$	0
	0	1	1	1	$-U_{dc}$	0
S_2	1	1	1	0	0	$+U_{dc}$
	1	1	0	1	0	$-U_{dc}$
S_6	1	1	0	0	0	0
S_5	1	1	1	1	0	0
	0	0	1	0	0	$+U_{dc}$
S_4	0	0	0	1	0	$-U_{dc}$
S_7	0	0	0	0	0	0
S_8	0	0	1	1	0	0

To modulate stator voltage vector, 8 basic vectors highlighted in Table 1. are chosen and called standard vectors. In which, the vectors S_5, S_6, S_7, S_8 making the voltage vector zero are selected so that during the modulation the switches have an equal number of switching respectively between the quadrants in the modulation plane.

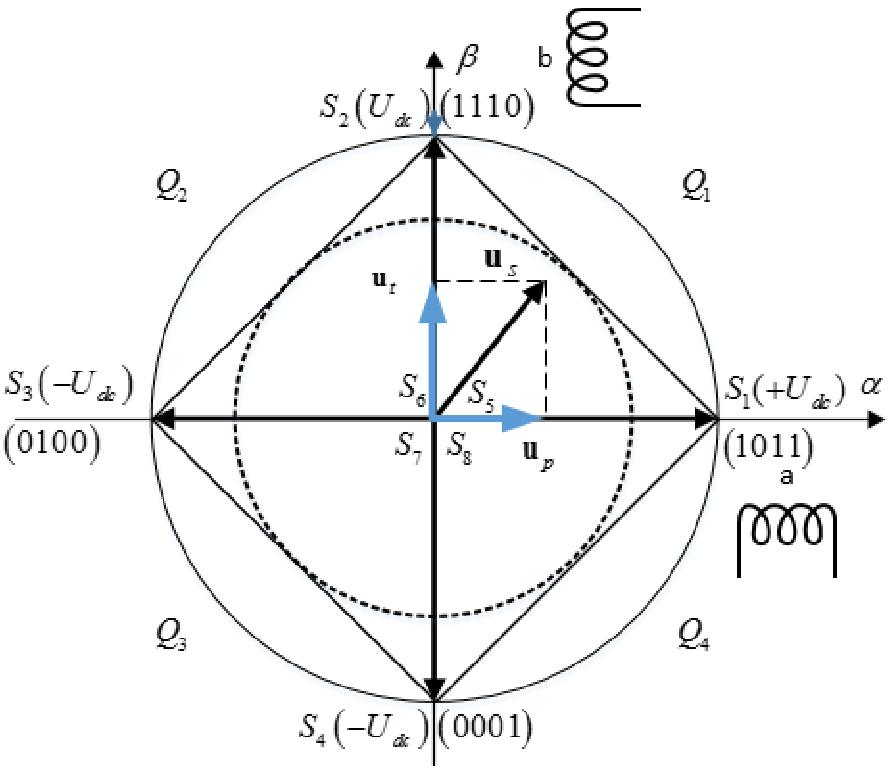

Figure 1: Modulation Plane in α,β Coordinates.

In order to form modulation region, the following formulas are used:

$$\mathbf{u}_s = \mathbf{u}_p + \mathbf{u}_t$$

$$\mathbf{u}_s \in Q_1 : \left|\mathbf{u}_p\right| = \frac{T_p}{T_{pulse}} U_{dc};\ \left|\mathbf{u}_t\right| = \frac{T_t}{T_{pulse}} U_{dc}$$

$$\mathbf{u}_s \in Q_2 : \left|\mathbf{u}_p\right| = -\frac{T_p}{T_{pulse}} U_{dc};\ \left|\mathbf{u}_t\right| = \frac{T_t}{T_{pulse}} U_{dc}$$

$$\mathbf{u}_s \in Q_3 : \left|\mathbf{u}_p\right| = -\frac{T_p}{T_{pulse}} U_{dc};\ \left|\mathbf{u}_t\right| = -\frac{T_t}{T_{pulse}} U_{dc}$$

$$\mathbf{u}_s \in Q_4 : \left|\mathbf{u}_p\right| = \frac{T_p}{T_{pulse}} U_{dc};\ \left|\mathbf{u}_t\right| = -\frac{T_t}{T_{pulse}} U_{dc}$$

$$T_p + T_t + T_{off} = T_{pulse}$$

Where: $\mathbf{u}_s$ is voltage vector need to be modulated in $\alpha\beta$ coordinates; $\mathbf{u}_p, \mathbf{u}_t$ is the right and the left boundary vector of $\mathbf{u}_s$ as Fig. 5; T_t, T_p: switching times of basic vectors corresponding to the quadrant $Q_i$containing u_s. T_{pulse} is modulation period; T_{off} : switching times of vector zero corresponding to the quadrant $Q_i$containing u_s.In the modulation plane in Fig. 5, switching device is considered ideal, switching time is zero. In fact, switching time must be taken into account and the condition that T_t, T_p, T_{off} are greater than switching time of switching device and processing time of microcontroller is added.

4. Conclusions

In this research, a configuration and switching rules to implement stator voltage vector modulation are proposed for PLM. In each quadrant from Q_1 to Q_4, it is always possible to determine any voltage vector corresponding to the command signal, this will be done by modulating the right and left boundary vectors and the modulation of the zero vectors. The obtained results are an important basis in the design of closed-loop control for Plolysolenoid motors based on FOC. With the specific characteristics of the power electronic converter, in the next studies, nonlinear control methods based on the continuous and discontinuous properties of the converter will be implemented and applied to permanent magnet PLM.

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