Appendix A
Description of the Experimental Setup

A.1 Description of the Prototype Tubular Surface-Mount Linear PMSM

The prototype tubular surface-mount linear PMSM used in this research is Model No. STA 2504S manufactured by Dunker Motor Advanced Motion Solutions and is categorised as servo tube by the manufacture. The complete experimental setup is shown in Fig. A.1. The manufacturer website for the prototype linear PMSM is: https://www.dunkermotoren.com.

A.2 Description of 3-Phase Voltage Source Inverter

The 3-phase 2-level voltage source inverter used for the prototype linear PMSM is manufactured by Semikron. The model no. "SKS 35F B6U+E1C1F+B6C1 21 V12". The manufacturer website is: https://www.semikron.com.

A.3 Description of Voltage Sensing Board

The schematic diagram for the voltage sensing board is provided in Fig. A.2.

A.4 Description of Current Sensing Board

The schematic diagram for the current sensing board is provided in Fig. A.3.

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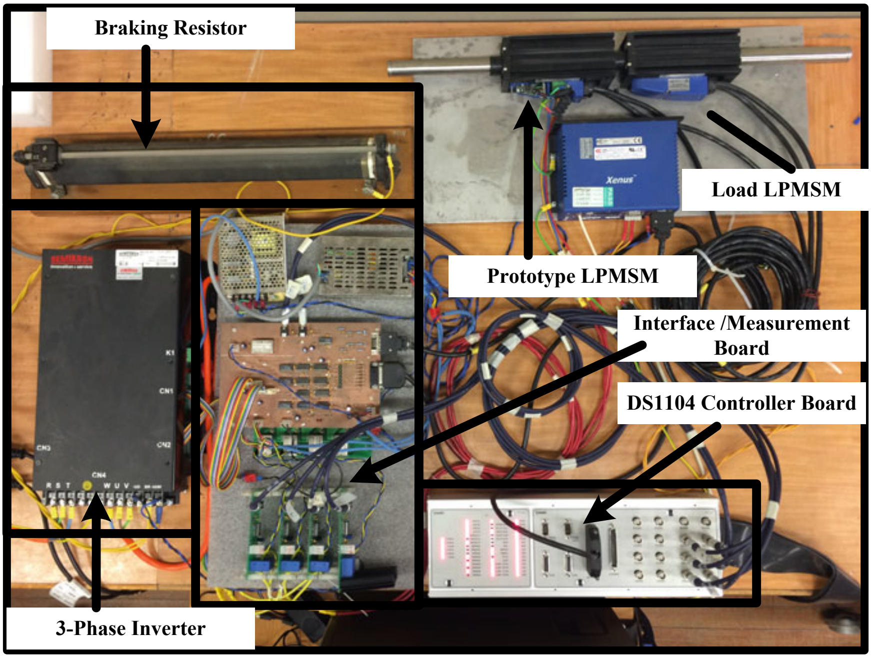

Fig. A.1 Experimental setup

A.5 Description of dSPACE© DS 1104 R&D Controller Board

In this research, DS 1104 controller board is used for the implementation of the control algorithms, processing of the feedback signals from current, voltage and speed sensors and generation of PWM signals for the voltage source inverter. The DS1104 controller board is specifically designed for development of high speed multilevel digital controllers and real-time simulations in various fields. It is a complete real-time control system based on a 603 Power PC floating point processor of 250 MHz. For advance I/O purposes, the board includes a slave DSP subsystem which performs digital input and output along with generation of PWM signals. The heart of this subsystem is a TMS320F240 digital signal processor from Texas Instruments. The controller board can be directly programmed using MATLAB/SIMULINK or C program. An overview of the features provided by the DS1104 board and technical specifications of the board are given in the 2. The architectural overview of the DS 1104 board is provided in Fig. A.4. The technical specifications of the controller board are provided in Table A.1.

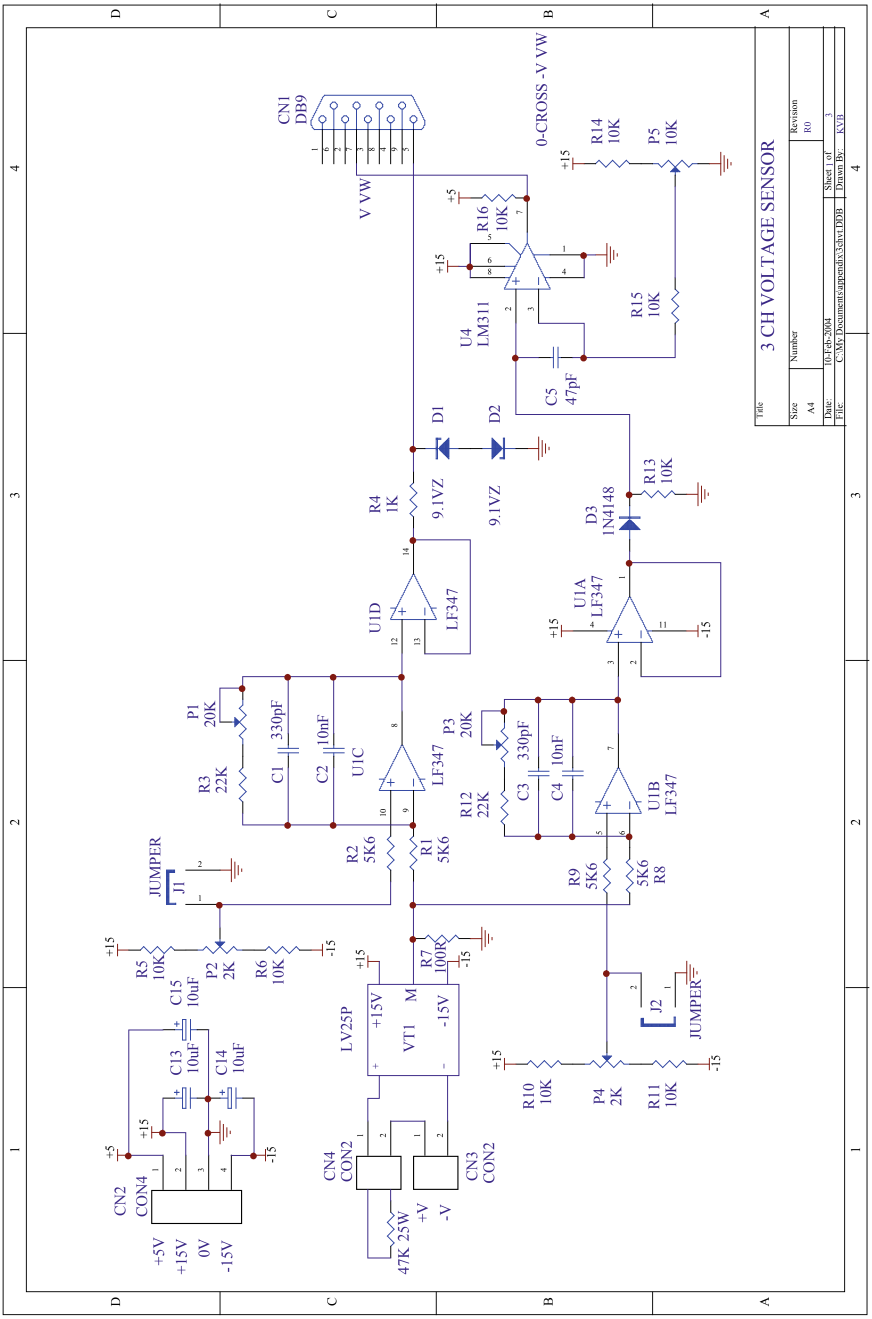

Fig. A.2 Schematic circuit diagram of voltage sensing board

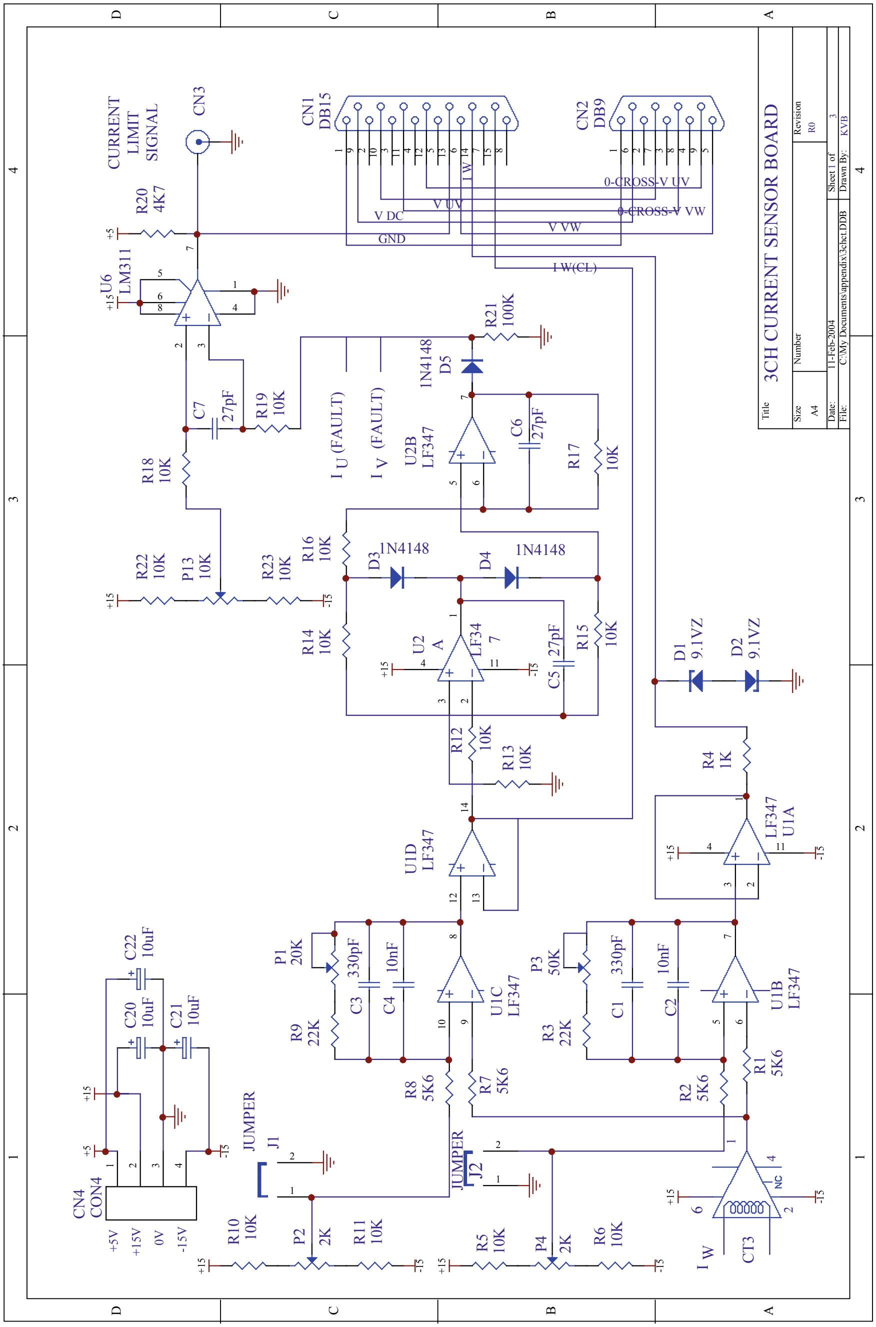

Fig. A.3 Schematic circuit diagram of current sensing board

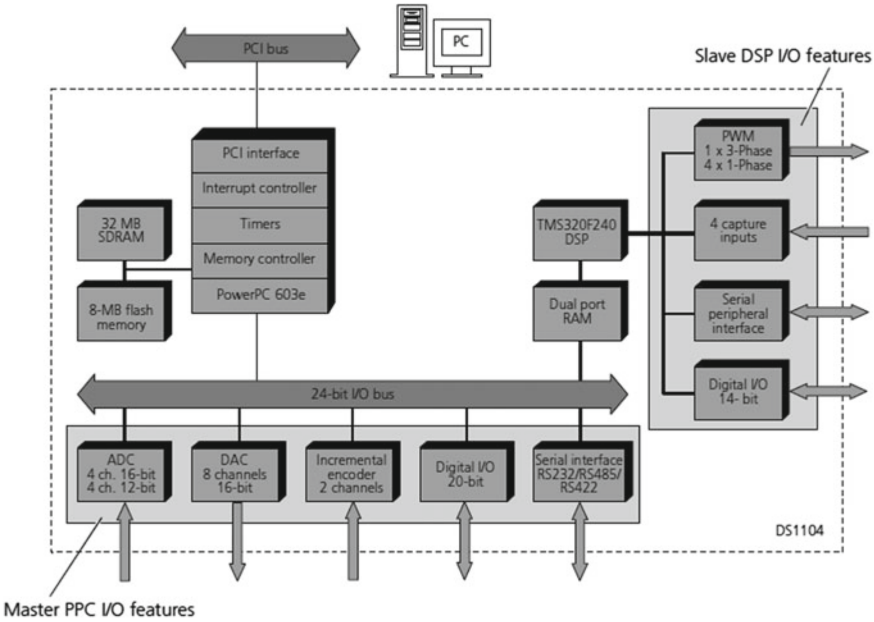

Fig. A.4 Architectural overview of DS 1104 controller board

Table A.1 Technical specifications of the DS1104 controller board

Manufacturer	dSPACE GmbH Technologiepark 25, 33100 Paderborn, Germany
Processor	• MPC 8240 with PPC630e core and on chip peripherals • 64-bit floating point processor • 250 MHz CPU
Memory	• Global memory: 32 MB SDRAM • flash memory: 8 MB
ADC	• 4 multiplexed channels 16 bit resolution, 2 μs conversion time • 4 A/D channels, 12 bit resolution and 800 ns conversion time
Incremental encoder interface	• 2 channels • Single ended TTL or differential RS422 input • 4 fold subdivision • Max 1.65 MHz • 24-bit loadable position counter • Rest on index
Slave DSP	• Texas instruments TMS320F240 DSP • 20 MHz clock frequency • 1X3-phase PWM output • 4X1 phase PWM output

Appendix B
Derivation of Expressions for $\frac{dF_T}{dt}$ and $\frac{d\lambda_s}{dt}$

B.1 Derivation of Expression for $\frac{dF_T}{dt}$ in Terms of Inverter Voltages

The values of i_α, i_β, $\frac{d\lambda_\alpha}{dt}$ and $\frac{d\lambda_\beta}{dt}$ can be achieved from (2.94) to (2.97) as:

$$\frac{d\lambda_\alpha}{dt} = v_\alpha - R_s i_\alpha \tag{B.1}$$

$$\frac{d\lambda_\beta}{dt} = v_\beta - R_s i_\beta \tag{B.2}$$

$$i_\alpha = \frac{\lambda_\alpha - \lambda_{pm,\alpha}}{L_s} \tag{B.3}$$

$$i_\beta = \frac{\lambda_\beta - \lambda_{pm,\beta}}{L_s} \tag{B.4}$$

By substituting (B.1) to (B.4) in (2.109) yields:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau} k_F P \left((v_\alpha - R_s i_\alpha) i_\beta + \lambda_\alpha \frac{di_\beta}{dt} - \left(v_\beta - R_s i_\beta\right) i_\alpha - \lambda_\beta \frac{di_\alpha}{dt} \right) \tag{B.5}$$

Equation (B.5) simplifies to:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau} k_F P \left(v_\alpha i_\beta - v_\beta i_{s\alpha} + \lambda_\alpha \frac{di_\beta}{dt} - \lambda_\beta \frac{di_\alpha}{dt} \right) \tag{B.6}$$

Now the values of $\frac{di_\alpha}{dt}$ and $\frac{di_\beta}{dt}$ can be achieved by differentiation of (B.3) and (B.4) respectively. Substituting these values of $\frac{di_\alpha}{dt}$ and $\frac{di_\beta}{dt}$ into (B.6):

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$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}k_F P\left(v_\alpha i_\beta - v_\beta i_\alpha + \frac{\lambda_\alpha}{L_s}\left(\frac{d\lambda_\beta}{dt} - \frac{d\lambda_{pm,\beta}}{dt}\right) - \frac{\lambda_\beta}{L_s}\left(\frac{d\lambda_\alpha}{dt} - \frac{d\lambda_{pm,\alpha}}{dt}\right)\right) \tag{B.7}$$

The value of $\frac{d\lambda_{r\alpha}}{dt}$ can be obtained by differentiating (2.98) as:

$$\frac{d\lambda_{pm,\alpha}}{dt} = \frac{d\left(\lambda_f \cos\theta_r\right)}{dt} = -\lambda_f \sin\theta_r \frac{d\theta_r}{dt} \tag{B.8}$$

From (2.99), it is clear that $\lambda_f \sin\theta_r = \lambda_{pm,\beta}$, therefore (B.8) becomes:

$$\frac{d\lambda_{pm,\alpha}}{dt} = -\lambda_{pm,\beta}\omega_r \tag{B.9}$$

Similarly, the values of $\frac{d\lambda_{r\beta}}{dt}$ can be achieved by differentiating (2.98) as:

$$\frac{d\lambda_{pm,\beta}}{dt} = \lambda_{pm,\alpha}\omega_r \tag{B.10}$$

Substituting of values of $\frac{d\lambda_{pm,\alpha}}{dt}$ and $\frac{d\lambda_{pm,\beta}}{dt}$ from (B.9) and (B.10) respectively, into (B.7):

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}k_F P\Bigg(v_\alpha i_\beta - v_\beta i_\alpha + \frac{\lambda_\alpha}{L_s}\left(v_\beta - R_s i_\beta - \lambda_{pm,\alpha}\omega_r\right) - \frac{\lambda_\beta}{L_s}\left(v_\alpha - R_s i_\alpha + \lambda_{pm,\beta}\omega_r\right)\Bigg) \tag{B.11}$$

Substituting the values of i_α and i_β from (B.3) and (B.4) in the first two terms of (B.11) within the brackets results in:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}k_F P\Bigg(v_\alpha\left(\frac{\lambda_\beta - \lambda_{pm,\beta}}{L_s}\right) - v_\beta\left(\frac{\lambda_\alpha - \lambda_{pm,\alpha}}{L_s}\right) + \frac{\lambda_\alpha}{L_s}\left(v_\beta - R_s i_\beta - \lambda_{pm,\alpha}\omega_r\right) - \frac{\lambda_\beta}{L_s}\left(v_\alpha - R_s i_\alpha + \lambda_{pm,\beta}\omega_r\right)\Bigg) \tag{B.12}$$

Simplifying (B.13) by re-arranging terms:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\left(v_\alpha\lambda_\beta - v_\alpha\lambda_{pm,\beta} - v_\beta\lambda_\alpha + v_\beta\lambda_{pm,\alpha} + \lambda_\alpha v_\beta - \lambda_\alpha R_s i_\beta - \lambda_\alpha\lambda_{pm,\alpha}\omega_r - \lambda_\beta v_{s\alpha} + \lambda_\beta R_s i_\alpha - \lambda_\beta\lambda_{pm,\beta}\omega_r\right) \tag{B.13}$$

Equation (B.13) can be re-arranged to cancel the similar terms with opposite signs as:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\Bigg(\underbrace{\cancel{v_\alpha\lambda_\beta - v_\alpha\lambda_\beta}}_{Zero} + \underbrace{\cancel{\lambda_\alpha v_\beta - v_\beta\lambda_\alpha}}_{Zero} - R_s\big(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\big)$$
$$-v_\alpha\lambda_{pm,\beta} + v_\beta\lambda_{pm,\alpha} - \omega_r\big(\lambda_\alpha\,\lambda_{pm,\alpha} + \lambda_\beta\lambda_{pm,\beta}\big)\Bigg) \quad \text{(B.14)}$$

The zero terms in (B.14) can be omitted to achieve the following expression for $\frac{dF_T}{dt}$ as:

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\Big(-R_s\big(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\big) - v_\alpha\lambda_{pm,\beta} + v_\beta\lambda_{pm,\alpha}$$
$$-\omega_r\big(\lambda_\alpha\,\lambda_{pm,\alpha} + \lambda_\beta\lambda_{pm,\beta}\big)\Big) \quad \text{(B.15)}$$

In (B.15), $\lambda_\alpha\,\lambda_{pm,\alpha} + \lambda_\beta\lambda_{pm,\alpha}$ represents the scalar product of the stator flux space vector $\overrightarrow{\lambda_s}$ and the rotor flux space vector $\overrightarrow{\lambda_f}$ in $\alpha\beta$-reference frame. It is clear form Fig. 2.8 that the angle between $\overrightarrow{\lambda_s}$ and $\overrightarrow{\lambda_f}$ is δ therefore:

$$\lambda_{s\alpha}\,\lambda_{r\alpha} + \lambda_{s\beta}\lambda_{\beta\alpha} = \overrightarrow{\lambda_s}.\overrightarrow{\lambda_r} = \lambda_s\lambda_f\cos\delta \quad \text{(B.16)}$$

From (B.15) into (B.16):

$$\frac{dF_T}{dt} = \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\Big(-R_s\big(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\big) - v_\alpha\lambda_{pm,\beta} + v_\beta\lambda_{pm,\alpha} - \omega_r\lambda_s\lambda_f\cos\delta\Big) \quad \text{(B.17)}$$

Equation (B.17) is simplified by re-arranging the terms:

$$\frac{dF_T}{dt} = -\frac{R_s}{L_s}\left(\underbrace{\frac{3}{2}\frac{\pi}{\tau}k_F P\big(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\big)}_{F_T}\right)$$
$$+\frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\big(-v_\alpha\lambda_{pm,\beta} + v_\beta\lambda_{pm,\alpha} - \omega_r\lambda_s\lambda_f\cos\delta\big) \quad \text{(B.18)}$$

From (1.62), it is clear that in (B.18), $\frac{3}{2}\frac{\pi}{\tau}P\big(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\big)$ represent the thrust force F_T, therefore (B.18) can be written as:

$$\frac{dF_T}{dt} = -\frac{R_s}{L_s}F_T + \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\big(-v_\alpha\lambda_{pm,\beta} + v_\beta\lambda_{pm,\alpha} - \omega_r\lambda_s\lambda_f\cos\delta\big) \quad \text{(B.19)}$$

Since, F_T on right hand side of (B.19) is the initial operating thrust force at the current instant of time; therefore replacing F_T by F_0 results in:

$$\frac{dF_T}{dt} = -\frac{R_s}{L_s} F_0 + \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\left(-v_\alpha \lambda_{pm,\beta} + v_\beta \lambda_{pm,\alpha} - \omega_r \lambda_s \lambda_f \cos\delta\right) \quad \text{(B.20)}$$

Substituting the value of ω_r from (2.44) into (B.20):

$$\frac{dF_T}{dt} = -\frac{R_s}{L_s} F_0 + \frac{3}{2}\frac{\pi}{\tau}\frac{k_F P}{L_s}\left(-v_\alpha \lambda_{pm,\beta} + v_\beta \lambda_{pm,\alpha} - P\frac{\pi}{\tau} \lambda_s \lambda_f v_m \cos\delta\right) \quad \text{(B.21)}$$

The effect of the various voltage vectors applied by the voltage source inverter on the thrust force of the surface-mount linear PMSM can be evaluated by using (B.21). Equation (B.21) can be solved using the prototype linear PMSM parameters in Table 1.1 for various voltage vectors to compute the rate of change of thrust force.

B.2 Derivation of Expression for $\frac{d\lambda_s}{dt}$ in Terms of Inverter Voltages

In order to formulate the effect of the inverter voltage vectors on the rate of change of stator flux, first the magnitude of the stator flux space vector is expressed in terms of $\alpha\beta$-components by using (2.132) as:

$$\lambda_s = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \quad \text{(B.22)}$$

Taking the time derivative of (B.22):

$$\frac{d\lambda_s}{dt} = \frac{1}{\sqrt{\lambda_\alpha^2 + \lambda_\beta^2}}\left(\lambda_\alpha \frac{d\lambda_\alpha}{dt} + \lambda_\beta \frac{d\lambda_\beta}{dt}\right) \quad \text{(B.23)}$$

Substituting (2.94) to (2.97) in (B.23), the following expression for $\frac{d\lambda_s}{dt}$ can be given as:

$$\frac{d\lambda_s}{dt} = -\frac{R_s}{L_s}\lambda_s + \frac{R_s}{L_s}\lambda_f \cos\delta + \frac{1}{\lambda_s}\left(v_\alpha \lambda_\alpha + v_\beta \lambda_\beta\right) \quad \text{(B.24)}$$

The rate of change in the stator flux magnitude is computed from (B.24) using the parameters of the prototype linear PMSM.