

Development of Closed-Loop Permanent Magnet Synchronous Motor Drive System Prototype

(Pembangunan Prototaip Sistem Gelung Tertutup Pacuan Motor Segerak Magnet Kekal)

Fardila Mohd Zaihidee^{a*}, Marizan Mubin^b, Hang Seng Che^c & Tang Jing Rui^a

^aFaculty of Technical and Vocational, Universiti Pendidikan Sultan Idris, Malaysia.

^bFaculty of Engineering, University of Malaya, Malaysia.

^cPower Energy Dedicated Advanced Center (UMPEDAC), University of Malaya, Malaysia.

*Corresponding author: fardila@ftv.upsi.edu.my

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ABSTRACT

Permanent magnet synchronous motors (PMSM) are widely used in low to mid-power applications and high-performance drives. They are preferred over brush-type motors and gradually replacing induction motors in various fields of application due to its advantages. Many researchers are proposing new control methods of PMSM drive system. However, the PMSM system is nonlinear and consists of time-varying parameters with high-order complex dynamics. Due to these factors, researchers cannot rely only on simulation results to prove superiority of their proposed controllers. To validate the results obtained by simulation, experimental validation is necessary, where a closed-loop PMSM drive system prototype has to be developed. This paper describes the development of a PMSM drive system prototype with closed-loop current, speed and position feedback using dSpace DS1104 controller board for a 1.93kW three-phase interior-mounted permanent magnet synchronous motor used for experimental validation of a proposed modified fractional order sliding mode speed controller. Using this prototype, the performance of any newly proposed control methods in real applications can be verified. Appropriate signal acquisition procedures of the feedback signals, as described in this work, are crucial to ensure the accuracy of closed-loop performance of the developed drive system.

Keywords: Permanent magnet synchronous motor; prototype; closed-loop control

ABSTRAK

Motor segerak magnet kekal (PMSM) digunakan secara meluas untuk aplikasi kuasa rendah dan sederhana serta dalam pacuan berprestasi tinggi. Motor ini digemari berbanding motor berus and sedikit demi sedikit menggantikan motor induksi dalam pelbagai bidang aplikasi kerana kelebihanannya. Ramai penyelidik mencadangkan kaedah-kaedah kawalan baru bagi sistem pacuan PMSM. Namun begitu, sistem PMSM tidak linear dan mengandungi parameter-parameter yang berubah mengikut masa. Atas faktor ini, penyelidik tidak boleh hanya bergantung kepada keputusan simulasi untuk membuktikan kelebihan kawalan yang dicadangkan. Untuk mengesahkan keputusan yang diperolehi melalui simulasi, pengesahan eksperimen diperlukan, di mana prototaip sistem gelung tertutup pacuan PMSM perlu dibangunkan. Artikel ini menerangkan pembangunan sistem pacuan PMSM dengan maklum balas arus, halaju dan kedudukan gelung tertutup menggunakan papan kawalan dSpace DS1104 bagi sebuah PMSM 1.93kW tiga fasa dakap dalaman yang digunakan untuk pengesahan eksperimen bagi kawalan halaju kawalan mod gelongsor tertib pecahan yang dicadangkan. Dengan menggunakan prototaip ini, prestasi sebarang kaedah kawalan yang dicadangkan boleh disahkan dalam aplikasi sebenar. Prosedur perolehan yang bersesuaian bagi isyarat maklum balas seperti yang diterangkan dalam artikel ini adalah penting untuk memastikan ketepatan prestasi sistem gelung tertutup yang dibangunkan.

Kata kunci: Motor segerak magnet kekal; prototaip; kawalan gelung tertutup

INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in low to mid-power applications and high-performance drives e.g., robotics, electric vehicles and machine tools.

PMSM has similar stator construction as in induction motors and similar field excitation concept as in brushless DC (BLDC) motor but has back EMF of sinusoidal type. Its rotor consists of permanent magnets, which generate a substantial air gap magnetic flux. PMSMs are preferred over

brush-type motors and gradually replacing induction motors in various fields of application due to its advantages such as compact structure, high air-gap flux density, high power density, high torque to inertia ratio, and high efficiency. Hence, many researchers are focusing on optimizing control of PMSM drive system. Many control methods have been proposed for speed control of PMSM such as sliding mode control (Mohd Zaihidee et al. 2021; Wang et al. 2020; Xu et al. 2021), predictive control (Li et al. 2022; Li et al. 2021), adaptive control (Jie et al. 2020), automatic disturbance rejection control (Li et al. 2020; Lin et al. 2021) and artificial intelligence incorporated controllers (You et al. 2021).

However, the PMSM system is nonlinear and consists of time-varying parameters with high-order complex dynamics (Shihua et al. 2013). Due to these factors, researchers cannot rely only on simulation results to prove superiority of their proposed controllers. To validate the results obtained by simulation, experimental validation is necessary, where a closed-loop PMSM drive system prototype has to be developed.

This paper describes the development of a PMSM drive system prototype with closed-loop current, speed and position feedback using dSpace DS1104 controller board for a 1.93kW three-phase interior-mounted permanent magnet synchronous motor used for experimental validation of a modified fractional order sliding mode speed controller proposed by Zaihidee et al. (2019).

CLOSED-LOOP PMSM DRIVE PROTOTYPE ARCHITECTURE

The developed closed-loop PMSM drive system prototype consists of mainly an interior PMSM with built-in encoder, three phase voltage source inverter, AC source, two programming PC, dSpace DS1104 controller, hysteresis brake, dynamometer controller, speed/torque transducer and conditioning circuit, as illustrated in Figure 1. C code of the designed controller, coordinate transformations and PWM is generated in MATLAB/Simulink and is uploaded to the DS1104 controller board. Inputs and outputs to and from the controller are obtained and distributed respectively using the CP1104 connector panel. Switching signals produced by the PWM are fed to the inverter. The inverter produces the appropriate output voltages for the motor. Encoder data is fed to the controller as feedback. From these data, the position of the rotor and the motor speed can be extracted. Other than that, output currents to the motor are measured using sensor circuitries and are also fed back to the controller as feedback to the current controllers. Input signals monitoring and output signals monitoring/manipulation are executed within the ControlDesk software environment. Hysteresis brake AHB-3 was used to produce the required load torque for evaluation of the controller's performance in various load conditions.

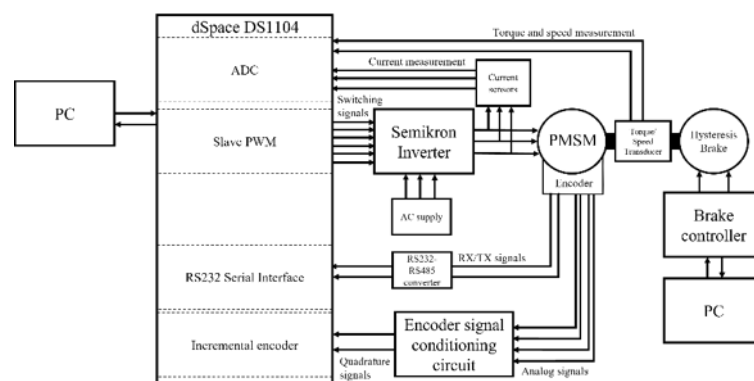


FIGURE 1. Closed-loop PMSM drive prototype architecture

DSPACE DS1104 CONTROLLER BOARD

The DS1104 R&D Controller Board is a real-time hardware based on the PowerPC 603e microprocessor and equipped with various I/O interfaces. In this prototype, external devices are connected to the controller board using connector panel CP1104 and LED panel CLP1104, which provides an additional array of LEDs indicating the states of the digital signals, as shown in Figure 2. The DS1104's main processing unit, MPC8240, consists of the master PPC that runs at 250 MHz (CPU clock), an interrupt controller, a synchronous DRAM controller, timers and a PCI interface. The master PPC controls the I/O features such as ADC unit, DAC unit, bit I/O, incremental encoder interface and serial interface.

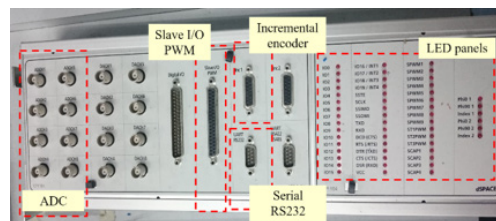


FIGURE 2. Connector panel CP1104 and LED panel CLP1104

The DS1104 contains two different types of ADC for the analogue input channels namely one 16-bit ADC with four multiplexed input signals (ADCH1-ADCH4) and four 12-bit parallel ADCs with one input signal each (ADCH5 - ADCH8). The analogue inputs are single-ended bipolar

inputs with an input voltage range between -10V and +10V. In addition, the DS1104 is also equipped with a universal asynchronous receiver and transmitter (UART) to perform serial asynchronous communication with external devices. The UART interface is based on a 16C550C-compatible communication element (TL16C550C from Texas Instruments) and is driven by a 16 MHz oscillator. The UART can be used in the RS232, RS422 or RS485 transceiver mode with selectable baud rates up to 115.2 kBd (for RS232) or 1 MBd (for RS422/ RS485), selectable number of data bits, parity bit and stop bits and selectable software FIFO buffer size.

The master PPC on DS1104 also controls an incremental encoder interface, which is available through two digital incremental encoder input channels (INC1, INC2). These channels support single-ended TTL signals with 1.65 MHz maximum encoder line count frequency, hence, with internal 4-fold subdivision of each encoder line, the DS1104 can therefore handle count frequencies of up to 6.6 MHz. The position counter has 24-bit resolution, with count direction depending on the encoder's rotation direction and can be reset by the encoder's index pulse.

The slave DSP on the DS1104 provides a timing I/O unit that can be used to generate and measure various pulse-width modulated (PWM) signals. In this work, 3-phase PWM signal (PWM3) is generated with non-inverted and inverted outputs with variable duty cycles, PWM frequencies (1.25 Hz - 5 MHz) and dead band. In PWM3 generation mode, the pulse pattern for the three non-inverted PWM signals SPWM1, SPWM3 and SPWM5 is as shown in Figure 3, where T_p is the PWM period.

The DS1104 also provides access to various hardware interrupts, originating either from on-board devices such as timers or from external devices connected to the board. In the latter case, the interrupts are sampled at a frequency of bus clock (BCLK)/64. Interrupt-driven subsystems can be implemented in MATLAB/Simulink environment by using specific interrupt blocks provided by RTI1104. In this

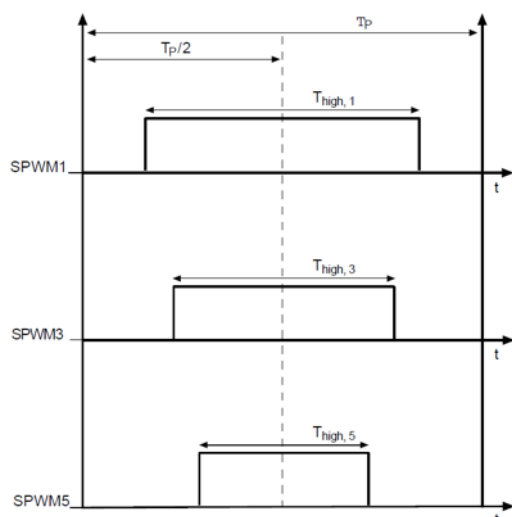


FIGURE 3. Pulse pattern of three non-inverted PWM signals of a 3-phase PWM signals

prototype, timer interrupt and Slave DSP PWM interrupt are used. Timer interrupts in DS1104 are obtained using 32-bit down counters driven by BCLK/8. The period of each timer can be selected. An interrupt is generated when the counter reaches zero. After that, the counter will be reloaded automatically which makes this type of interrupt suitable for triggering periodic tasks.

Usage of dSpace DS1104 controller board is extended with the usage of ControlDesk, which is a real-time experiment and visualisation software that functions as a user interface between programming tool and test equipment controlled by dSpace controller boards, as shown in Figure 4. Users can select appropriate instruments based on desired application such as plotter to plot analogue data, on/off button to activate/deactivate a switch, numeric input to assign any numeric data to a variable. Each instrument has at least one variable assigned to it. These variables are variables that are programmed in MATLAB environment, built and loaded into connected dSpace controller.



FIGURE 4. ControlDesk software panels

PERMANENT MAGNET SYNCHRONOUS MOTOR

This PMSM drive prototype is realized using Schneider Electric BSH1002P12A1A three-phase AC servo motor, an interior 1.93kW permanent magnet synchronous motor, as shown in Figure 5. The motor's nameplate data is tabulated in Table 1.

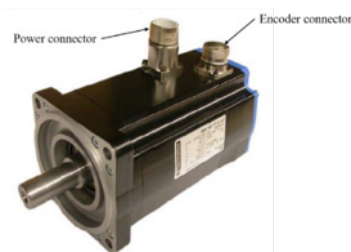


FIGURE 5. BSH1002P12A1A three-phase AC motor

TABLE 1. Motor name plate data

Motor parameter	Symbol	Motor data
Nominal output power	PN	1.93kW
Maximum voltage	U_{max}	480V _{rms}
Maximum current	I_{max}	17.1A _{rms}
Maximum mechanical speed	n_{max}	6000min ⁻¹
Continuous stall torque	M_0	5.8Nm

BSH1002P12A1A motor is compact in size with a length of only 204.5mm, 100mm in width and 138.4mm in height. This interior PMSM has 4 pole pairs of permanent magnets buried in the rotor, hence, it has a small effective air gap and a more robust construction compared to surface PMSMs. One remarkable parameter feature of IPMSM is unidentical value of d-axis and q-axis inductance, as shown in the motor’s parameter list in Table 2.

TABLE 2. PMSM parameters

Motor parameter name	Symbol	Motor parameter value
Stator resistance	R_s	1.2
d-axis stator inductance	L_d	6mH
q-axis stator inductance	L_q	6.75mH
Number of poles	p	8
Inertia	J	2.31 kgcm ²
Back emf constant	K_e	77 V _{rms} /krpm
Torque constant	K_t	0.9Nm/A

As seen from Figure 5, BSH1002P12A1A PMSM has two connectors namely power connector and encoder connector. Schneider Electric VW3M5101R30 power cable is used to supply power to the motor through its industrial M23 power

connector on the motor side. The cable core consists of 4 units of 1.5 mm² cables and 2 units of 1 mm² cables, as shown in Figure 6. Table 3 shows the pin assignment of the power cable.

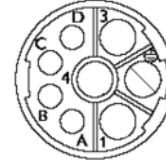


FIGURE 6. Power cable core

TABLE 3. Pin assignment of M23 power connector

Pin	Designation	Meaning	Range
1	U	Power	3 AC 0 - 480V
2	PE	Shield	
3	W	Power	3 AC 0 - 480V
4	V	Power	3 AC 0 - 480V
A	Brake + (if any)	Brake	DC 24V
B	Brake - (if any)	Brake	DC 0V
C	-	N/A	
D	-	N/A	

The other M23 industrial connector namely the encoder connector is used for motor feedback system. The motor used in this prototype is equipped with a built-in absolute multiturn SinCos Hiperface SICK SKM36-HFA0-K02 encoder. It provides both absolute and incremental position of the rotor from its binary code digital signal and its differential analogue sin cos signals respectively, as summarized in Figure 7.

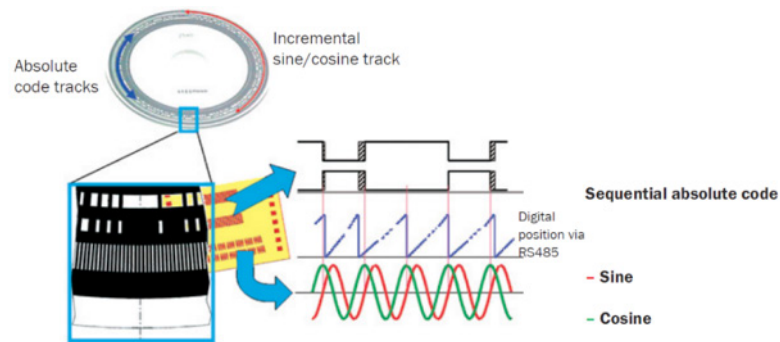


FIGURE 7. Hiperface SICK SKM36-HFA0-K02 encoder data

These signals are fed to the controller either directly or through a signal conditioning circuit through encoder cable VW3M8101R30 as shown in Figure 8. Its corresponding pin assignment is tabulated in Table 4. Pins 10 and 11 are used to supply the encoder with 10V DC for power. Details on the working principle of this encoder as a feedback system in the developed closed-loop PMSM drive prototype will be detailed in the next section.

Figure 9 shows the motor in use is securely fixed to a T-slot base plate using Magtrol Adjustable Motor Fixtures AMF-3, which is individually shown in Figure 10. The motor fixture not only secures the motor in place while running any test, but also versatile enough to enable easy motor centering for optimum coupling to other components such as transducer and dynamometer in this work. Furthermore, this type of fixture is chosen due to its two adjustable bridges feature that allows clamping position variation. In addition, its locking thumb screw feature provides better protection against vibration. Lastly, all motor-to-fixture contact surfaces on Magtrol AMF-3 are nylon padded for scratch-free clamping.

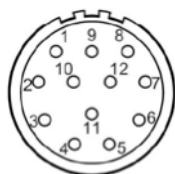


FIGURE 8. Encoder cable core

TABLE 4. Pin assignment of M23 encoder connector

Pin	Designation	Meaning	Range
1	Sensor PTC	Temperature	
2	Sensor PTC	Temperature	
3	-	Not assigned	
4	REF SIN	REF signal	
5	REF COS	REF signal	
6	Data +	RS 485	
7	Data -	RS 485	
8	SIN +		
9	COS +		
10	U	Power	DC 7 – 12V
11	GND	Ground	DC 0V
12	-	Not assigned	

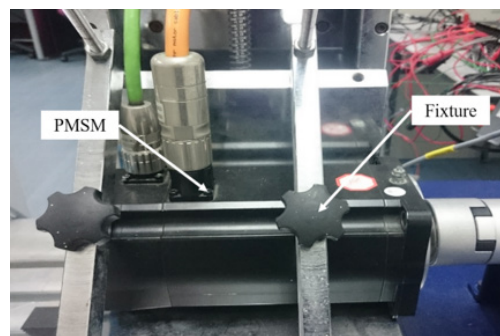


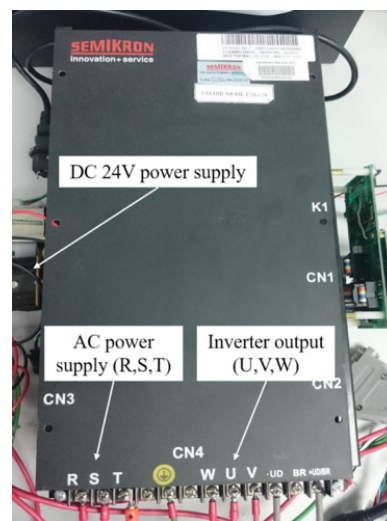
FIGURE 9. PMSM with fixture



FIGURE 10. Magtrol Adjustable Motor Fixtures AMF-3

SEMIKRON THREE PHASE SIX SWITCHES TWO-LEVEL VSI

PMSM drive prototype developed in this work uses Semikron three phase six switches two-level VSI Semikron SKS 13F B6U+B6CI+E1CIF*2 09 V12, as shown in Figure 11.



(a)

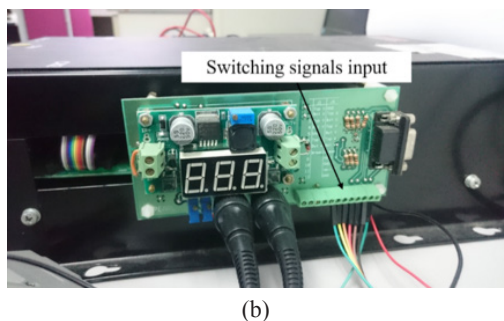


FIGURE 11. Semikron SKS 13F B6U+B6CI+E1CIF*2 09 V12 voltage source inverter (a) top view (b) side view

Figure 12 shows the complete circuit inside Semikron VSI that consists of a rectifier that converts input AC supply to DC link, with which the succeeding inverter circuit operates. The maximum output voltage and current of the inverter is 380V AC and 13A respectively. The inverter's absolute maximum switching frequency is 20kHz, but it operates optimally at maximum 10kHz. A DC 24V is also supplied separately to the inverter to power up additional internal submodules such as cooling fan and LED display.

The switching sequence of six switches in the inverter circuit depends on switching signals, which are externally fed from the controller as CMOS signal between 0 to 15V. The Semikron inverter was powered by Chroma 61511

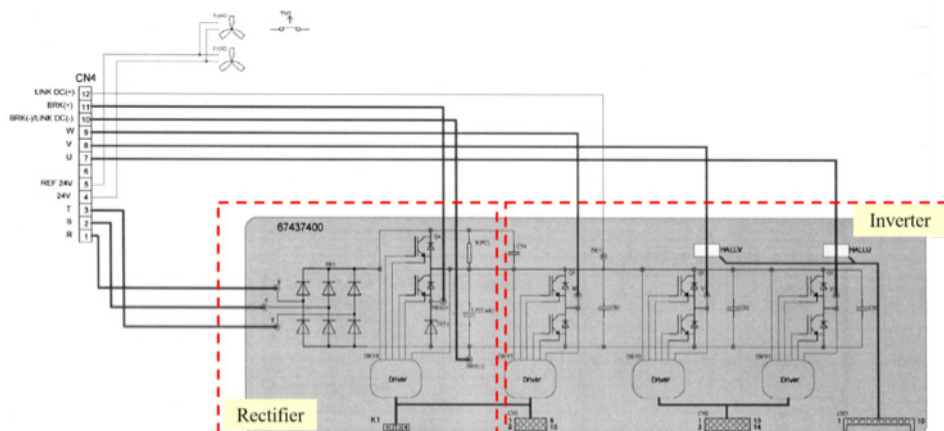


FIGURE 12. Semikron SKS 13F VSI circuit

programmable AC supply, which can deliver a clean and balanced AC supply to the system. With a power rating of 12KVA, it can supply a single phase or three phase supply with maximum output voltage up to 300V AC and output frequency from 15Hz to 1500Hz. In this work, the supply was tuned at 100V with a frequency of 50Hz.

15V power supply and can measure current between 0 and 36A. In this work, turns ratio of 1:1000 is selected. A variable resistor is placed in series to 0V connection for transducer's calibration, which is executed prior to taking the actual current measurement. Figure 14 shows the schematic of the current sensor circuit developed for this prototype.

FEEDBACK FOR CLOSED LOOP PMSM DRIVE PROTOTYPE

For closed-loop operation of PMSM drive, several feedback signals are required to be fed to the main controller. These include motor phase currents as feedback to current controllers, rotor absolute position data for initial motor start-up and incremental position data for speed calculation and coordinate transformations.

MOTOR PHASE CURRENT

PMSM phase currents are measured using a developed current sensor circuit, as shown in Figure 13 and fed to the dSpace DS1104 controller through ADC input of dSpace CP1104 connector panels. The current measurement is executed using current transducer LEM LA25-NP, which has excellent accuracy ($\pm 0.5\%$) and very good linearity of measurement ($< 0.2\%$ linearity error), as well as highly suited for application in variable speed drives. The transducer requires



FIGURE 13. Current sensors

Three-phase current readings are fed to the controller through analogue input channels ADCH2, ADCH3 and ADCH4. These channels have 16-bit resolution for 10V input, whereas the current transducers have 0.1 mV/mA resolution. Hence, the overall current feedback resolution achieved in this prototype is around 3 mA. MATLAB/Simulink DS1104 ADC_Cx blocks are used to capture the measurement values in the controller.

Drives control application in this prototype requires accurate timing for the control of analogue inputs and incremental encoder position readouts. Hence, these actions are synchronized with the PWM signal i.e. using the interrupt provided by the ST1PWM signal line of the DS1104. PWM generation performed in this work, enable

interrupt generation by the slave DSP at the beginning or in the middle of each PWM period. The I/O components are triggered synchronously with the PWM interrupt. For this purpose, the parameter DS1104SLAVE_PWMINT block is set so that A/D conversion is triggered in the middle of the PWM period (0.5).

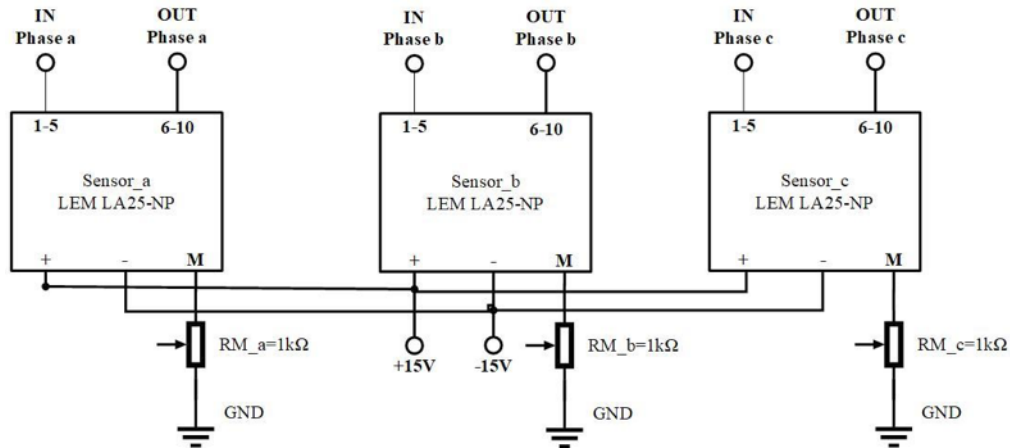
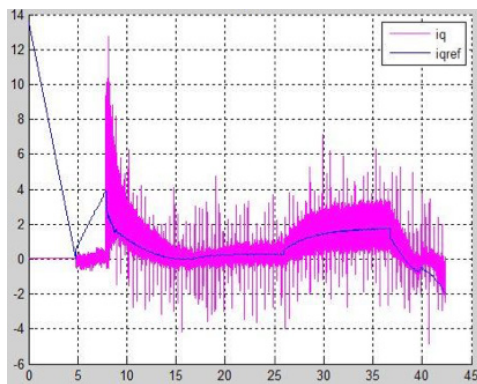
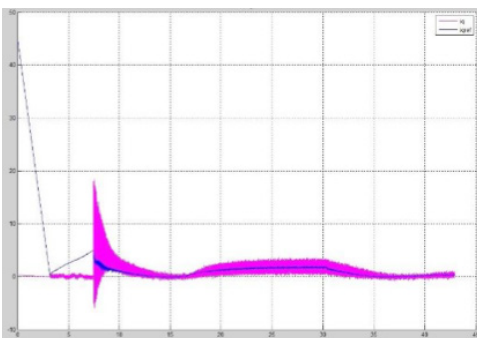


FIGURE 14. Schematic of current sensor circuit

An example of current measurement before and after implementation of soft-synchronisation with PWM signals are shown in Figure 15(a) and (b) respectively.



(a)



(b)

FIGURE 15. Current measurement (a) before synchronisation (b) after synchronisation

RS232 ROTOR ABSOLUTE POSITION

Apart from current feedback, the designed PMSM speed controller also requires rotor absolute position information for motor start-up. This is due to the dependency of PMSM operation on the rotor position or angle. Built-in absolute multiturn SinCos Hiperface SICK SKM36-HFA0-K02 encoder in the motor can provide an absolute position with a resolution of 4,096 increments per revolution and 4,096 revolutions with the multiturn system. The data is obtained through RS485 serial communication using Data+ and Data-digital signals supplied through pin 6 and 7 of the encoder cable respectively. Hiperface encoder uses half-duplex two-line connection for the serial communication. Serial communication data of the encoder follows asynchronous half-duplex UART protocol with binary data format. Parameter settings for communication is fixed according to encoder specification prior to command sending to ensure successful communication and correct data is received. UART parameter settings for Hiperface encoder in use is listed in Table 5.

TABLE 5. UART parameter settings for SKM36-HFA0-K02 encoder

Parameter	Setting
Data rate	9600 Baud
Data bits	8, LSB first
Start bit	1
Stop bit	1
Parity	Even

On the controller side, parameters are set in dSpace DS1104SER_SETUP block. This block is compulsory to be put in Simulink model if any other serial blocks are in use. Each data transmission consists of a master request frame followed by a slave response frame. In this work, dSpace DS1104 is the master and the encoder is the slave. The master transmission must be terminated through a timeout condition after the last byte is transmitted. Then, the slave transmission will initiate within a specified response time. Data transmission uses bus topology and addressing scheme. Each frame in the data bus contains an address byte, command bytes and optionally data bytes of varying length and a trailing checksum to detect transmission errors. The default address for encoder used in this work is 40h. Checksum byte is defined through an XOR operation on all frame bytes including the address.

The absolute position value is obtained by using command identifier 42h. Command identifier is used to construct command bytes to be sent to the encoder, together with other corresponding bytes according to data frame format. Figure 16(a) and (b) show the data bus that are sent and received by the master (controller) respectively in one cycle of “Read position” command. The position data consists of 32-bit value with most significant bits sent first from 0x0 to 0xFFFFF80 that represents from 0 to 360 degrees or rad. Checksum for the data from encoder to controller changes according to the current position data.

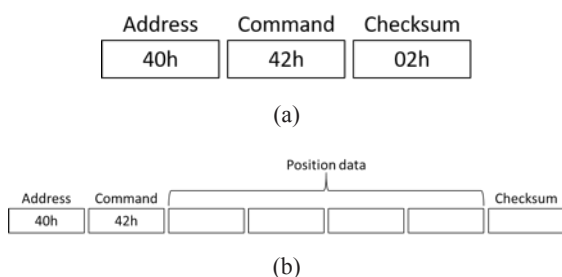


FIGURE 16. Data bus structure for serial communication (a) from master to slave to enquire to read position data (b) from slave to master with current absolute position data (Stegmann 2016)

To ensure successful absolute position reading communication, a few other supporting commands are also used. Command 50h is used to read the encoder status. This command returns active warning and error codes of the encoder, if any. Else, the encoder will return status code 00h. After all active warnings and errors have been solved, encoder software reset can be executed. To do so, command 53h is used. This command initializes the encoder with power-on initialization process. Unlike other commands, the slave does not send any data to the master as a response in this case.

Serial communication is initiated by the controller using one of DS1104 timer interrupts. The timer is set at 0.08 seconds period or 12.5 Hz frequency, considering the response time required for each cycle and time-out time. This interrupt triggers data sending from the controller to

the slave (encoder), which is executed inside a Function-Call subsystem. A multi-port switch block is used to enable four options of commands to be chosen and sent to the encoder, depending on the user-defined “Command” value. Command sending is executed using DS1104SER_TX block.

On the other hand, the DS1104SER_TX block is used for data reception from the slave. Similar to the command sending procedure, the length of data expected from the slave is also individually configured, according to selected command.

In this prototype, due to the limitation of RS485 serial communication of dSpace DS1104 controller in terms of speed, RS232 interface has to be used instead. Hence, a Toshiba RS232-RS485 converter CNV-02-B is connected between dSpace CP1104 RS232 port and the encoder to ensure correct and fast absolute position data acquisition, as detailed in Figure 17.

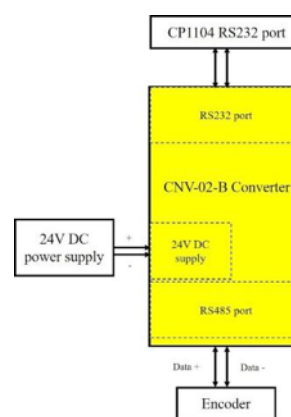


FIGURE 17. Connection of CNV-02-B RS232-RS485 converter

The converter must be configured according to hardware communication specifications. For correct half-duplex data transfer between encoder and CP1104, converter configuration in Table 6 is chosen.

TABLE 6. Configuration of CNV-02-B RS232-RS485 converter

Parameter	Switch position	Description
RS485 type	ON	2-wire half-duplex network
RS485/RS422 selection	ON	To/from RS485 conversion
Direction control	OFF	Auto-direction control with termination
Termination	ON	

Although the speed limitation of serial communication has been solved with the converter, rotor absolute position data acquisition in this prototype still suffers from the limitation of sampling time by DS1104 controller. Hence, position data accuracy is only guaranteed for very low

speed operation of the motor e.g. up to 100 rpm. However, this issue is not crucial since absolute position data is only used during motor start-up in this work i.e. when the rotor is in a standstill. When the rotor already rotates, absolute position data is not required by the controller anymore, since the position data is provided by a high-resolution incremental position data. Figure 18 shows rotor absolute position data from 0 to 6.28 rad, extracted from received serial communication data using “Read Absolute Position” command repeatedly.

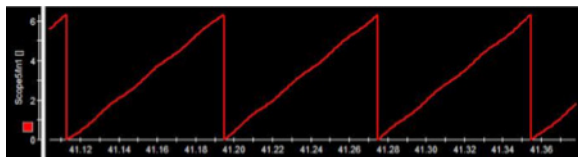


FIGURE 18. Rotor absolute position curve from serial communication

INCREMENTAL POSITION DATA

Incremental position data is obtained from Hiperface SICK SKM36-HFA0-K02 encoder via its analogue differential sin and cos signals, as shown in Figure 19. Reference sin/cos voltage level (REFSIN, REFCOS) is constant at DC

2.5V, resulting in differential sin/cos (SIN, COS) voltages of between 2.0V and 3.0V or peak-peak voltage of 1.0V. These analogue differential signals are fed to a signal conditioning circuit in order to generate square pulses (A and B) or quadrature signals for quadrature counting inside DS1104 controller. Figure 20 shows the schematic of signal conditioning circuit. Each analogue signal is amplified and fed to a comparator to obtain a quadrature signal. The amplifier used in this work is AD8044AR quad amplifier from Analog Devices Inc., whereas the comparator is the LM339N quad comparator by Texas Instruments.

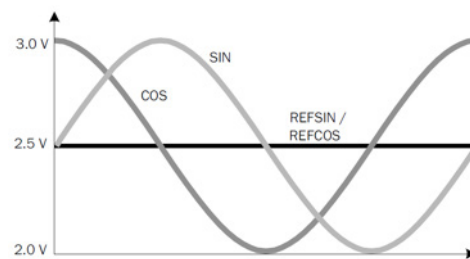


FIGURE 19. Analogue differential sin/cos signals of Hiperface SICK SKM36-HFA0-K02 encoder (clockwise rotation) (Stegmann 2016)

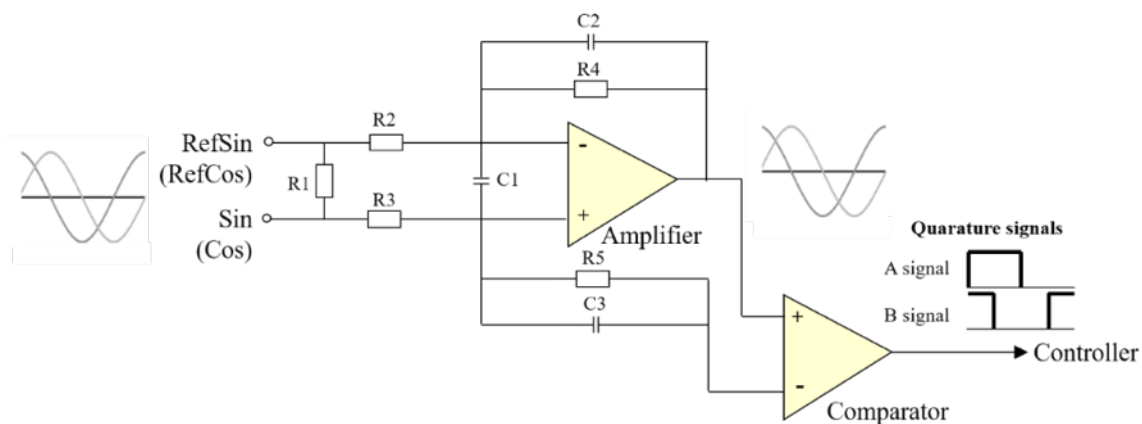


FIGURE 20. Encoder signal conditioning circuit schematics (Stegmann 2016)

Figure 21 shows an example of an analogue sin signal and its corresponding square pulses after being fed through the signal conditioning circuit when the motor is moving at 75 rpm. From each SKM36-HFA0-K02 encoder, one set of quadrature signals can be obtained, which consists of two square pulses with 90 degrees phase shift between each other, as shown in Figure 22. These pulses are fed to dSpace DS1104 controller through an incremental encoder input connector (INC1).

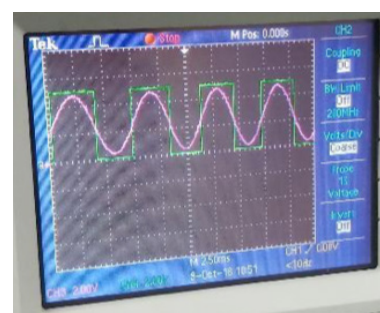


FIGURE 21. Analogue sin signal from encoder (purple) and its resulting square pulses (green)

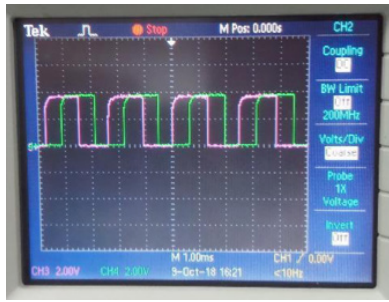


FIGURE 22. Resulting square pulses from sin signal (green) and cos signal (purple) when the motor is moving in forward direction

The combination of A and B signals in a quadrature counter logic allows determination of the incremental position with 4 steps per sin/cos signal period. This type of encoding is referred to as quadrature encoding because there are four output states: signal A rising, signal A falling, signal B rising, and signal B falling. By counting the generated pulse, the amount of rotation can be determined. For this purpose, one signal (A or B) is sufficient. However, the second pulse is required for determining the direction of rotation, by reading which signal is leading and which is following. In MATLAB/Simulink environment, firstly, DS1104ENC_SETUP block is used to set the global parameters for the 2 encoder channels. Quadrature counting is performed using pre-programmed DS1104ENC_POS_C1 block. The complete subsystem to extract incremental

position data from quadrature signals are shown in Figure 23. Table 7 shows counter operations performed is DS1104 controller based on A and B signals sampled currently (A_n, B_n) and the previous signals (A_{n-1}, B_{n-1}).

TABLE 7. Quadrature counter operation algorithm

				Counter operation
0	0	0	0	No action
0	0	0	1	+1
0	0	1	0	-1
0	0	1	1	Invalid
0	1	0	0	-1
0	1	0	1	No action
0	1	1	0	Invalid
0	1	1	1	+1
1	0	0	0	+1
1	0	0	1	Invalid
1	0	1	0	No action
1	0	1	1	-1
1	1	0	0	Invalid
1	1	0	1	-1
1	1	1	0	+1
1	1	1	1	No action

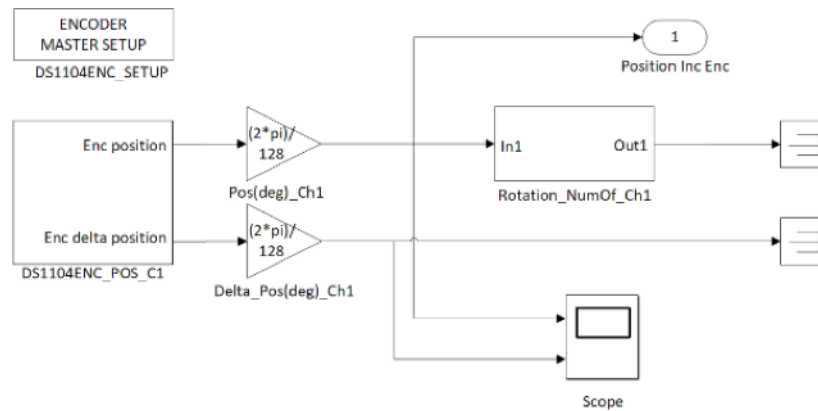
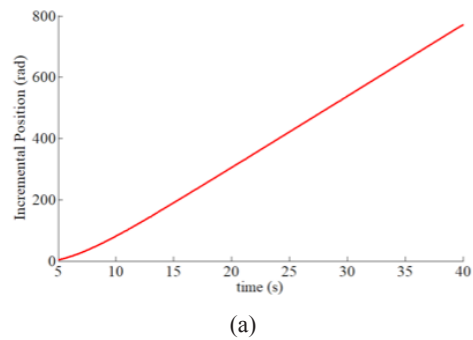


FIGURE 23. Extraction of incremental position data from quadrature signals

SKM36-HFA0-K02 encoder has a resolution of 128 sin/cos periods per revolution, i.e. up to 512 states per revolution, resulting in 0.7 degrees incremental position data maximum resolution. From the obtained incremental position data, the speed of rotation can be calculated using equation (1).

$$\omega_m = \frac{\theta_{m,n-1} - \theta_{m,n}}{T_s} \quad (1)$$

Figure 24 (a) and (b) show an example of incremental position data extracted and the corresponding calculated speed respectively.



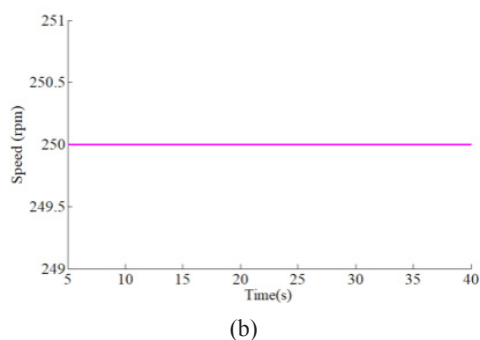


FIGURE 24. (a) Extracted incremental position and (b) its corresponding calculated speed curve

TESTING LOAD

In this prototype, hysteresis brake AHB-3 is used to produce the required load torque for evaluation of controller's performance in various load conditions. This model can provide load torque between 0.7 and 3.6 Nm for speed up to 2000rpm and power up to 1800W. Torque is produced strictly through a magnetic air gap between the rotor and the pole structure, resulting in smooth, infinitely controllable, speed independent and quiet torque loads. Complete torque control is obtained by adjusting DC current supplied to the field coil. The amount of braking torque transmitted by the brake is proportional to the amount of current flowing through the field coil, regardless of the direction of current flow (polarity). In addition, the brake's compressed-air cooling system offers excellent heat dissipation.

The hysteresis brake is controlled through Magtrol Dynamometer Controller DSP6001, which can be programmed using Magtrol M-TEST 5.0 Motor Testing software. Prior to any test, the connected motor test equipment must first be set up within M-TEST environment. The output load torque produced is controlled by a PID controller embedded inside the DSP6001 controller. Initially, the proportional, integral and derivative gains of this PID controller is tuned to suit its usage to the motor in use. Magtrol M-TEST 5.0 software is also a visualisation software, where among others, the motor torque and speed can be displayed. These data were provided by TMB 307/411 in-line torque and speed transducer via IEEE bus with acquisition speed of 120 torque and speed points per second. The transducer is equipped with an integrated conditioning electronic module providing 0 to ± 10 V DC torque output and an open collector speed output. By employing non-contact differential transformer torque measuring technology, this transducer has remarkable properties such as high reliability, high overload protection, excellent long-term stability and high noise immunity.

Other than that, power measurement data of the motor in the test is obtained using Magtrol 6350 Power Analyzer connected to the prototype. It provides voltage, current,

power etc. data through IEEE bus at up to 100 data per second for display in M-TEST environment and on its front panel display.

CONCLUSION

This paper describes the development of a closed-loop PMSM drive system prototype with current, speed and position feedback using dSpace DS1104 controller board for a 1.93kW three-phase interior-mounted permanent magnet synchronous motor. This closed-loop PMSM drive system prototype is developed to replicate the real implementation of PMSM in industries. Using this prototype, the performance of any newly proposed control methods in real applications can be verified. Appropriate signal acquisition procedures of the feedback signals, as described in this work, are crucial to ensure the accuracy of closed-loop performance of the developed drive system.

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