SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage: https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

dSPACE Implementation of Motor Drives using Asymmetric Converter

Ahmad Firdaus Ahmad Zaidi[1,*], Syahrul Ashikin Azmi[1,2], Leong Jenn Hwai[1], Kamarulzaman Kamarudin[1], Hasimah Ali[1], Mohd Shuhanaz Zanar Azalan[1], Anas Mohd Noor[3], Nurul Iman Ramzan[3]

[1] Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis, Arau, Perlis, Malaysia
[2] Center of Excellence for Renewable Energy (CERE), Universiti Malaysia Perlis, Arau, Perlis, Malaysia
[3] Faculty of Electronic Engineering & Technology, Universiti Malaysia Perlis, Arau, Perlis, Malaysia

ARTICLE INFO

Article history:
Received 3 July 2023
Received in revised form 15 October 2023
Accepted 25 October 2023
Available online 11 November 2023

Keywords:
dSPACE; motor drives; asymmetric bridge converter; PI-control

ABSTRACT

This paper deals with the dSPACE DS1104 based implementation of closed-loop motor drive system using asymmetric converter. The mathematical model of the drive has been simulated in the MATLAB/Simulink environment to analyze the performance of the drive system. The simulated results are then validated with the experimental investigation. For experimental work, the pulse width modulation (PWM) has been implemented in MATLAB environment with Simulink real-time interface. Meanwhile, the hardware implementation consisting of dSPACE digital signal processor, voltage source inverter and generator-coupled motor. Variable speed test was performed on the loaded motor in open loop and closed-loop design to obtain speed tracking response parameter as well as speed ripple. Overall performance of developed system is satisfactory where in low-speed operation, experimental results show good speed tracking performance with ripple within 20%.

1. Introduction

The purpose of motor control in variable speed drive is to obtain a cost-effective control of motor parameters such as speed, torque, and position. Widely used in industry to drive conveyors, centrifuges and pumps, variable speed drive provides superior efficiency and substantial cost reduction than the conventional constant speed drive combined with mechanical component (such as throttle valve or damper) [1]. Variable speed drive extends its use in more precise and complex applications such as Electric Vehicle (EV) and air drones, where more sophisticated control algorithms such as vector control and Model Predictive Control (MPC) are required [2]. With the advance of embedded computing technology through digital hardware platform such as Field Programmable Grid Array (FPGA) and Digital Signal Processor (DSP), incorporating the complex algorithm into motor drive design has been made possible. This, combined with seamless design integration through MATLAB/Simulink programming which is intuitive in nature, has greatly reduced the development and testing time for new advanced algorithm in motor drives [3]. In a typical design approach, the

* *Corresponding author.*
E-mail address: ahmadfirdaus@unimap.edu.my

https://doi.org/10.37934/araset.33.3.5161

entire system is modeled, and the controller is designed such that the closed-loop system meets specific design requirements. The performance criteria are observed in MATLAB/Simulink simulation before hardware implementation. A combination of controller emulation using a software platform, along with the actual hardware under control, does greatly hasten the design procedure and can predict the system performance more accurately. Previous motor-control drive works has been implemented using FPGA platform, and DSP, specifically dSPACE1104 [3-9]. The aim of this work is to develop a digital hardware-based closed-loop motor drive control system that has the flexibility to design and test advanced control algorithm on variety of motor types. This work consists of the development of closed-loop motor-drive control system using platform dSPACE1104. The converter in use is asymmetric converter which is popular with Switched Reluctance Motor (SRM) but can also be used with DC Motor in uni-directional operation. Incremental encoder was used to feedback speed parameter and Proportional-Integral (PI) controller is used to compensate speed error for the system to meet drive requirement.

2. Motor Control: Theoretical and Practical Consideration

2.1 Modelling of Separately-Excited DC Motor

Brushed DC motor was first commercialized in 1886 [10]. Even though motor design has evolved since, several type of DC motor namely: series motor, permanent magnet motor (PMDC) and separately excited DC motor remains prominent in the industry in electrical propulsion, cranes, paper machines and steel rolling mills applications [19].

Separately excited type is still used particularly in educational research labs as they provide stable, linear output over wide variation of load. In this topology, field and armature windings have separate power supply. The equivalent circuit of an independently excited DC motor is shown in Figure 1 [11].

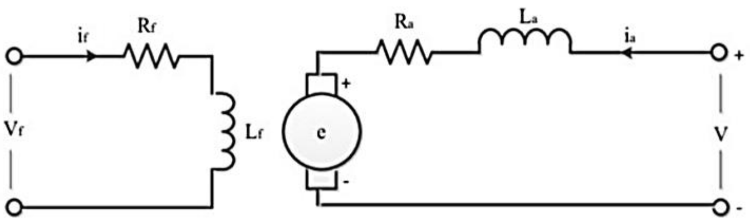

Fig. 1. Equivalent circuit of Separately-Excited DC motor [11]

On the armature side, circuit parameter is described as follows:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + K_e \omega_r \tag{1}$$

where, $V_a$is armature voltage, i_a is armature current, R_a is armature resistance, L_a is armature inductance, K_e is back-emf constant and ω_r rotor speed. Term $K_e \omega_r$ is back-emf component and is speed-dependent. When current flows in the armature winding surrounded within flux field, the rotor will generate torque to start rotation. Consequently, back EMF is produced in proportional to rotating speed. Net rotor current will generate net torque to keep motor rotation at determined speed.

On the field side, circuit parameter is described as follows:

$$V_f = R_f i_f + L_f \frac{di_f}{dt} \tag{2}$$

where, V_f is field supply voltage, R_f field resistance, L_f field inductance, and i_f field current. Field current produces flux through the field winding. The field current is unaffected by changes in the armature current, leading to stable and constant magnetic flux.

For direct-drive motor-load system, equation of motion is described by:

$$T_e = J_{eq} \frac{d\omega_r}{dt} + B_{eq}\omega_r + T_L \tag{3}$$

where, T_e is required electromagnetic torque, $J_{eq} = J_m + J_L$ and $B_{eq} = B_m + B_L$ respectively are equivalent moment of inertia and equivalent damping coefficient which accounts for both motor and load, $\frac{d\omega_r}{dt}$ is required acceleration and, T_L is load torque. When motor is coupled to the load, motor must generate torque equal to the load torque to enable uniform rotational speed.

Developed electromagnetic torque T_e , is proportional to armature current for a constant flux in air gap and considering fixed field in separate excitation:

$$T_e = K_t i_a \tag{4}$$

Therefore, controlling armature current will control torque.

2.2 Proportional-Integral (PI) Closed-Loop Control

Since the net armature current affect the torque generated by motor, control can be realized using PWM technique where average voltage and thus, average current to armature are controlled through inverter / converter circuit. This technique reduces power loss associated to voltage drop as it decreases average power delivered to a load through fast switching control [12]. A variable duty cycle PWM is compatible with digital control and PWM at high switching frequency works well for motor control as inertia load are resistant to discrete effects [13]. The converter circuit typically have fixed DC Bus Voltage as input, and the controlled output is achieved through switching of MOSFET/IGBT transistors of the converter according to PWM signal [20]. In closed-loop control such as in Figure 2, speed is measured through sensor/ encoder and fed-back to the computer for comparing with reference speed [13]. The error difference will be used to drive the control signal and modulated into PWM signal to drive the converter. In more advanced scheme, cascaded control has been employed where speed control implemented at outer loop and current control at inner loop [14]. While this method allows better control at above base speed operation, stability and complexity involving bandwidth matching pose a challenge.

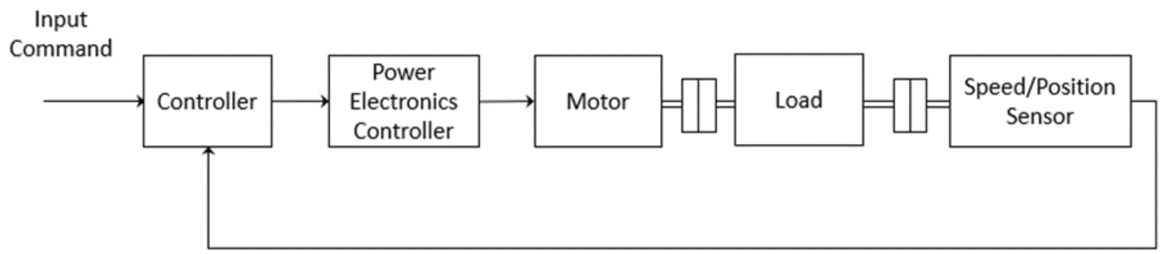

Fig. 2. Closed-loop variable speed control [13]

In Proportional-Integral (PI)-control scheme, the controller generates an output signal, $u(t)$, which is proportional to the input signal, $V_i\,(t)$, as well as the integral of the input signal, denoted by [15]:

$$u(t) = K_p V_i\,(t) + K_i \int V_i\,(t) \tag{5}$$

The reference speed and the actual speed are compared using the comparator, and the error signal obtained is then sent to the PI control. The correct response can be attained by tuning the integral gain K_i and proportional gain K_p. The duty cycle is then varied, changing the input value to the PI controller.

2.3 Asymmetric Bridge Converter

There are various topologies of converter circuit to drive DC motor with the most popular is the H-bridge circuit. H-bridge circuit allows operation on both forward and reverse rotation due to ability to supply bipolar current [16]. Alternatively, asymmetric converter can also be used to drive DC motor.

Figure 3 shows a topology of one phase asymmetric converter. The converter is widely used with Switched Reluctance Motor (SRM) that operates on three, four or five phases depending on the motor type. Apparently for this topology, identical topology is cascaded to the converter depending on the number of phases to be operated. Two switches are present in each phase so that each SRM phase can operate independently [17].

An asymmetric converter has three operating modes that supply a different voltage level across each phase of the machine. By controlling the state of the two switches in each phase leg, it is possible to generate three voltage levels: $+V_{DC}$, $-V_{DC}$, and zero voltage to the phase [18]. To drive the DC motor, only one phase of the circuit is operated by switching the two transistors in the phase. However, the output phase current is unipolar, thus allowing only one direction control for the DC motor.

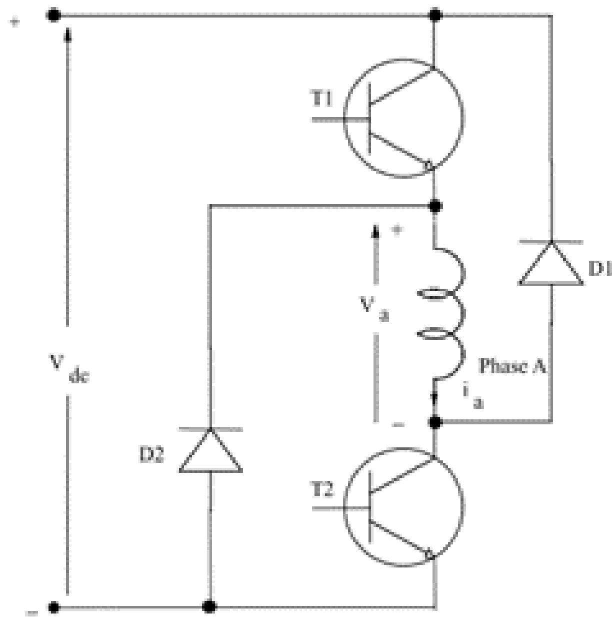

Fig. 3. Asymmetric converter (one phase) [17]

3. Proposed Separately Excited DC Motor Closed-Loop System in MATLAB/Simulink

3.1 Simulation Design

Based on topology in Figure 2, the motor control drive system is first designed and simulated using MATLAB / Simulink before verification using hardware platform. The simulated motor parameters were as in Table 1. Sampling time selected was at 1e-4 (frequency of 10kHz). Three-phase asymmetric converter was used to drive the motor with only one phase of the converter driven by PWM signals. Proportional-Integral (PI) gain are selected at 0.5 and 10 respectively and the load torque is at 20Nm.

Table 1
Simulation parameters

Item	Value
Winding	Separately-excited 150V
Rated Voltage	240V DC
Rated Power	5 hp
Rated Speed	1750 rpm

3.2 Experimental Design

Figure 4 shows block diagram of experimental asymmetric converter with closed-loop PI control and PWM as modulator. Figure 5 shows the experimental setup of the motor drive system. The proposed control is realized through dSPACE1104 controller board (based on architecture DSP TMS320F240) in the computer. Variable DC Power supply was used to provide 70V DC BUS converter voltage with 1000uF capacitor as stabilizer. The asymmetric converter is a three-phase type consists of MOSFET IRFP4310 transistors and diodes. The maximum voltage rating for the MOSFET is 100V and hence operable voltage is limited at 70V.

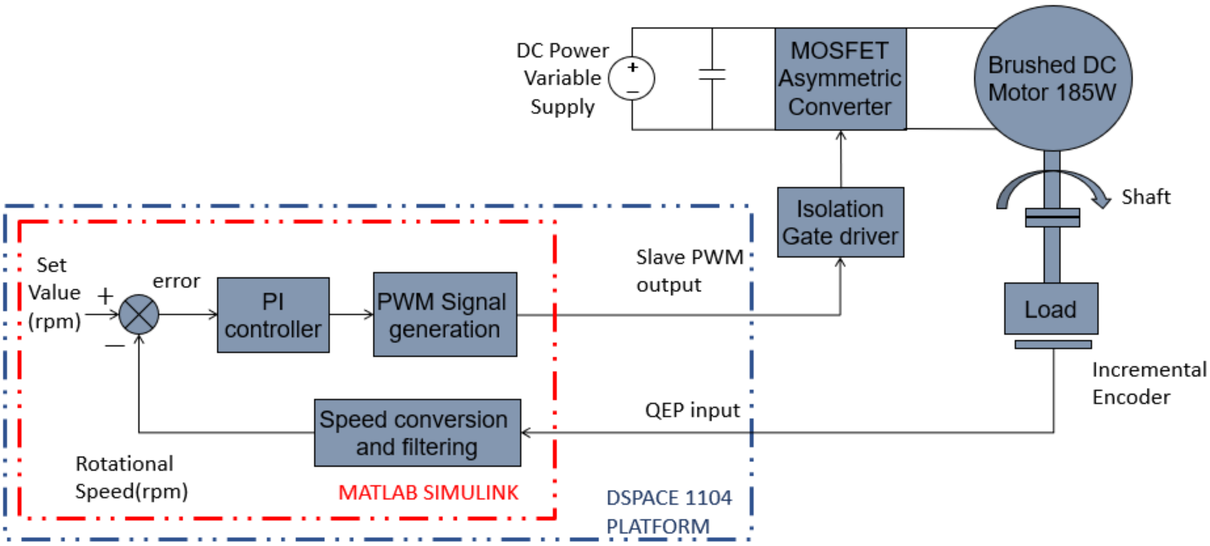

Fig. 4. Block diagram of experimental asymmetric converter with closed-loop PI control and PWM as modulator

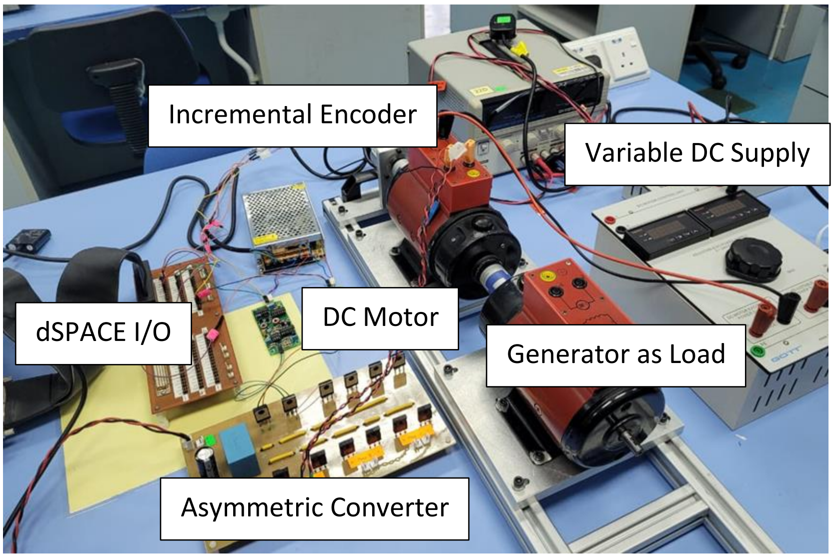

Fig. 5. Experimental setup of the PI-Control Separately-Excited DC motor using dSPACE hardware platform

The motor-load consisted of 185W separately excited Brushed DC Motor coupled to DC Generator connected to several bulbs (each rated 60W) to provide various load torque. Table 2 shows the experimental parameter. SICK incremental encoder with resolution 2000ppr to measure motor rotational speed and is fed back to the controller board. Only one phase of the asymmetric converter is used to drive the motor. Each MOSFET transistor is driven by PWM signal through a gate driver circuit, that provides adequate voltage and current to drive the MOSFET from low power PWM signal ex-dSPACE1104 output. Through split inductor design in the circuit, isolation between high power side asymmetric converter and low power side dSPACE1104 is possible to protect the latter from overcurrent and short-circuit that may occur on high side.

Table 2
Experimental parameters

Item	Value
Winding	Separately-excited 240V
Rated Voltage	240V DC
Rated Current	1.2 A
Rated Power	185 W
Rated Speed	1400 rpm
Load	2 bulbs (120W)

Programming dSPACE1104 is realized through MATLAB / SIMULINK RTI (real-time interfacing) blocks, as shown in Figure 6. Sampling and switching frequency utilized was 1kHz. Encoder signals were configured as single-ended to the QEP dSPACE input. From there, the signal was converted to RPM unit through calculation and filtered using 10Hz low pass filter to smoothen the speed signal. The signal then is fed-back to summation block where reference signal is compared. The error than is processed using PI-control with parameters similar to simulation, before control signal in the form of PWM duty cycle is generated and fed to PWM channel. Once design and parameter setting is finalized, the SIMULINK RTI program is run using BUILD command where it is converted to several files that will be read by CONTROLDESK software, a dSPACE accompanying software. The speed response signal is accessible in time waveform from plotter in CONTROLDESK software.

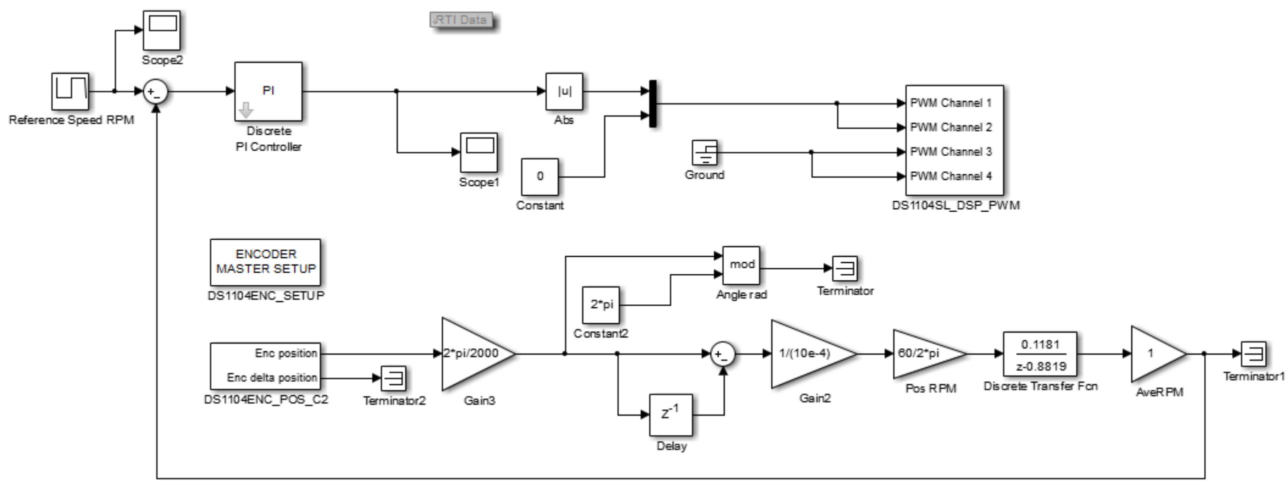

Fig. 6. SIMULINK RTI block program for the experimental setup

4. Results and Discussions

Figure 7 shows the simulated result of 3-level phase voltage ex-asymmetric converter. Figure 8 shows the simulated speed response (in rpm) for the PI-controlled motor (orange plot) versus the reference (blue plot). From simulation, the speed response tracks the reference well. The reference speed was for the motor to rotate between 300rpm and 100rpm alternately. The speed ripple was recorded below 10%.

Figure 9 shows the phase voltage waveform ex asymmetric inverter at output terminal. To emphasize the clarity of three-level voltage, the data was collected at open loop with duty cycle set at 50% and DC bus voltage at 50V.

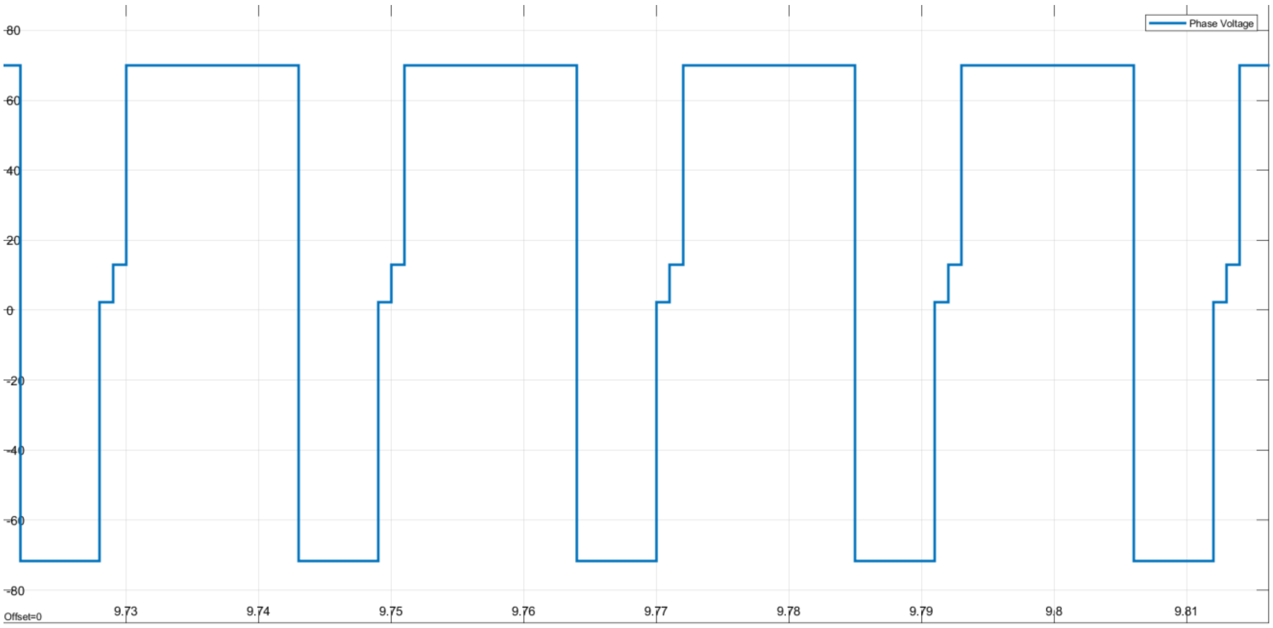

Fig. 7. Simulated three-level phase voltage

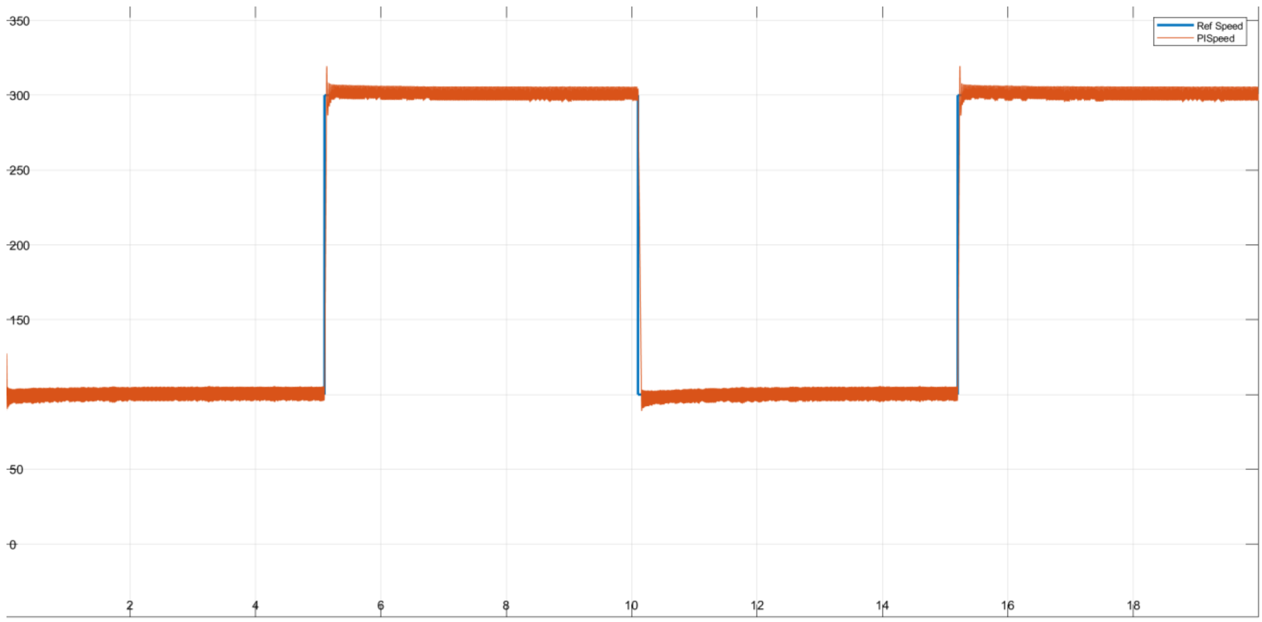

Fig. 8. Simulated speed response of PI-control

Figure 10 shows experimental open loop response for motor under test. In the open loop, duty cycle was varied between 0.6 to 0.8 alternately in space of 5 seconds. Figure 11 shows experimental motor speed response (red) versus reference (green) when the motor under test was subjected to variation of speed command 5 seconds low speed (100rpm) and 5 seconds higher speed (300rpm) with control implemented. Limitation on speed command for testing was imposed as the converter operable voltage was limited at 70V. Overall, the response was satisfactory and shows good tracking and stability. However, there is still ripple present within 20% in the speed response. At higher speed, the ripple may be reduced as rotor inertia will cancel the ripple effect. The experimental rig may also be improved with employing higher resolution encoder and better noise shielding technology for sensor cable to achieve better ripple performance.

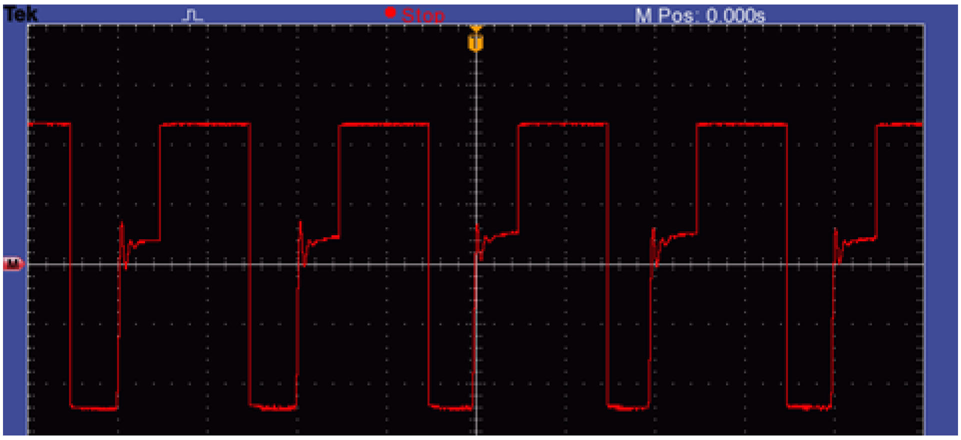

Fig. 9. Three-level Phase voltage at the motor input terminal (oscilloscope settings: 10V/div vertical and 1ms/div horizontal)

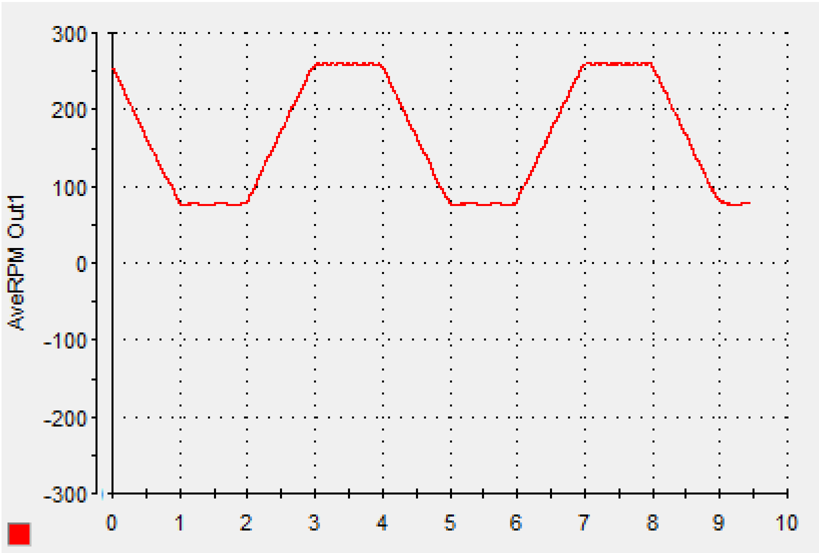

Fig. 10. Open loop response for speed control of DC Motor as displayed on dSPACE CONTROLDESK plotter

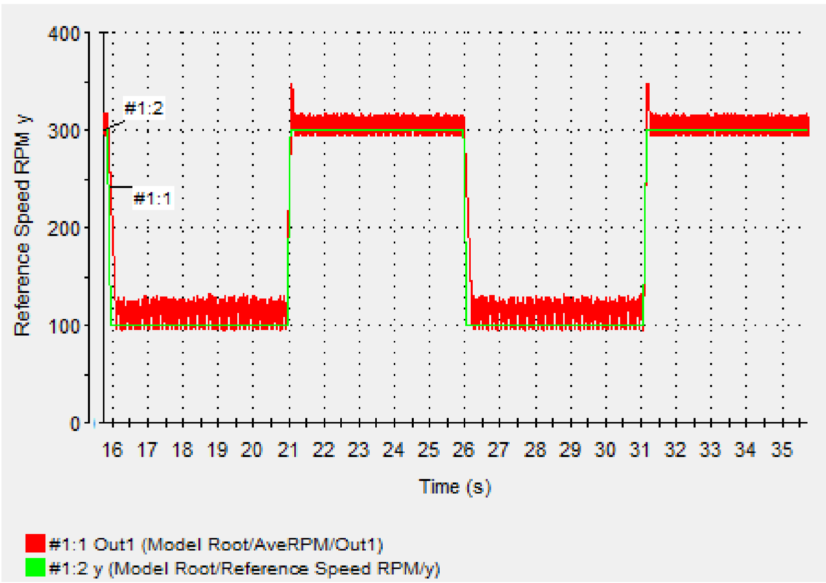

Fig. 11. Experimental speed response as displayed on dSPACE CONTROLDESK plotter

4. Conclusions

Flexible motor drive system has been successfully implemented in hardware using dSPACE1104 platform where closed-loop control using PI-controller has been achieved. Asymmetric converter was used where it enabled unipolar operation. Good tracking performance was observed in experimental speed response while the ripple was acceptable at 20% during low-speed operation. The limitation imposed on maximum bus DC voltage at asymmetric converter constraints the speed testing from operating at higher speed.

Acknowledgement
The authors would like to acknowledge and Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis for the funding and continuous support for this research.

References
[1] Saidur, Rahman, Saad Mekhilef, Mian Basharif Ali, Azadeh Safari, and Hussein A. Mohammed. "Applications of variable speed drive (VSD) in electrical motors energy savings." *Renewable and sustainable energy reviews* 16, no. 1 (2012): 543-550. https://doi.org/10.1016/j.rser.2011.08.020
[2] Firdaus, AZ Ahmad, S. A. Azmi, K. Kamarudin, L. J. Hwai, H. Ali, M. S. Z. Azalan, and Zamri Che Mat Kasa. "Assessment of control drive technologies for induction motor: Industrial application to electric vehicle." In *Journal of Physics: Conference Series*, vol. 1878, no. 1, p. 012047. IOP Publishing, 2021. https://doi.org/10.1088/1742-6596/1878/1/012047
[3] B. A. Cozma and E. Cigan, “FPGA-Based Systems Increase Motor-Control Performance,” no. March, pp. 1–8, 2015.
[4] Nekoei, Farzad, Yousef S. Kavian, and Ali Mahani. "Three-phase induction motor drive by FPGA." In *2011 19th Iranian Conference on Electrical Engineering*, pp. 1-6. IEEE, 2011.
[5] Shah, Vaibhav. "FPGA Implementation of Sensorless Field Oriented Current Control of Induction Machine." In *2017 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*, pp. 1-5. IEEE, 2017. https://doi.org/10.1109/ICCIC.2017.8524311
[6] Saravanan, P., R. Arumugam, and M. Senthil Kumaran. "FPGA Based Speed Control of SRM with Optimized Switching Angles by Self Tuning." *Circuits and Systems* 7, no. 08 (2016): 1530. https://doi.org/10.4236/cs.2016.78134
[7] Abbou, A., T. Nasser, H. Mahmoudi, M. Akherraz, and A. Essadki. "Induction Motor controls and Implementation using dSPACE." *WSEAS Transactions on Systems and Control* 7, no. 1 (2012): 26-35.
[8] Isa, Siti Noormiza Mat, Zulkifilie Ibrahim, Jurifa Mat Lazi, Md Hairul Nizam Talib, Nurazlin Mohd Yaakop, and Ahmad Shukri Abu Hasim. "dSPACE DSP based implementation of simplified fuzzy logic speed controller for vector controlled PMSM drives." In *2012 IEEE International Conference on Power and Energy (PECon)*, pp. 898-903. IEEE, 2012.
[9] Trabelsi, R., A. Khedher, MF Mimouni, F. Msahli, and A. Masmoudi. "Induction Motor Drive Under Nonlinear Backstepping Control Using DSpace DS1104 Control Board." (2010).
[10] Bitar, Zeina, Samih Al Jabi, and Imad Khamis. "Modeling and simulation of series DC motors in electric car." *Energy Procedia* 50 (2014): 460-470. https://doi.org/10.1016/j.egypro.2014.06.056
[11] Mohan, Ned. *Advanced electric drives: analysis, control, and modeling using MATLAB/Simulink*. John wiley & sons, 2014. https://doi.org/10.1002/9781118910962
[12] Rashid, Muhammad H. "Power Electronics Circuits, Devices and Applications Seventh Impression." (2009).
[13] Mohan, Ned, Tore M. Undeland, and William P. Robbins. *Power electronics: converters, applications, and design*. John wiley & sons, 2003.
[14] Aghaee, Marziyeh, and Ali Akbar Jalali. "BLDC motor speed control based on MPC sliding mode multi-loop control strategy–implementation on Matlab and Arduino software." In *Electrical Engineering (ICEE), Iranian Conference on*, pp. 795-800. IEEE, 2018. https://doi.org/10.1109/ICEE.2018.8472464
[15] Habbi, Hanan Mikhael D., Hussein Jalil Ajeel, and Inaam Ibrahim Ali. "Speed control of induction motor using PI and V/F scalar vector controllers." *International Journal of Computer Applications* 151, no. 7 (2016): 36-43. https://doi.org/10.5120/ijca2016911831
[16] Hart, Daniel W., and Daniel W. Hart. *Power electronics*. Vol. 166. New York: McGraw-Hill, 2011.
[17] Krishnan, Ramu. *Switched reluctance motor drives: modeling, simulation, analysis, design, and applications*. CRC press, 2017. https://doi.org/10.1201/9781420041644

[18] Taylor, Joshua, Diego F. Valencia, Berker Bilgin, Mehdi Narimani, and Ali Emadi. "Comparison of current control strategies for low-and high-power switched reluctance motor drives." In *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, pp. 198-203. IEEE, 2020. https://doi.org/10.1109/ITEC48692.2020.9161762

[19] Nurhaida, A. S., AZ Ahmad Firdaus, Kamarulzaman Kamarudin, S. A. Azmi, M. J. M. Ridzuan, and S. M. Hafis. "Design and development of three-phase voltage source inverter for variable frequency drive." In *IOP conference series: Materials science and Engineering*, vol. 705, no. 1, p. 012016. IOP Publishing, 2019. https://doi.org/10.1088/1757-899X/705/1/012016

[20] Azmi, S. A., M. F. N. Tajuddin, M. F. Mohamed, and L. J. Hwai. "Multi-loop control strategies of three-phase two-level current source inverter for grid interfacing photovoltaic system." In *2017 IEEE Conference on Energy Conversion (CENCON)*, pp. 277-282. IEEE, 2017. https://doi.org/10.1109/CENCON.2017.8262498