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Control of A Switched Reluctance Motor Based on Asymmetric Converter and Digital Signal Controller for Forward and Reverse Mode

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ABSTRACT

The Switched Reluctance Motor (SRM) is one of the best choices for industrial and electric vehicle applications, selected for its optimal performance. This is due to the advantages of SRM, including the use of permanent magnet-free technology and a simple construction consisting of an iron core on the rotor and stator windings. A rotary encoder is utilized to detect the rotor position due to its high precision. However, synchronization with the rotor position is required during installation to achieve optimal SRM performance. The rotor position obtained from the rotary encoder is processed by the digital signal controller to determine the firing angle on the rotor. The research objective is to control the SRM to rotate in both directions. To support this study, laboratory tests were conducted for validation by changing the phase sequence in the asymmetric converter, causing differences in the three-phase current waveforms for forward and reverse rotations. The results of this research show that the SRM can rotate bidirectionally.

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1. INTRODUCTION

Switched Reluctance Motor is the best choice to support development of electric motor technology. Market demands are one of the things that influence the industrial sector, especially in the automotive industry sector, where in this modern era, combustion engines are rarely used because they produce combustion fumes [1].

Switched Reluctance Motor is one of the best option in EV industry and selected for optimal its continued growth in usage [2]. This motor consists of stator in the form of windings and rotor in the form of solid iron with salient poles. SRM has some advantages, such as high speed and lower cost than BLDC motor. In addition, SRM has low maintenance costs. Simple inner rotor structure of SRM makes it easier to operate at high speed without any mechanical issues and no need for additional mechanical protection systems. However, still required special circuit to operate this motor [3].Switched Reluctance Motor is new drive system. Compared to with other types of motor, SRM own lots of advatages like simple structure, reliable performance, more parameters can be controlled, adjusted good speed, large starting torque, and low current start, so SRM has becoming a new highly competitive variable-speed motor [4].

The operation of SRM requires rotor position information. A rotary encoder is used in the process of detecting the rotor position in SRM. This device has a high level of precision as well as adjustable ignition angles. Accurately determining the ignition angle can affect the performance of SRM [5]. This research aims to control the SRM so that it can rotate in two directions by explaining the design and implementation of an asymmetric converter with dsPIC30F4012 control. To validate this research, hardware testing was carried out directly in the laboratory.

2. RESEARCH METHOD

SRM is a type of electric motor with a simple construction in its rotor, consisting of an iron core, and a winding stator. In the rotor, there are no permanent magnets or windings, allowing this motor to rotate at high speeds[6]. SRM has high initial torque, resulting in higher efficiency compared to other types of electric motors. Its operating principle is based on the reluctance phenomenon.

2.1 Working Principle

In this research, an SRM electric motor is used because it has a minimalist construction with a rotor made of iron core and a stator in the form of windings. When a phase is supplied with current, the stator will create an electromagnetic field to attract the surrounding rotor[7]. The SRM construction used in this study has six stators and four rotors. Based on the operating principle of the SRM, we can determine an equivalent circuit for each phase, as shown in Fig 1.

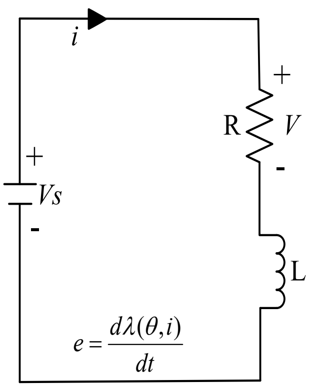

Figure 1. Equivalent circuit of SRM

The equivalent circuit of the SRM as seen in Fig 1 consists of elements such as resistance (R), inductance (L), and Electromotive Force (EMF). When the SRM motor rotates, the windings in the motor will generate back-EMF or counter-voltage with a polarity opposite to the voltage source.[8].

$$V = R.i + L\frac{di}{dt} + \omega.i\frac{dL}{d\theta} \quad (1)$$

In that equation, "V" represents voltage, "R" is resistance, "I" is phase current, "L" is inductance, "θ" is rotor position, and "ω" is rotor rotational speed.

2.2 Asymmetric Converter

In the operation of SRM, an asymmetric converter is used to provide excitation current to the SRM stator. The use of an asymmetric converter in SRM operation can involve magnetizing and demagnetizing operating modes. In the equivalent circuit of the asymmetric converter in magnetizing mode, there are components such as a DC source (Vdc), capacitor (Cs), switches (S), stator phase windings (L), and diodes (D). The magnetizing mode is the excitation process given to the phase windings by turning on switches (S1) and (S2) simultaneously. The Magnetizing operating mode can be shown in Fig 2.

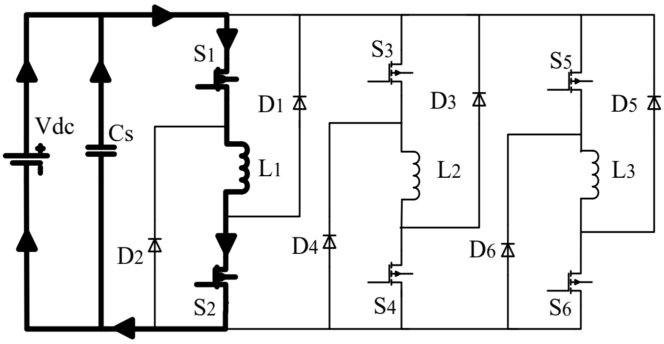

Figure 2. Current flow of phase-A under magnetizing mode in the asymmetric converter

The demagnetizing operating mode occurs after the magnetizing phase in the stator windings. In the equivalent circuit of the asymmetric converter in this demagnetizing mode, there are components such as a DC source (Vdc), capacitor (Cs), switches (S), stator phase windings (L), and diodes (D). This mode operates when both switches, namely switch one (S1) and switch two (S2), are turned off simultaneously. Energy flows towards the load (L1) and passes through diodes (D1 & D2) from the stator winding[9]. The demagnetizing operating mode can be shown in Fig 3.

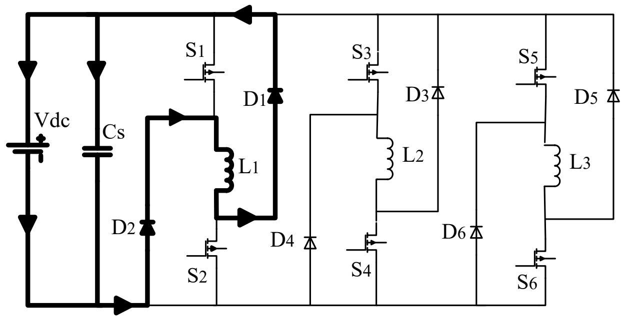

Figure 3. Current flow of phase-B under demagnetizing mode in the asymmetric converter

2.3 Rotary Encoder

To determine the phase angle of the SRM, a rotary encoder is used as the rotor position sensor. In one rotation, the rotary encoder generates 2500 pulses, and the equation for calculating the pulses on the rotary encoder can be found in Equation 2.

$$N_p = \frac{J_p \theta_{on}}{360} \quad (2)$$

In that equation, "N_p" is Value Pulse "J_p" is Amount Pulse, "θ_{on}" is Turn on Angle, "360" is Angle mechanic in rotation,

The rotary encoder produces 2500 pulses in one complete rotation, and the mechanical angle in one rotation is 360°. The data detected by the rotary encoder is used as input to be processed by the digital signal controller.

In this study, the rotary encoder used is an incremental encoder of the Single-Ended type. The purpose of using this rotary encoder is to detect position and motion[10]. Optical sensors are used to obtain a series of consecutive pulses. The digital code generated will serve as information to be processed and transmitted by the control circuit.

The electric motor currently used must be capable of operating with maximum efficiency, and precision is one of the key factors in enhancing SRM performance. The rotary encoder consists of a thin disk with holes along the edge of the disk's circumference. An LED is placed on one side of the disk to direct light onto the disk. On the opposite side, there is a phototransistor positioned to detect the light coming from the LED on the opposite side.[11]

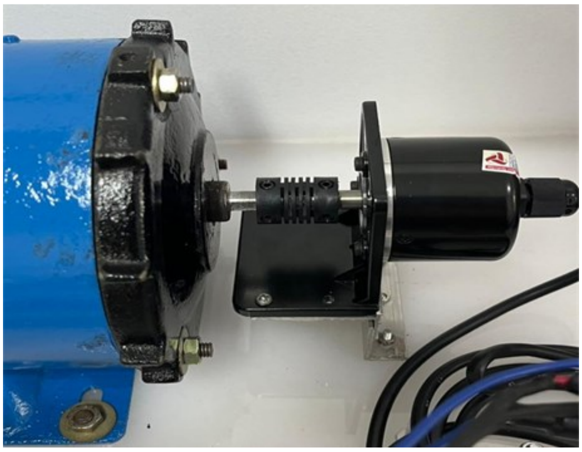

Figure 4. Rotary Encoder on SRM

2.4 Rotor Position Detection and Profile Inductance

The SRM used has a construction with six stators and four rotors, where each stator winding produces inductance characteristics related to the rotor position. Pulse injection method is employed to determine the inductance profile by applying High-Frequency Pulse Width Modulation (PWM) [12]. A frequency of 10 kHz and a voltage of 5 volts are provided to each motor phase as part of the pulse injection method to detect the rotor and stator positions. The inductance profile will yield values inversely proportional to the current pulse. The current pulse can be found in Equation 3.

$$i = \frac{U}{L}\Delta t \tag{3}$$

Where i represents the current pulse, U is the pulse voltage, L is the inductance, and Δt is the time used to deliver the pulse. The current pulse process is depicted in Fig 5.

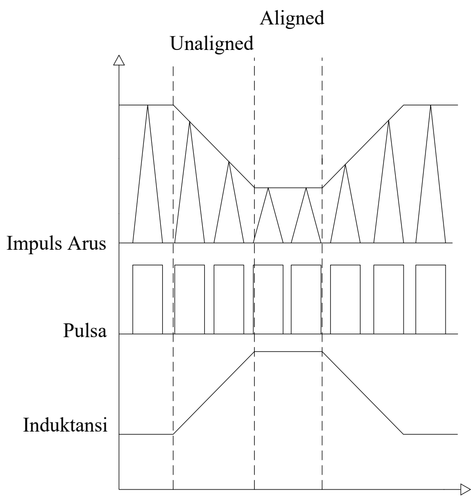

Figure 5. Inductance Profile

2.5 Turn on Determination of SRM

The determination of the phase ignition angle has an impact on the performance of the SRM. The phase current and the shape of the SRM voltage waveform change as the rotor position approaches the stator from minimum to maximum inductance. The phase turn on angle can be identified by observing the SRM inductance. When the stator and rotor positions are not aligned (unaligned), the SRM experiences minimum inductance[12].

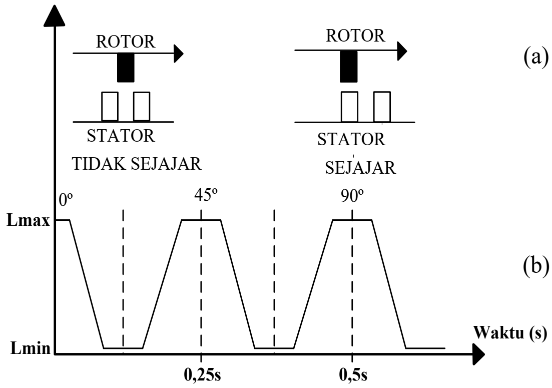

Figure 6. (a) Rotor position relative to the stator (b) Inductance profile of SRM

As the rotor approaches the stator, the SRM inductance begins to increase until the rotor and stator are aligned. The inductance decreases as the rotor starts to move away from the stator. Based on the number of rotors used in the SRM, there are 4 inductance profiles generated in one revolution. By dividing 360 mechanical degrees by the number of stators (four), each inductance profile will have 90 mechanical degrees[14]. During the magnetization process, the energy supplied by the DC source produces a magnetic flux, where $\theta on \leq \theta \leq \theta off$. In this research, the SRM uses four rotors, so the maximum inductance values are located within a 90-degree mechanical interval, and each phase ignition angle shifts by 30 degrees relative to the others.

2.6 Switches Configuration on and Reverse Mode

In the truth table below, you can observe the activation of the asymmetric converter switch for forward and reverse mode. This table provides information about the switch states, where if it has a value of 1, the switch will be in the ON position, whereas if it has a value of 0, the switch will be in the OFF position[15]. In other words, this table depicts how the conditions of the asymmetric converter switch are in forward and reverse mode.

Tabel 1. Switch condition of forward mode operating

	S1	S2	S3	S4	S5	S6
T1	1	1	0	0	0	0
T2	0	0	1	1	0	0
T3	0	0	0	0	1	1

From this table, it can be concluded that in the truth table above, the conditions of the asymmetric converter switch for forward and reverse mode are observed to be different. When the switch has a value of 1, it will be in the ON position, while if it has a value of 0, it will be in the OFF position. This indicates that these switches are not active simultaneously under certain conditions because, based on the input conditions provided by the microcontroller, only one switch will be active in a condition.

Tabel 2. Switch condition of reverse mode operating

	S1	S2	S3	S4	S5	S6
T1	1	1	0	0	0	0
T2	0	0	0	0	1	1
T3	0	0	1	1	0	0

2.7 Design of Digital Control System

System control that will applied for this control Switched Reluctance Motor utilise digital control. The programming process for dsPIC30f4012 was carried out with the help of microC for dsPIC software[16]. dsPIC30Ff4012 plays a role as inner core components digital signal controller. dsPIC30f4012 is selected as control asymmetric converter because it has fast response and higher speed. Data from rotary encoder containing position from the rotor on a Switched Reluctance Motor.

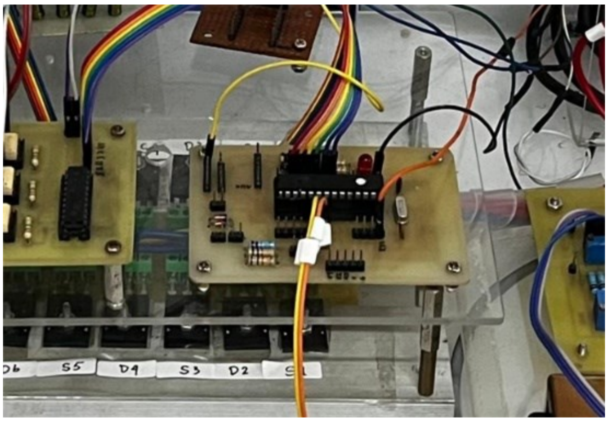

Figure 7. dsPIC30f4012 microcontroller

To determine the demagnetizing or magnetizing process of the Switched Reluctance Motor through microC software for dsPIC. Once the demagnetizing or magnetizing process has been determined, the digital signal controller will generate a switching pattern. This switching pattern is used to determine which switches should be ON or OFF in the converter circuit, as shown in the flowchart below.

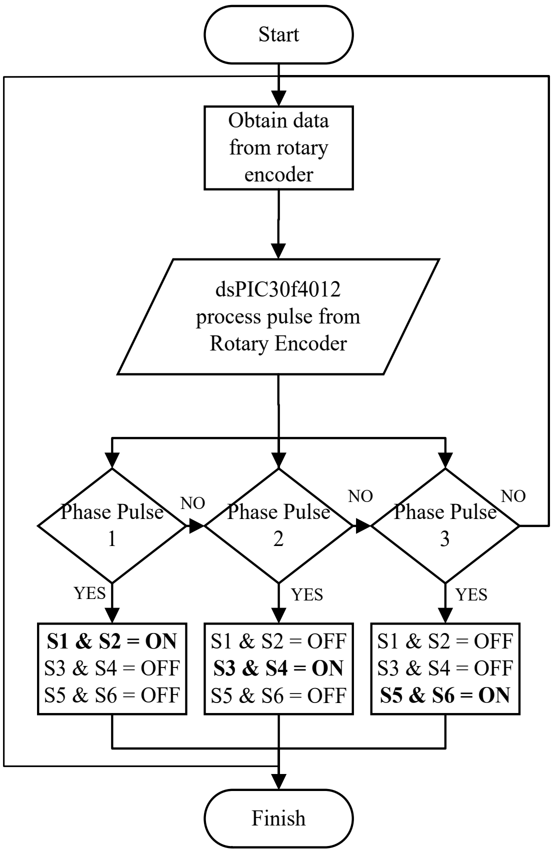

Figure 8. Flowchart of SRM control system

3. RESULTS AND DISCUSSIONS

In this chapter, we will discuss the results of our research in detail. Previously, laboratory testing was conducted using the method described above on a prototype consisting of a three-phase SRM drive, dsPIC30f4012 control system, rotary encoder, and asymmetric converter. The main objective of this research is the control of the SRM in both directions based on the asymmetric converter and digital signal controller. We have collected data and conducted in-depth analysis to evaluate the outcomes.

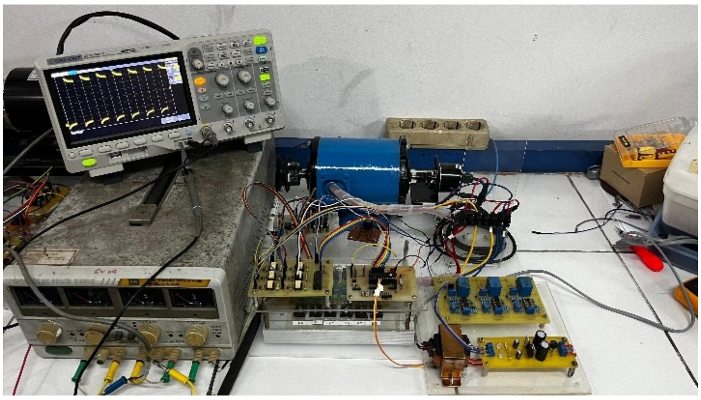

Figure 9. Prototype of SRM drive

By synchronizing the rotor and stator positions using pulses from the rotary encoder in the laboratory testing, pulses with a frequency of 10 kHz and a voltage of 5 volts were generated. The output current pulses appearing in the stator windings were used to determine the inductance profile and rotor position. To identify the rotor's position in each rotation, the Z-pin on the rotary encoder was utilized. An illustration of the current pulses and Z-pin pulses can be seen in Fig 10.

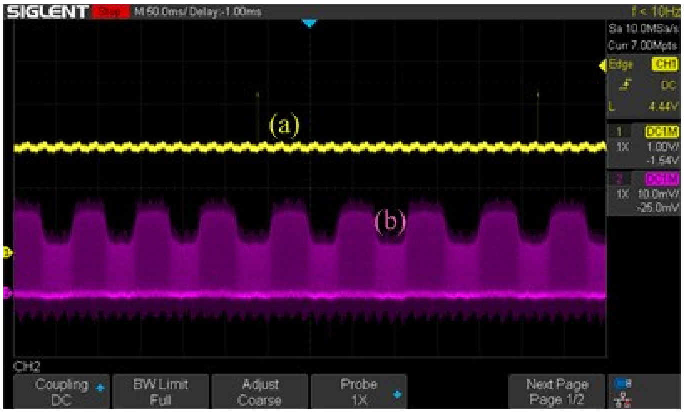

Figure 10. Experimental result of (a) Pulse Z of rotary encoder, (b) Injencted Current on Phase A

Below are the prototype testing parameters that have been implemented to observe the results of the laboratory testing. It can be explained that the prototype uses an SRM, Rotary Encoder E50S8-2500-3-V-5 as a rotor position sensor, asymmetric converter consisting of MOSFET IRFP250N, dsPIC30F4012 as a microcontroller. These parameters are shown in Table 3.

Tabel 3. SRM Drive Parameters

Parameters	**Value**	**Unit**
Rotary Encoder E5028-2500-3-V-5		
Output Pins	3	-
Pin A	2500	PPR
Pin Z	1	Impulse
Input Voltage	5	Volt
dsPIC30F4012		
Memory	16	Mbit
Clock	50	MHz
Voltage	5	Volt
3-Phase Asymmetric Converter		
IRFP250N	10	-
DC Link	12	Volt

The first test was conducted in the forward mode direction, resulting in current and voltage waveforms as seen in Fig 11 and Fig 12. This test was obtained by adjusting the phase angle activation pattern in the asymmetric converter. The speed achieved in the laboratory test during forward rotation was 1532 RPM, as shown in Fig13.

Figure 11. Experimental result of forward mode (a) Current waveform on Phase A, (b) Current waveform on Phase B, (c) Current waveform on Phase C

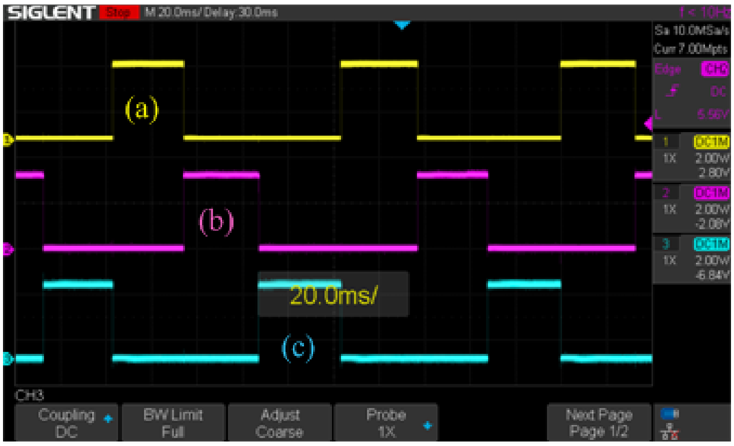

Figure 12. Experimental result of output signal from DSC forward mode (a) Voltage waveform on Phase A, (b) Voltage waveform on Phase B, (c) Voltage waveform on Phase C

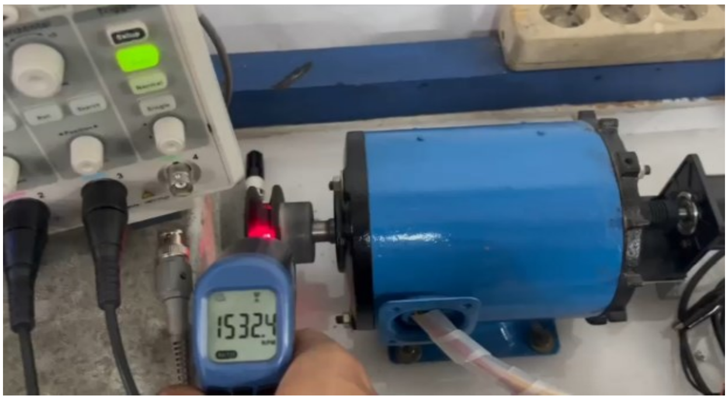

Figure 13. Experimental result of forward mode SRM speed measurement

In the second test, reverse mode direction was achieved by adjusting the phase angle in the asymmetric converter by changing the phase sequence to Phase A, Phase C, and Phase B. Fig 14 and 15 depict the current and voltage oscilloscope waveforms as the results of the second test in the reverse direction.

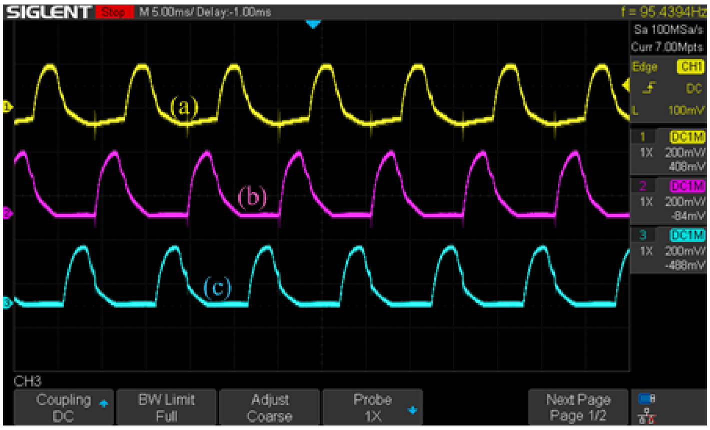

Figure 14. Experimental result of reverse mode (a) Current waveform on Phase A, (b) Current waveform on Phase B, (c) Current waveform on Phase C

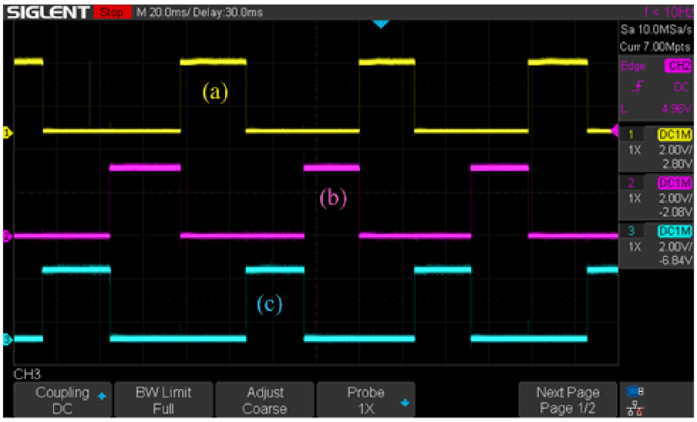

Figure 15. Experimental result of output signal from DSC reverse mode (a) Voltage waveform on Phase A, (b) Voltage waveform on Phase B, (c) Voltage waveform on Phase C

Figure 16. Experimental result of reverse mode SRM speed measurement

The laboratory test results indicate that during reverse mode, the achieved speed is 1603 RPM, as shown in Fig 16.

4. CONCLUSION

From the laboratory testing results with bidirectional SRM control based on asymmetric converter and digital signal controller, Pulse Z from the rotary encoder is used to determine the switching pattern by the DSC and is forwarded to the asymmetric converter. The difference in phase current angles generated by SRM was observed using an oscilloscope, allowing for precise determination of phase turn on angle. This enables the SRM to rotate in both directions, resulting in maximum performance. This is supported by the analysis and testing results conducted in this research. This study provides advancements in electric propulsion, particularly for SRM, in the context of electric transportation and industrial applications.

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REFERENCES

[1] Y. Nakazawa, K. Ohyama, H. Fujii, H. Uehara, and Y. Hyakutake, "Improvement of Efficiency of Switched Reluctance Motor by Single Pulse Control Based on Linear Torque Equation."

[2] Siddhant College of Engineering and Institute of Electrical and Electronics Engineers, *2017 2nd International Conference for Convergence in Technology (I2CT).*

[3] C. Huang, G. Yang, H. Chen, and X. Liu, "Inhibitory effect of radial force to switched reluctance motor with stator pole slot," in *Proceedings - 14th International Conference on Computational Intelligence and Security, CIS 2018*, Institute of Electrical and Electronics Engineers Inc., Dec. 2018, pp. 500–503. doi: 10.1109/CIS2018.2018.00119.

[4] IEEE Industry Applications Society and Institute of Electrical and Electronics Engineers, *2017 20th International Conference on Electrical Machines and Systems (ICEMS) : 11-14 Aug. 2017.*

[5] Institute of Electrical and Electronics Engineers, *SPEEDAM 2018 - proceedings : International Symposium on Power Electronics, Electrical Drives, Automation and Motion : Amalfi (Italy), 20th-22nd June, 2018.*

[6] M. Dong, "Research on reduction the torque ripple in switched reluctance motor," in *Proceedings - 2016 IEEE International Symposium on Computer, Consumer and Control, IS3C 2016*, Institute of Electrical and Electronics Engineers Inc., Aug. 2016, pp. 1071–1074. doi: 10.1109/IS3C.2016.270.

[7] Dānishgāh-i Shīrāz and Institute of Electrical and Electronics Engineers, *2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC) : Shiraz University, Iran, 12-14 Feb. 2019.*

[8] V. Wijaya and S. Riyadi, "Implementation of Input Capture Method on Switched Reluctance Motor to Obtain Precise Commutation Signals."

[9] S. Riyadi, "Regular paper A Control Strategy for SRM Drive to Produce Higher Torque and Reduce Switching Losses Electrical Electrical Electrical Electrical Systems Systems Systems Systems," 2018.

[10] C. Gong, S. Li, T. Habetler, J. Restrepo, and B. Soderholm, "Direct position control for ultrahigh-speed switched-reluctance machines based on low-cost nonintrusive reflective sensors," in *IEEE Transactions on Industry Applications*, Institute of Electrical and Electronics Engineers Inc., Jan. 2019, pp. 480–489. doi: 10.1109/TIA.2018.2868037.

[11] J. X. Wang and X. Cui, "Rotary Encoder Based Self-Positioning Method for Mobile Robot," in *Proceedings - 2018 5th International Conference on Information Science and Control Engineering, ICISCE 2018*, Institute of Electrical and Electronics Engineers Inc., Jan. 2019, pp. 500–504. doi: 10.1109/ICISCE.2018.00111.

[12] MC2D (Organization), Institute of Electrical and Electronics Engineers, IEEE Industry Applications Society, and IEEE Power & Energy Society, *2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER) : 10-12 April 2018.*

[13] S. Riyadi, "A simple method to control the excitation angle for switched reluctance motor," *Indonesian Journal of Electrical Engineering and Informatics*, vol. 9, no. 2, pp. 384–393, Jun. 2021, doi: 10.52549/ijeei.v9i2.2814.

[14] S. Y. Wang, C. M. Lin, J. H. Chou, and F. Y. Liu, "Design of the adaptive sliding self-organizing cerebellar model articulation controller for switched reluctance motors," in *Proceedings - 2018 International Symposium on Computer, Consumer and Control, IS3C 2018*, Institute of Electrical and Electronics Engineers Inc., Feb. 2019, pp. 145–148. doi: 10.1109/IS3C.2018.00044.

[15] N. Yan, X. Cao, and Z. Deng, "Direct torque control for switched reluctance motor to obtain high torque-ampere ratio," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5144–5152, Jul. 2019, doi: 10.1109/TIE.2018.2870355.

[16] A. Wibisono, U. I. Katolik Soegijapranata Jl Pawiyatan Luhur, B. Dhuwur Semarang, and S. Riyadi, "PROtek : Jurnal Ilmiah Teknik Elektro Kendali Kecepatan Switched Reluctance Motor Berbasis FPGA", doi: 10.33387/protk.v9i2.4317.