Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol.xx, No.x, Month 201x, pp. 1~8
ISSN: 2089-3272

Optimum Switching Angle Of Switched Reluctance Motor Using Response Surface Methodology

Agus Adhi Nugroho[1,2], Muhammad Khosyi'in[1,2], Bustanul Arifin[1,2], Bhakti Yudho Suprapto[1], Muhamad Haddin[2], Zainuddin Nawawi[1]

[1]Dept. of Electrical Engineering
Universitas Sriwijaya
Palembang, Indonesia
[2]Dept. of Electrical Engineering
Universitas Islam Sultan Agung
Semarang, Indonesia
e-mail: agusadhi@unissula.ac.id, chosyi@unissula.ac.id, bustanul@unissula.ac.id, bhakti@ft.unsri.ac.id, haddin@unissula.ac.id, nawawi_z@unsri.ac.id

Abstract

Switched Reluctance Motor has many advantages compared to another electric motor. Simple structure, low-cost production, robustness, high fault tolerance became the better achievement, but the difficult control of excitation angle at power converter becomes the crucial problem, especially for traction use that needs higher torque at low speed for starting and acceleration. This research emphasized finding the optimum switching angle at low speed using Response Surface Methodology to achieve the highest torque as indicated by the best speed at the constant torque region. The adaptive combination of optimum angles reached 2691 rpm better speed compared to a single combination angle that reached only 2568 rpm using Matlab simulation. And from experimental data shown that adaptive combination angle achieved 2475 rpm better speed compared to single excitation angle reached only 2340 rpm using this method.

Keyword: *switched reluctance motor, optimum angles, constant torque region, response surface methodology*

1. Introduction

Switched Reluctance Motor (SRM) has many advantages compared to another previous electric motor. Simple structure with no winding construction in the rotor side, low cost since no permanent magnet installed, robustness, high fault tolerance, the ability to operate in the harsh environment, and suitable for high-speed operation become the better achievement compare to another motor[1], [2], yet suitable for electric vehicle[3]–[5]. Strong structure, heat tolerance, fast response, high starting torque, high efficiency, and wide operating range become the other benefit of SRM[6], [7].

Besides the advantage of SRM, there is torque ripple, acoustic noise, and also demand unique of control requirement become the weak point of SRM[8]–[10]. One of the problems of SRM is the difficult control of the electronic power converter to feed the machines [11], and the excitation angle needs special attention [12].

According to the traction use like in an electric vehicle, the high torque at low speed becomes crucial since the need for starting and acceleration. Therefore this research will emphasize finding the turn-on and turn-off angle characteristic at low speed and how to find the best combination angle for high torque as indicated by the best speed acceleration especially for low speed using the Response Surface Methodology (RSM).

The torque generated in Switched Reluctance Motor depends on phase current, rotor, and stator position[4], [13]. The analytic (online) method used to improve and optimize the torque per ampere performance[10], [14], calculate the back electromotive force which taken into account[15], [16], minimize the torque ripple[17]–[19], and efficiency optimization, etc[9], [20].

Received May 9, 201x; Revised August 3, 201x; Accepted August 16, 201x

There are methods to overcome SRM weakness according to the difficulties in control the converter to feed the machines, the one is the analytic (online) method applied in the Matlab/Simulink by inserting the turn on and turn off angel formula directly to the block and the simulation started. This method inserts the back emf into account and simple in control, this leading cheaper in application and simple to do[16], but at low speed (below 5000 Rpm) it is not worked properly [21]. Resistor abandoned in this method and the shape of current profile distorted [22].

The self-tuning (offline) method separates the simulation and the calculation to optimize the turn-on and turn-off-angle. In [23] made the simulation running in the Matlab/Simulink first, then the result will be optimized by a certain method. This method has several advantages over the analytic method (online) since the back electromotive and stator resistor are taken into account, hence more precise results both in low speed and high speed [16]. The self-tuning keeps the torque ripple minimize and achieves better performance compared to another method [13]. The offline method achieves better efficiency and a lower torque ripple [24]. Longer simulation time and plenty of data to find the best combination angle become challenging tasks since spending much longer time and complex calculations using huge data.

Many optimation methods have been used to optimize the offline method, there are Artificial Neural Network[10], [25], Particle Swarm Optimization [11], [18], [26], 2D & Hooke Jeeve Pattern [7]. This research use Response Surface Methodology (RSM) to find the best combination of turn on and turn off-angle. The same method RSM already use for finding an optimal design to find stable torque in Switched Reluctance Motor [19], also structural optimization to decrease torque ripple to suppress vibration and noise [27]. This method also uses for finding suitable performance on torque ripple, cogging torque, and also Total Harmonic Distorsion from back electromagnetic in Permanent Magnet Synchronous Motor (PMSM) [28], and also this RSM used to find empiric model, performance, and design variable [29]. Efficiency optimization approach, power factor, and optimum design process of single-phase SRM for vacuum cleaner using geometric and electrical parameters using RSM [20].

The Switched Reluctance Motor used in this research is 3 phase 6 stator pole and 4 rotor pole, 12 volts DC, and the maximum reference current of 1 Ampere. The voltage equation of Switched Reluctance Motor:

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

R, i, θ, λ, is resistance, current, rotor position, flux linkage.

Hence the energy equation of SRM :

$$P = Vi = R\,i^2 + \frac{d}{dt}\left(\frac{1}{2}\,L\,i^2\right) + \frac{1}{2}i^2\,\frac{dL}{d\theta} \quad (2)$$

Equation 2 state the $R\,i^2$ represent stator winding loss, the $\frac{d}{dt}\left(\frac{1}{2}L\,i^2\right)$ represent the rate of change of magnetic stored energy, and the $\frac{1}{2}i^2\,\frac{dL}{d\theta}\omega$ represents the mechanical output on the shaft. The most effective use of energy maintained when the current constant during the positive slope of $\frac{dL}{d\theta}$. The torque production in the SRM provides by the tendency of the rotor to attain the position of minimum reluctance at exited stator phase. The instantaneous torque expression at phase is [30]:

$$T(\theta, i) = \frac{1}{2}i^2\,\frac{dL(\theta)}{d\theta} \quad (3)$$

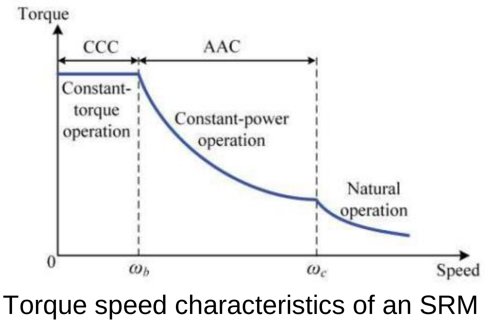

Figure 1. Torque speed characteristics of an SRM drive

There are three regions of the torque-speed characteristic of SRM as seen in Figure 1. Current Chopping Control (CCC) is where the Constant torque region is positioned as an area below the base speed (ω_b) where the back EMF is lower than DC source voltage. In this position the back emf is small, hence the current rises quickly to reach the reference value, the current reference set by a regulator such as a hysteresis current controller. This constant torque region which defined as the highest speed at which the maximum rated current can be applied at rated voltage and fixed excitation angle [30].

When the motor speed increased until the back emf equal to DC bus voltage, then the current starts to decrease, this can be overcome by advancing the turn-on angle to maintain the current rise to the desired level against the small back emf (at lower speed). Another action that coincides is with adjusting the turn-off angle also to maintain the dwell angle to prevent producing the braking torque [30].

If the speed continuing to increase and the back emf exceed the DC bus voltage (high-speed operation), then the current starts to decrease and again turn on an angle and turn off angle adjusted to maintain dwell angle with the single pulse mode of operation. The controller keep maintained the torque inversely proportional to the speed. The turn-on angle advanced until reaching maximum before the dwell angle reaches the upper limit in the maximum position (ω_c), this scheme is called an advance angle control (AAC) where the constant power operation has a wider operation to reach the higher speed called constant power region.

When the dwell angle occupies half of the rotor pole pitch (half electrical cycle) then it cannot increase furthermore because the flux would not return to zero and the current conduction would become continuous. The current and torque decrease since the back emf becomes prominent and the torque in this region is governed by natural characteristic falling similar to those of DC series motor(natural operation) which is back emf proportional to current, and the torque proportional to the square of the current [1].

Since the torque of Switched Reluctance Motor depends on the phase current and the exact position of stator and rotor, therefore the excitation angle, both turn on and turn off angle became the main parts in developed the mechanical output in the shaft (equation 3). The simulation using Matlab Simulink will prove that changing the turn-on and turn-off angle causing the speed achieved in the simulation to different each other with the same duration of time and the adaptive optimum combination angle will reach better speed compared to a single excitation angle. Then from this hypothesis this research trying to find the best excitation angle for low speed (constant torque region) using Response Surface Methodology (RSM) to find the best combination of turn on and turn off-angle.

2. Research Method

From the background state that this research is conduct to find the SRM turn-on and turn-off angle characteristic under low-speed range (in constant torque region), the best combination angle both turn-on and turn-off angle in the range of constant torque region (low speed) since this SRM will be applied for electric drives such as in an electric vehicle, in which high torque at low speed became the main characteristic for traction application. The self-tuning (offline) method is used to find the simulation data using Matlab/Simulink 2018b and the optimization of the turn on and turn off angle will use the Response Surface Methodology. The result of the best turn-on and turn-off angel performance will be compared with the SRM controlled with a fixed excitation angle such as in the hall effect controller to move the SRM.

The specification data of the Switched Reluctance Motor used in this simulation is 6/4 type SRM, 6 pole stator winding, and 4 rotor poles, and the basic data from switched reluctance motor direct measurement is the stator resistance 0.5 ohm, aligned inductance 23.6. e^{-3} H, unaligned Inductance 0,898. e^{-3}H, and the other data using the standard from Matlab Simulink.

2.1. Asymmetric Bridge Converter

The converter here uses the asymmetric bridge converter that has the ability can be controlled individually every phase so it is possible to overlap the converter. The 3 phase asymmetric bridge converter consists of 2 Mosfet, 2 diodes every phase and can be operated for magnetization and demagnetization [31].

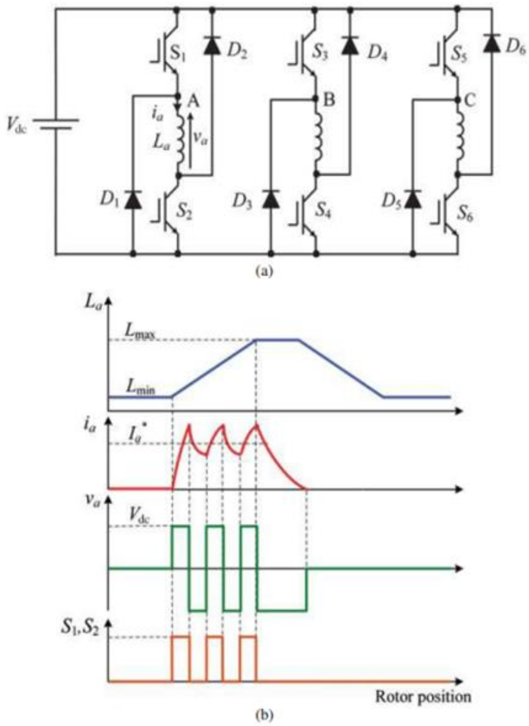

Figure 2. Three-phase Asymmetric bridge converter (a) topology and (b) operating waveform

This converter can be controlled either using voltage pulse width modulation or current pulse width modulation. From Figure 2 when the upper switch S_1 and lower switch S_2 of the first bridge are started to turn on (conduction state) then the current Ia started to increase until the current reaches the upper limit of hysteresis current controller and make both switches S_1 and S_2 are turned off causing the current decreased by the free-wheeling via the diode D_1 and D_2, leading to return the magnetic energy stored in inductor back to DC source. Then when the current drop below the lower limit of the hysteresis band the switch is then turned on again until the conduction period is finished[1].

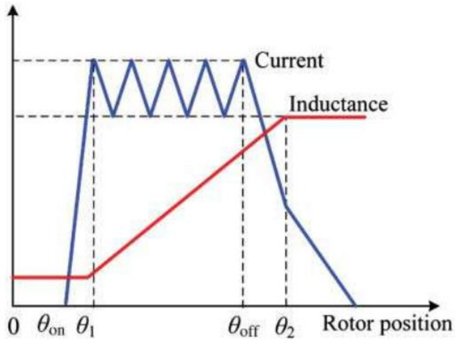

Figure 3. Current Chopping Control for Low-Speed Operation

Since the back emf small at low speed, the speed below base speed ω_b called current chopping control, when the converter switches turned on, the phase current rises and falls limited by the hysteresis current controller. The phase current is regulated at the rated value offering a constant torque operation. The turn-on and turn-off angles should coincide with the rotor positions θ_1 and θ_2 of the positive slope region of the phase inductance. It is necessary to turn in advance θ_{on} by θ_1 - θ_{on} and also the θ_{off} by θ_2 - θ_{off} as depicted in Figure 3, both advanced angle is dependent on the phase current and also the rotor speed.

2.2. Response Surface Methodology

Response surface methodology is a practical application in developing an approximation model for the true response surface. The approximation is based on observed data from the real process, system and is an empirical model. RSM build by statistical technique collection using multiple regression for developing, improving, and optimizing processes. Response surface methodology has important application in the design, development, and formulation of the new product and also improvement of the existing product design. Many factors considered according to RSM are the critical factors and region of interest where the factor influencing the product is known, the factors that vary continuously throughout the experimental range are tested, and a mathematical function relates to the factors to the measured response [32].

To find the optimum switching angle of SRM in every simulation step, here use RSM with two free variables (θ_{on} and θ_{off} angle) to find the highest speed. The central composite design is used with 2 order 2k factorial, so there are 12 simulations for central composite design (CCD). The simulation will be run for constant torque region (low speed) and the starting time from 0.5 seconds and step increased every 0.5 seconds. The simulation will stop after the highest current has been achieved according to the definition of constant torque [30]. Methodological test such as Analysis of variance (ANOVA) to find the best fit done if some of the tests such as model response must be significant, the lack of fit must be not significant, adjusted R2 and predicted R2 for a reasonable agreement must be less than 0,2 and the last is the adequate precision must be higher than 4 [32]. If the model proposed is not fulfilled those requirements, then the combination angle must be recombined, and the simulation and hence the test should be done again.

3. Results and Analysis

The SRM used in the simulation is a 6/4 (six stator pole and four-rotor pole), 12 volts with a three-phase asymmetric bridge converter. The direct measurement of stator resistance is 0.5 ohm, aligned inductance 23.6. e^{-3} H, unaligned Inductance 0.898. e^{-3}H, and the other data using the standard data from Matlab Simulink.

3.1. Constant Torque Region

The constant torque region is defined as the highest speed when the maximum rated current can be applied to the motor at the rated voltage. To determine constant torque region position is indicated by the current that tends to decreased started from around t=8.55 second as seen in Figure 4. This point (rounded to 9 seconds) becomes the boundary for the simulation time to find the optimum excitation angle within this constant torque region ω_b which is the lowest possible speed for the motor to operate at its rated power [33], as seen in Figure 1.

The low-speed simulation duration given from the constant torque region is done in a short period as long as 9 seconds and this is used to find the constant torque region (the position is below the base speed ω_b).

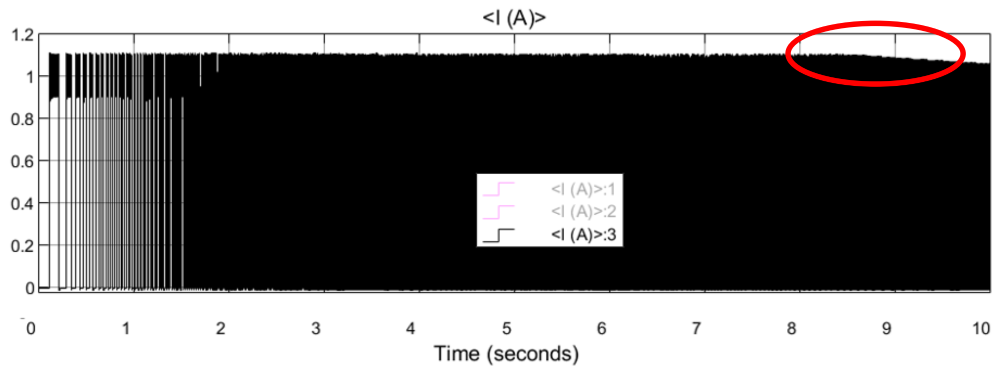

Figure 4. Current at Constant torque region using fixed angle excitation.

How to find the constant torque region as is defined as the highest speed when the maximum rated current can be applied to the motor at the rated voltage when applied with a fixed firing angle excitation (fixed turn on at 45 degrees and turn off-angle at 90 degrees).

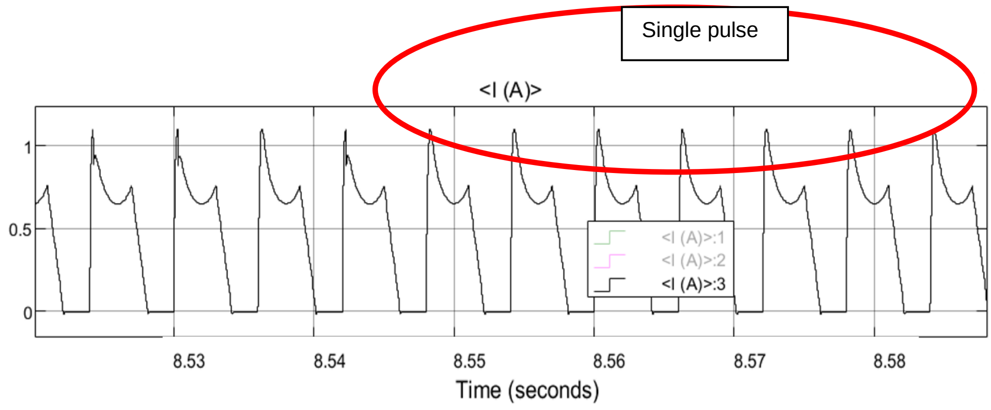

Figure 5. Current Shape in The Base Speed ω_b.

Depicted in Figure 5 is the detailed shape of the current in the base speed region ω_b, as seen in the current shape changed from current limited by hysteresis current limiter to single pulse current at around t = 8.55 second.

3.2. Optimum Switching Angle

The θ_{on} and θ_{off} angle of simulation starting from 45 degrees for θ_{on} and 90 degrees for θ_{off}, and this starting angle will be used for basic comparison angle. The simulation continued to find the best torque indicated by the higher speed that can be achieved for the same duration time of the simulation. The duration of the simulation starting from 0.5 seconds and increased to another 0.5 seconds every time. After the trial and error method to find the highest speed of this simulation then the Response Surface Methodology was applied to analyze whether the maximum speed of this simulation fulfills the RSM requirement.

Base on the main control scheme current chopping control (CCC), the previous simulation that reached the base speed ω_b, as indicated by the current shape no longer chopped therefore the duration time of this position will be used as a base speed ω_b and called as a constant torque region where the constant torque operation is capable. And from this constant torque region, the response surface methodology was applied to find the best combination angle beyond this constant torque region. The central composite design was used with 2 order and 2k factorial. The first simulation at 0.5-second simulation and combination of angle using the response surface methodology described in Table 1 are as follows :

Table 1. Simulation Angle with RSM.

Std	run	Turn on angle	Turn off angle	Speed (Rpm)
1	10	43	88	212.5
2	1	47	88	212.4
3	4	43	92	212.9
4	9	47	92	212.8
5	6	42.1716	90	211.8
6	2	47.8284	90	211.8
7	3	45	87.1716	212.8
8	5	45	92.8284	214
9	8	45	90	214
10	12	45	90	214
11	7	45	90	214
12	11	45	90	214

From Table 1 the simulation angle with response surface methodology, the analysis of variance (ANOVA) for quadratic model 2k factorial for the speed response is stated in Table 2. The Model F value represents the measurement of significance of the overall ANOVA model of which 91 points imply that the model is significant. There is only a 0.01% chance that an F value this large could occur due to noise, the higher the F value, the better the model. The value of P represents the probability value is less than 0.05, and this can be used to indicate that the model terms are significant.

Table 2. ANOVA for Quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	8.39	5	1.68	91.00	< 0.0001	significant
A-turn on	0.0050	1	0.0050	0.2713	0.6211	
B-turn off	0.7794	1	0.7794	42.29	0.0006	
AB	0.0000	1	0.0000	0.0000	1.0000	
A^2	7.57	1	7.57	410.66	< 0.0001	
B^2	0.5290	1	0.5290	28.70	0.0017	
Residual	0.1106	6	0.0184			
Lack of Fit	0.1106	3	0.0369			
Pure Error	0.0000	3	0.0000			
Cor Total	8.50	11				

In this case, the value of B, A^2, B^2 are significant model terms, and if these values are greater than 0.1000 then this indicates that the model terms are not significant. If their values are many insignificant model terms (not include those required to support hierarchy), so the model reduction may improve the model.

Table 3. Fit Statistics

Std. Dev.	0.1358	R^2	0.9870
Mean	213.08	Adjusted R^2	0.9761
C.V. %	0.0637	Predicted R^2	0.9074
		Adeq Precision	23.0249

From Table 3 can be seen that the value of Predicted R^2 0.9074 is in reasonable agreement with the value of Adjusted R^2 0.9761; so the difference between Predicted R^2 and Adjusted R^2 is less than 0.2. The Adeq Precision value measures the ratio of signal to noise, and the point 23.025 (which is greater than 4) indicates that the signal is adequate, which means that this model can be used to navigate the design space.

Table 4. Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	214.00	1	0.0679	213.83	214.17	
A-turn on	-0.0250	1	0.0480	-0.1425	0.0925	1.0000
B-turn off	0.3121	1	0.0480	0.1947	0.4296	1.0000
AB	0.0000	1	0.0679	-0.1661	0.1661	1.0000
A^2	-1.09	1	0.0537	-1.22	-0.9562	1.04
B^2	-0.2875	1	0.0537	-0.4188	-0.1562	1.04

Table 4 state the coefficient in terms of coded factors, the Coefficient Estimate represents the expected change in response per unit change in factor value when all remaining factors are kept constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the VIFs are 1 and if the value of VIFs greater than 1 indicates multi-collinearity, the higher the VIF value, the more severe the correlation of factors. And as a rough rule, the value of VIFs less than 10 points is tolerable.

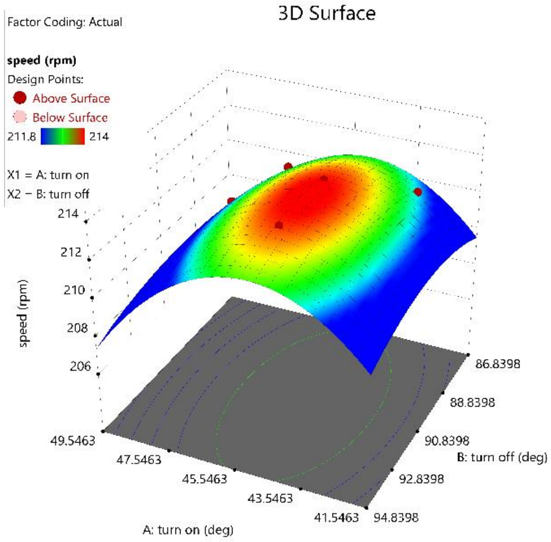

Figure 6. Response Surface Plot for Optimum Switching Angle

Figure 6 shows the response surface optimum angle for 0.5 second simulation time, and this picture shows that the optimum angle found in the combination of 45º for θ_{on} and 90º for θ_{off}, and the rotor speed reached 214 rpm. This speed is the optimum for 0.5 second simulation time.

The second simulation continuing and the duration of the simulation increased to 1.5 seconds, and then extended to 3 seconds, 4 seconds, 6 seconds, and the last 9 seconds to reach the constant torque region. The combination of angles and speed results is stated in Table 6.

Table 5. Combination Angle and The Rotor Speed

t on	t off	Dwell	Duration of simulation (second)					
(deg)	(deg)	angle	0.5	1.5	3	4	6	9
45.00	90.00	45.00	**214.00**	630.10	1,212.00	1,530.00	2,031.00	2,568.00
45.00	88.00	43.00	213.60	**631.40**	1,222.00	1,550.00	2,071.00	2,636.00
44.78	87.44	42.66	213.60	631.40	**1,223.00**	1,550.00	2,071.00	2,569.00
44.66	86.44	41.78	213.20	630.80	1,221.00	**1,555.00**	2,078.00	2,668.00
44.66	85.00	40.34	209.30	620.50	1,214.00	1,551.00	**2,092.00**	2,682.00
44.33	84.44	40.11	210.10	622.80	1,216.00	1,553.00	2,090.00	**2,686.00**

The combination angle and the rotor speed in Table 5 can be analyzed that at the specific duration of simulation time, the highest speed occurred in specific combination degree of turn-on angle and turn-off angle started from (45º and 90º) for simulation time 0.5 second. Then the duration of simulation increased to 1.5 second and excitation angel adjusted again until reached the highest speed, and so on, this combination angle changes for every increase of simulation duration time proved that the excitation of the SRM phase must be changed when duration time of simulation changed (speed changes) to achieve the best torque as indicated by increasing of the speed.

Table 5 show the turn-on angle and turn-off angle are turned in advanced gathering the speed increasing, but the magnitude is not linear both turn-on and turn-off angle as seen in the dwell angle, the magnitude of dwell angle decreased gathering to the speed increased.

When the combination angels of Table 5 are combined as a function of the speed and applied adaptively to the speed then the highest speed achieved 2691 rpm, this is a higher speed 118 rpm compared to a single excitation angle at 45º and 90º that reach only 2568 rpm for the same duration simulation time for 9 seconds. This proved that this combination angle suitable to be applied at SRM as a drive for vehicle application since the torque produced by the adaptive combination of optimum excitation angle gaining higher torque as indicated by higher speed achieved.

3.3. Experimental Result

The switched reluctance motor for the experimental system setup is seen in Figure 7. A 6/4 Switched reluctance motor with a three-phase asymmetric bridge converter connected to a 12 volt DC 32 ampere power supply. The microchip for controlling the excitation of the MOSFET is DSPIC 30F4012. The first experiment was done with the excitation angle starting from a 45-degree turn-on angle and 90 degrees for turn-off-angle. And the average speed reached around only 2340 rpm.

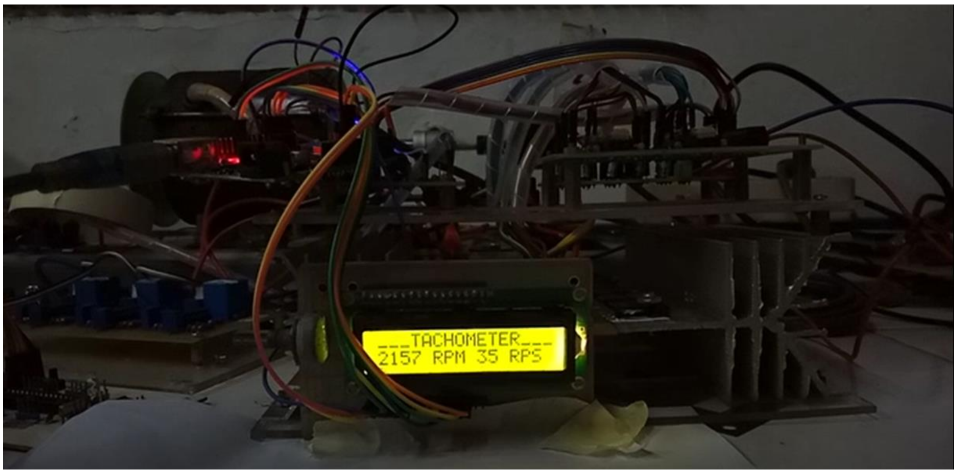

Figure 7. Switched Reluctance Motor Experimental System

The experiment continued with the combination of adaptive angles starting the turn-on angle from 45 degrees and then decreased until 44.33 degrees, while the turn-off angle started from 90 degrees and decreased until 84.44 angles for the running time duration of 9 seconds as stated in table 5. The decrease of turn-on and turn-off angles is gathered with the increase of speed. This experiment proved that the combination of decreased angles has more torque as indicated by a higher achieved speed of 2475 rpm compared to the single switching angle that only reaches 2340 rpm. This proves that the experimental equipment has the same behavior as the Matlab simulation when applied with adaptive optimum excitation angle to reach the higher torque compared to a single excitation angle.

4. Conclusion

According to traction application such as in electric vehicle use, the high torque at low speed become crucial since the need for starting and acceleration. How to determine for low speed (constant torque region) already found at around 9 seconds, while the adaptive combination angle already proved that the torque as indicated by the higher speed already achieved by the Matlab simulation at 2691 rpm compared to single combination angle reached only 2568 rpm.

The experimental data also proved that adaptive combination excitation angles achieve better torque as indicated by the higher speed at 2475 compare to single excitation angles at 2340 Rpm. This experimental data has evident that using Response Surface Methodology to find the best adaptive combination excitation angles is achieved.

The next research will be to conduct a similar method for constant power operation and also natural operation.

Acknowledgment
This paper is supported by Universitas Islam Sultan Agung and Universitas Sriwijaya.

References

[1] Kwok Tong Chau, Electric Vehicle Machines and Drives Design, Analysis and Application. John Wiley & Sons, 2015.
[2] M. Takeno et al., “Test Results and Torque Improvement of the 50-kW Switched Reluctance Motor Designed for Hybrid Electric Vehicles,” IEEE Trans. Ind. Appl., vol. 48, no. 4, pp. 1327–1334, 2012.
[3] S. Muthulakshmi and R. Dhanasekaran, “Intelligent Controller Based Speed Control of Front End Asymmetric Converter fed Switched Reluctance Motor,” 2016 Int. Conf. Adv. Commun. Control Comput. Technol., no. 978, pp. 426–431, 2016.
[4] S. M. Castano and J. Maixe, “Torque Control Optimization of a Switched Reluctance Motor Drive for a 42V Automotive Application,” in 2007 IEEE International Symposium on Industrial Electronics, 2007, pp. 1171–1176.
[5] J. L. Beniwal and R. K. Tripathi, “Speed Control of SRM Drives using a New Power Converter Configuration in Electric Vehicles,” in 2014 Australasian Universities Power Engineering Conference (AUPEC), 2014, no. October, pp. 1–6.
[6] H. Chen, Q. Wang, and H. H.-C. Iu, “Acceleration Closed-Loop Control on Switched Reluctance Linear Launcher,” IEEE Trans. Plasma Sci., vol. 41, no. 5, pp. 1131–1137, 2013.
[7] X. D. Xue et al., “Optimal Control Method of Motoring Operation for SRM Drives in Electric Vehicles,” IEEE Trans. Veh. Technol., vol. 59, no. 3, pp. 1191–1204, 2010.
[8] R. Krishnan, Switched Reluctance Motor Drivers: Modeling, Simulation, Analysis, Design, and Applications. CRC Press, 2017.
[9] X. Gao, X. Wang, Z. Li, and Y. Zhou, “The Design of Switched Reluctance Motor Torque Optimization Controller,” Int. J. Control Autom., vol. 8, no. 5, pp. 27–36, 2015.
[10] M. Hamouda and L. Számel, “Optimum Control Parameters of Switched Reluctance Motor for Torque Production Improvement over the Entire Speed Range,” Acta Polytech. Hungarica, vol. 16, no. 3, pp. 79–99, 2019.
[11] Thi Mai Phuong Dao, Y. N. Wang, and N. K. Nguyen, “A Novel Control Approach For Switched Reluctance Motors Based On Fuzzy Logic And Particle Swarm Optimization Techniques,” Univ. Politeh. Bucharest Sci. Bull. Ser. C-Electrical Eng. Comput. Sci., vol. 78, no. 3, pp. 85–96, 2016.
[12] J. Larminie and J. Lowry, Electric Vehicle Technology Explained. John Wiley & Sons, 2012.
[13] R. Orthmann and H. P. Schoner, “Turn-Off Angle Control of Switched Reluctance Motors for Optimum Torque Output,” in 1993 Fifth European Conference on Power Electronics and Applications, 1993, pp. 20–25, Vol 6.
[14] C. Lin and B. Fahimi, “Optimization of commutation angles in SRM drives using FRM,” in 2012 IEEE Transportation Electrification Conference and Expo (ITEC), 2012, pp. 1–6.
[15] M. Hamouda and L. Számel, “A New Technique for Optimum Excitation of Switched Reluctance Motor Drives Over a Wide Speed Range,” Turkish J. Electr. Eng. Comput. Sci., no. 26, pp. 2753–2767, 2018.
[16] Y. Z. Xu, R. Zhong, L. Chen, and S. L. Lu, “Analytical Method to Optimise Turn-On Angle and Turn-Off Angle for Switched Reluctance Motor Drives,” IET Electr. Power Appl., vol. 6, no. 9, pp. 593–603, 2012.
[17] D. Cajander and H. Le-huy, “Design and optimization of a torque controller for a switched reluctance motor drive for electric vehicles by simulation,” vol. 71, pp. 333–344, 2006.
[18] V. V. Prabhu, V. Rajini, M. Balaji, and V. Prabhu, “A Comparative Study of Operating Angle Optimization of Switched Reluctance Motor with Robust Speed Controller using PSO and GA,” vol. 10, 2015.
[19] J. H. Choi, D. J. Kim, Y. Do Chun, P. W. Han, D. H. Koo, and J. Lee, “Approximate optimization for minimum torque ripple of three phase switched reluctance motor using response surface modeling,” Int. J. Appl. Electromagn. Mech., vol. 39, no. 1–4, pp. 825–833, 2012.
[20] J. Choi, D. Koo, S. Kim, Y. Kim, and J. Ahn, “Approximate optimization for maximum efficiency of high speed single phase switched reluctance motor using response surface modelling,” vol. 28, pp. 227–235, 2008.
[21] M. Hamouda and L. Számel, “Optimum Excitation Angles for Switched Reluctance Motor Drives,” XXXIII. Kandó Conf. Óbudai Univ., pp. 128–142, 2017.

[22] M. Hamouda and L. Szamel, "Torque Control of Switched Reluctance Motor Drives for Electric Vehicles," in Proceedings of the Automation and Applied Computer Science Workshop, 2017, pp. 9–20.
[23] X. Wang, Z. Yang, T. Wang, and D. He, "Design of A Wide Speed Range Control Strategy of Switched Reluctance Motor for Electric Vehicles," no. August, pp. 294–299, 2015.
[24] A. M. Omekanda, "A New Technique for Multidimensional Performance Optimization of Switched Reluctance Motors for Vehicle Propulsion," IEEE Trans. Ind. Appl., vol. 39, no. 3, pp. 672–676, 2003.
[25] B. Fahimi, G. Suresh, J. P. Johnson, M. Ehsani, M. Arefeen, and I. Panahi, "Self-Tuning Control of Switched Reluctance Motors for Optimized Torque Per Ampere at All Operating Points," in APEC '98 Thirteenth Annual Applied Power Electronics Conference and Exposition, 1998, no. Vol. 2, pp. 778–783.
[26] J. Mukherjee and S. Chowdhuri, "Multiobjective Optimisation by PSO for Switched Reluctance Motor (SRM) Drive," in 2014 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO), 2014, pp. 391–396.
[27] C. Huang and G. Yang, "Optimization Design of Switched Reluctance Motor Based on Response Surface Method," 2018 IEEE Student Conf. Electr. Mach. Syst., pp. 1–6, 2018.
[28] S. I. Kim, G. H. Lee, J. J. Lee, and J. P. Hong, "Simple Design Approach For Improving Characteristics of Interior Permanent Magnet Synchronous Motors for Electric Air-Conditioner Systems in HEV," Int. J. Automot. Technol., vol. 11, no. 2, pp. 277–282, 2010.
[29] L. Qinghua, M. A. Jabbar, and A. M. Khambadkone, "Response Surface Methodology Based Design Optimisation of Interior Permanent Magnet Synchronous Motors for Wide-Speed Operation," Second Int. Conf. Power Electron. Mach. Drives (PEMD 2004), vol. 2, no. 6, pp. 546–551, 2004.
[30] I. Husain, "Switched reluctance machines," in The Power Electronics Handbook: Industrial Electronics Series, 1st ed., T. L. Skvarenina, Ed. CRC Press, 2002, pp. 1–20.
[31] S. Riyadi, "Control Strategy for Switched Reluctance Motor With Rotary Encoder Based Rotor Position," Adv. Electr. Electron. Eng., vol. 16, no. 3, pp. 261–270, 2018.
[32] D. C. R. H. M. Montgomery, Response-Surface-Methodology. Published by John Wiley & Sons, Inc., Hoboken, New Jersey, 2009.
[33] J.-W. Ahn, "Switched Reluctance Motor," in Torque control, vol. i, no. 8, Moulay Tahar Lamchich, Ed. Janez Trdine 9, 51000 Rijeka, Croatia: InTech, 2011, pp. 201–252.