Design and Development of Spice-Assisted Hybrid Driver Circuit for Measurement of 4 KW (5.5 HP) Switched Reluctance Motor

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Abstract

The first part of the paper presents the use of the M57962L hybrid driver for switching the current through phase windings of Switched Reluctance Motor. The Integrated Chip M57962L manufactured by Mitsubishi Electric provides a better option for SR Motor. M57962L chip with a single in-line hybrid circuit is available for driving the IGBT. In the second part, hardware design using IGBT and its gate driver circuit is designed. The third part of the research paper presents the analysis and implementation of hardware for inductance and flux measurement.

Keywords: *Flux measurement, Free Wheeling, IGBT, Inductance, SRM*

1. Introduction

SRM (Switched Reluctance Motor) offers flexibility in operational systems including hardware and software parts and allows for four-quadrant operation in all types of load conditions. The electronic control of the motor provides huge benefits like a reduction in torque ripple of SRM thus reducing acoustic noise [1-4]. The capabilities of the Switched Reluctance (SR) Motor Drive in small integral-horsepower sizes are discussed along with special features, [4,17]. Control Techniques for SRM is explained [5]. The design and simulation process of SRM for high-speed applications are presented [6]. Recently, most electrical appliances use the BLDC motors, and now Switched Reluctance Motor seems to be a replacement for conventional electric motors [5-6]. Due to strong coupling, and high nonlinearity in the motor drive system, it is difficult to model and control, however, the drive becomes programmable and hence there is vast control over the performance parameters of the motor for industrial use is possible [7-10]. The structural modification is proposed for the sensitivity analysis of the SR Motor [9]. A detailed SR Motor model with Pspice simulation is presented [2,6,18]. Therefore, the industry needs to replacement of conventional drives such as Brushless DC Motors, DC motors, Induction motors, etc. with SRMs. For the detailed analysis and application of SR Motor in Industries, there is a need to measure the torque, speed, and flux linkages in static mode. Therefore, efforts are taken to develop a suitable model using an integrated circuit M57962L Hybrid Driver. The simulation is done using Pspice with the development of Analog Behavioral Models (ABM).

2. Proposed Methodology

The measurement system is developed for Inductance profile, flux linkages to rotor, torque, and speed. However, for inductance and flux measurement, a special rotor blocking system is developed.

2.1 Measurement of Phase Inductance of 4 KW SRM

The phase inductance measurement is carried out using hardware to Sense voltage across the winding of SRM for different rotor positions and Senses current through the phase winding for different rotor positions. The above data is then stored in the DSO and then transferred to a computer for storing data in an excel file. This data is processed using MATLAB software for calculations of phase inductance, plotting the flux-linkage characteristics.

2.2 Design and Development of Hardware for Measurements on SRM

The hardware development aims to acquire the voltage and current data from SRM and process the same analysis. Therefore, hardware and software development leads to developing the design and development of electronic hardware, the design, and development of mechanical hardware, and the development of software. The electronic hardware system required for data

capturing is mainly focused on the following, Data sensing and processing using an advanced digital storage oscilloscope IGBT-based Chopper Power Module (For one phase) and hence the Gate Diver Circuit for IGBT, Voltage and Current Data Acquisition Circuit using Op-Amp and Microcontroller based Signal Generator Card is developed. The data is acquired and processed for the determination of performance characteristics. Data sensing and processing using advanced digital storage oscilloscope. The flux-linkage is the non-linear type of function current flowing through the winding for different rotor positions. There are two types of measurement methods seen such as direct measurement and another is indirect measurement method. For measurement of flux-linkage characteristics, a suitable dc voltage from the battery is taken. The current is fed to the winding via a solid-state relay. A proper switching arrangement is used to supply enough current to phase the windings of the motor. The waveforms are digitally stored in the Falcon make DSO and is interfaced with the computer to store the result in an excel file. The results are stored in the file. A MATLAB program is developed for the calculation of integration of v-ir voltage developed across the winding.

2.3 IGBT-based Chopper Power Module (For one phase)

Figure 1 shows the IGBT-based power module for one phase the IGBT is rated for 600V DC, and a 60 Ampere current rating is used. The FWDs are utilized in the power stage. The free-wheeling diodes (FWD) have a reverse recovery time of 10 ns and are rated at 600 VDC, 60 A.

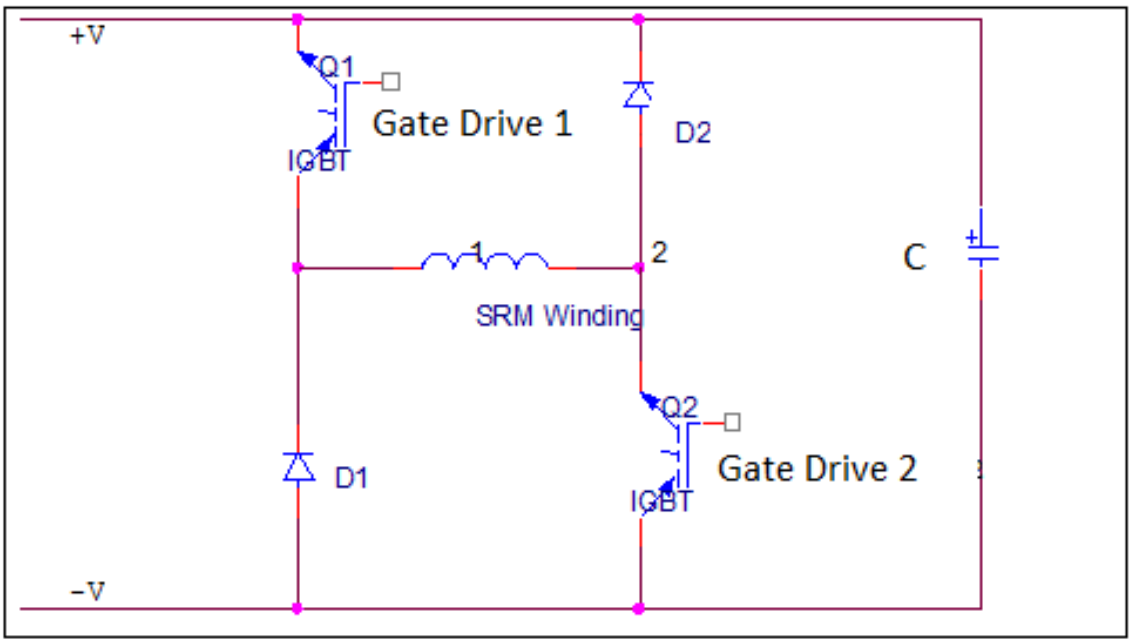

Figure 1. IGBT-based Chopper Power Module

2.4 Gate Diver Circuit for IGBT

As the principle of operation of SRM is based on switching the phase voltage ON and OFF, and hence there is a need for highly reliable, high-withstanding capacity and short-circuit protection of Insulated Gate Bipolar Transistor Modules (IGBT) with the minimum external component requirement. One such integrated circuit Mitsubishi Electric make M57962L chip provides a good solution for the same. M57962L chip with a single in-line hybrid circuit is available for driving the IGBT (Insulated Gate Bipolar Transistor). The selection of the IGBT is based on the following considerations.

2.5 Output Current Limit

As per the observation of a sudden rise in the current concerning each phase, there is needed to limit the current required to drive the IGBT. External resistance is kept in series with the gate for the same purpose. The series resistance can be calculated with R Series (MIN) = (VCC + VEE)/Peak Current for the IGBT gate., consider VCC = 15V and -VEE = 10V RG(MIN) for M57958L which will be R1 = (15V + 10V)/5A = 5Ω (R1 = R Series), a standard resistance of 4.7 Ohms is selected for limiting the gate current.

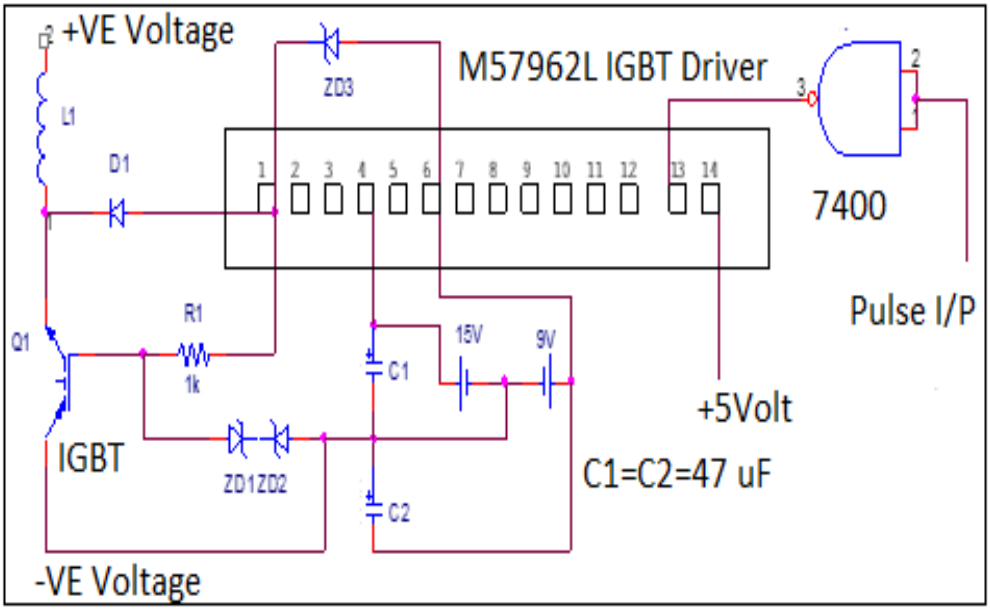

Figure 2. Proposed M57962L-based IGBT Gate Driver Circuit

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The diode D1 called a detect diode should be a fast recovery type and its rating should be equal to the rating of the IGBT transistor being used. A Zener is used to protect the M57962L IC's detect input from high transient voltages which occurs during recovery of the detect diode. To properly drive the internal, opt isolator, it includes a built-in particular resistance of 185-ohm at the input side. To maintain the recommended opto-drive current of 16mA at various input voltages, an additional resistor should be applied.

2.6 Voltage and Current Data Acquisition Circuit using Op-Amp.

A typical circuit is used for the same which composes a voltage sensing circuit that is coupled to an optical isolator circuit. An HT 100 hall current sensor measures the phase current. The circuit can amplify the voltage signals and current from phase winding and produces a quantity of V-iR.

2.7 Microcontroller-based Signal Generator Card

A microcontroller card is designed with the program for generating the pulses to control the Insulated Gate Bipolar Transistor (IGBT) ON and OFF at intervals. A Special software program is developed to generate the chopping signals.

2.8 Development of Software.

Software is developed and used to acquire data and store it in the appropriate locations. This data from the software is imported for numerical analysis. The data is processed for the calculation of inductance and flux characteristics at different rotor positions. A MATLAB program is developed for calculations of flux data and rising phase inductance. The numerical integration of V-ir is performed using Simpson's 1/3 rule and codes for the same are written in the MATLAB software.

3. Calculation of Chopping-Mode Torque

The torque in copping mode is calculated as,

$$\tau = i^2 L_U (s\lambda_U - 1)\frac{qN_r}{4\Pi}(2 - \frac{C}{S_{MAG}}) \quad (1)$$

Where, τ = Instantaneous torque, i = Instantaneous peak phase current, L_U= Unaligned inductance of a phase, λ = Un-saturation inductance ratio, S_{MAG}= the proportion of the peak phase current to the current needed to just saturate the magnetic circuit in the corresponding position. Let, τ = 38 N-m, q = 4, Nr = 6, L_U= Unaligned inductance of a phase is 10mH, λ = 15, C = 0.6, S = 0.3, S_{MAG}= 4.5 and from equation 1, i = 11.7 amp

3.1. Physical Construction of the power module

It is necessary to construct or built the power module to avoid lead inductances, stray capacitance, and to avoid lead sparks, etc. A separate part for gate divers is arranged. A current sensor (HT 100) is mounted near the IGBT module. The interface circuit is also mounted near to power module.

3.2. Rotor blocking system for statics analysis

A mechanical rotor bocking arrangement is developed for static types of testing for a 4KW Switched Reluctance Motor. A rotor cast iron disc is developed with a 1.5-millimeter thickness, a redial gap length of 28 mm, a total of 120 nos. of the rotor teeth, and an outer diameter of 200 mm are used. The torque of the SR motor is considered about 24 N-m. The locking is done with two screw fitting arrangements. The rotor is rotated in a step of 3 degrees for each reading.

Table (1). Specifications of Rotor Disc.

Sr.No.	Parameter	Unit/Measure
1	Stator Poles	8
2	Rotor Poles	6
3	Outer Diameter	200 mm
4	Thickness	1.4 mm
5	Radial Gap length	28 mm
6	Stator Pole Pitch	45^0
7	Rotor Pole Pitch	60^0
8	Rotor Pole Arc	27^0
9	Stator Pole Arc	21^0

Using the above data a rotor holding arrangement is developed as shown in as shown below in figure (3).

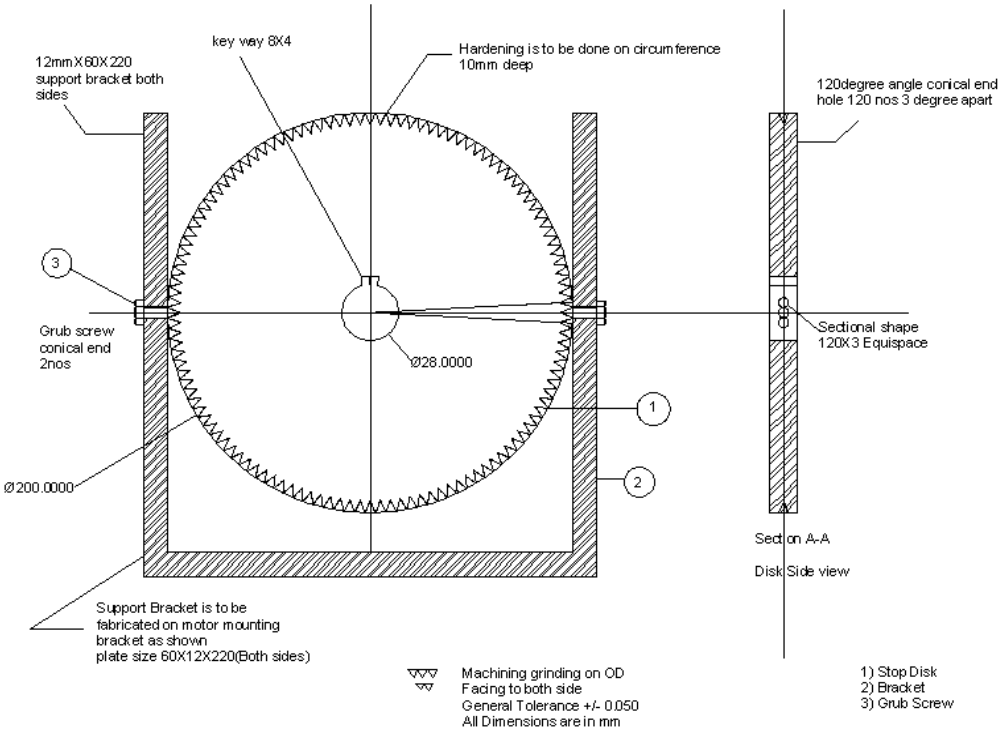

Figure 3. The proposed rotor-blocking system

4. Experimental Results and Discussions

The table was made to record flux linkages versus different rotor positions and phase currents. The plot of Flux Linkages versus Phase current for different rotor positions with a 3-degree step is shown in Figure 3.

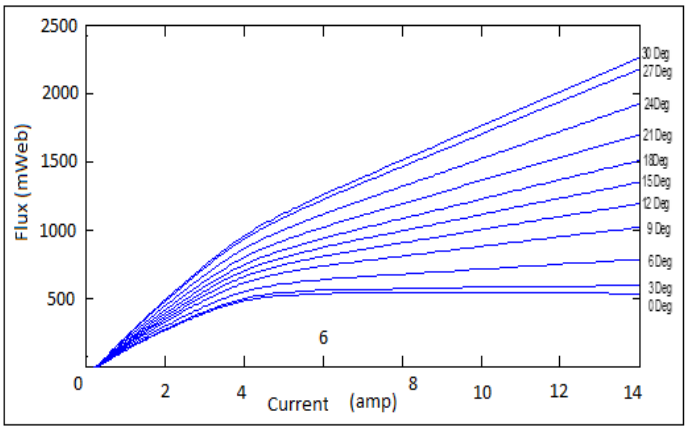

Figure 3. Flux-linkage Vs Phase current at different Rotor Positions

The inductance profile is plotted for different rotor positions under different rotor positions of the SR Motor and the rotor locking arrangement is made for the same. The result is shown in figure 4. It is observed that heavy stress on inductance creates noise during rotor blocked position and a heavy current pass through the phase winding of the stator.

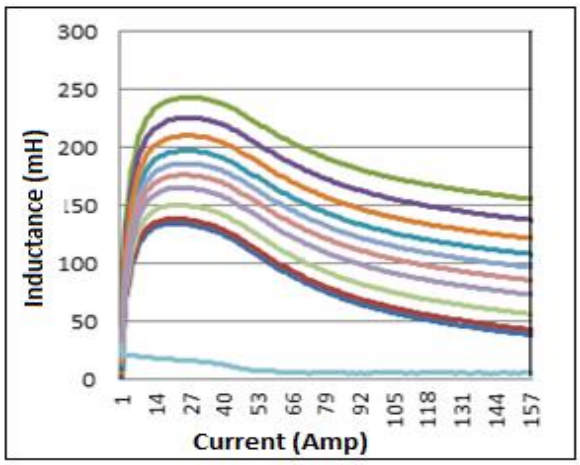

Figure 4. Inductance Profile of SR Motor under different Rotor Positions

Conclusion

The study is conducted for the design and development of hardware and software for the measurement of inductance and flux linkages profiles for a 4.5KW Switched Reluctance Motor. A separate rotor blocking arrangement is designed for static characteristics of Switched Reluctance Motor. M57962L-based IGBT Gate Driver circuit is designed for driving the IGBT

modules. A copping mode torque is calculated mathematically and the same is validated experimentally. The data acquisition technique is developed for acquiring the instantaneous data of static as well as dynamic modes. For transient and steady-state analysis, spice modeling techniques are used.

Acknowledgments

The author thanks all the technical staff of DIETMS for their continuous support of technical achievements.

References

[1] I. Husain; M. Ehsani D., "Torque Ripple Minimization in Switched Reluctance Motor Drives by PWM Current Control", IEEE Transactions on Power Electronics, Vol.11,(1996) pp. 83-88.

[2] Kirti R. Chichate; Sachin R. Gore; Ajay Zadey, "Modelling and Simulation of Switched Reluctance Motor for Speed Control Applications", 2nd International Conference on Innovative Mechanisms for Industry Applications (ICIMIA), IEEE Xplore,(2020) pp. 637-640.

[3] Lawrenson P.J.; J.M. Stephenson; P.T. Blenkinsop; J. Corda; N.N. Fulton, "Variable speed Switched Reluctance Motor", IEEE Proceedings, Part B, Vol.27 (4), (2015) pp. 253-65.

[4] M.R. Harris; John W. Finch; John A. Mallick; Timothy J. E. Miller., "A Review of the Integral-Horsepower Switched Reluctance Drive", IEEE Transactions on Industry Applications, Vol IA-22, (1986), pp.716 – 721.

[5] Reyad Abdel-Fadil; László Számel., "State of the Art of Switched Reluctance Motor Drives and Control Techniques", IEEE explore Twentieth International Middle East Power Systems Conference (MEPCON), Cairo (Egypt), (2019), pp. 779-784.

[6] Swasti Chakrabarty; Ragavan Kanagaraj, "Design, Simulation, and Analysis of Switched Reluctance Motor for High-Speed Applications", IEEE National Power Electronics Conference (NPEC), (2022), pp. 1-22,

[7] Shoujun Song; Weiguo Liu; Youlin Wang, "Modeling, Dynamic Simulation and Control of a Four-phase Switched Reluctance Motor", IEEE International Conference on Control and Automation, Guangzhou, China. (2007), pp. 1290-1295

[8] Walivadekar V.N.; V.V. Athani; G.N. Acharya, "Equivalent Circuit for Switched Reluctance Motor", International Conference on Computers, Communication and Automation 'TENCON'-93, (2002) 06 August.

[9] Wang X.; L. Yuan; Y. M. Zhan; H. Chen; M. Wardach; R. Palka; M. Orabi, "Sensitivity Analysis on Novel U-Shape Dual-Stator Switched Reluctance Motor", IEEE Transactions on Applied Superconductivity, Vol.31, Issue: 8, (2021)

[10] L. Chang, "Comparison of AC Drives for Electrical Vehicle – A Report on Experts opinion survey." 'IEEE AES System Magazine, (1994), pp 7-10

[11] Bimal K Bose, "Evaluation of Modern Power Semiconductor Devices and Future Trends of Converter"; IEEE Trans. On IA, Vol.28 (2), (1992), pp.403-1.

[12] Bimal K Bose, "Power Electronics - A Technology Review", Proceedings of the IEEE vol.80(8), (1992), pp 1303-34.

[13] Thomas A. Lipo, "Recent Progress in Development of Solid State AC Motor Drives", IEEE Trans on PE, Vol3(2), (1988), pp.105-17.

[14] Bimal K Bose, “Power Electronics and Motion Control- Technology status and Recent Trends’’, IEEE Trans on IA, Vol.29(5), (1993), pp. 902-09.

[15] [15] TJE Miller, “Brushless Permanent Magnet and Reluctance Motor Drives”, Oxford Science Publications, Clarendon Press, Oxford, (1989).

[16] Bostanci, E.; Moallem, M.; Parsapour, A.; Fahimi, B., “Opportunities and Challenges of Switched Reluctance Motor Drives for Electric Propulsion: A Comparative Study”, IEEE Transactions on Transportation Electrification, Vol.3(1), (2017), pp. 58–75.

[17] Martyn R. Harris; John W. Finch; John A. Mallick; Timothy J. E. Miller ., “A Review of Integral Horse Power Switched Reluctance Drive”, Conference Record 1885 IEEE IAS Annual Meeting. (1885) 6th – 11th Oct, pp. 783-89.

[18] I. Husain, S. A. Hossain, “Modeling, simulation, and control of switched reluctance motor drives”, IEEE Transactions on Industrial Electronics, Vol. 52, No. 6, (2005) pp. 1625–1634

[19] I. Husain, M. Ehsani, “Torque ripple minimization in switched reluctance motor drives by PWM current control”, IEEE Transactions on Power Electronics, Vol. 11, No. 1, (1996) pp. 83-88.

[20] J. Ye, B. Bilgin, A. Emadi, “An offline torque sharing function for torque ripple reduction in switched reluctance motor drives”, IEEE Transactions on Energy Conversion, Vol. 30, No. 2,(2015) pp. 726-735.

[21] R. Suryadevara, B. G. Fernandes, “Control Techniques for Torque Ripple Minimization in Switched Reluctance Motor: An Overview”, IEEE 8th International Conference on Industrial and Information Systems, Peradeniya, Sri Lanka, (2013)

[22] P.J. Lawrenson; J.M. Stephenson; P.T. Blenkinsop; J. Corda; N.N. Fulton, “Variable speed Switched Reluctance Motor”, IEE Proceedings, Part B Vol.127 (4), (1980), pp. 253-65

[23] Ibrahim Sengor; Abdullah Polat; Lale T. Ergene, “Design and Analysis of Switched Reluctance Motors”, 8th International Conference on Electrical and Electronics Engineering (ELECO), IEEE, (2014), January 16

[24] William F. Ray; Peter J. Lawrenson; Rex M. Davis; J. Michael Stephenson; Norman N. Fulton; Roy J. Blake, “High Performance Switched Reluctance Motor & Brushless Drives” Conference Record 1985, IEEE IAS Annual Meeting. (1985) 6th–11th Oct, pp1169-76.

[25] Iqbal Husain, M.Ehsani, “ Torque Ripple Minimisation in Switched Reluctance Motor Drives by PWM Current Control”, IEEE Trans 1465.5/94, (1994).

[26] R.M. Davis; W.F. Ray; R.J. Blake, “Inverter Drive for Switched Reluctance Motor: Circuits and Component Ratings”, IEE Proceedings, Part B, Vol. 128(2), (1981), pp. 126-36.

[27] Mehrdad Ehsani; James T. Bass; Timothy J. E. Miller; Robert L. Steigerwald, “Development of Unipolar Converter for Variable Reluctance Motor Drives” IEEE Trans on Industrial Applications, Vol 23 (3), (1987) pp 545-53

[28] T. Husain, A. Elrayyah, Y. Sozer, I. Husain, “Unified Control for Switched Reluctance Motors for Wide Speed Operation”, IEEE Transactions on Industrial Electronics, Vol. 66, No. 5, (2019) pp. 3401-3411