IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 30, 2017, accepted January 25, 2018, date of publication February 7, 2018, date of current version March 13, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2803128

A Flexible Mathematical Model for Dissimilar Operating Modes of a Switched Reluctance Machine

ALI ASGHAR MEMON[1], SYED ASIF ALI SHAH[1], WAJIHA SHAH[1], MAZHAR HUSSAIN BALOCH[1], GHULAM SARWAR KALOI[2], AND NAYYAR HUSSAIN MIRJAT[1]
[1]Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro 76062, Pakistan
[2]Quiad-e-Awam University of Engineering, Science and Technology, Larkana 45320, Pakistan

Corresponding author: Ali Asghar Memon (ali.asghar@faculty.muet.edu.pk)

ABSTRACT Switched reluctance motor (SRM) is an energy efficient machine, which receives electrical energy from the power source and returns part of the stored magnetic energy back to the supply, during each cycle of the machine operation. Characteristically, the SRM possesses nonlinear characteristics due to dual saliency and magnetic saturation. The exertion is realized in developing a mathematical model of the machine in presence of huge input data tables, famously, known as static characteristics. These data tables are required for mathematical modeling of the machine in a single pulse, steady state and transient performances separately. This paper presents a simple and flexible mathematical model of a switched reluctance machine in MATLAB/Simulink environment. In Simulink, based on graphical coding environment, the proposed model uses fewer data tables and less simulation time. Furthermore, with less addition to the same proposed model, another operating mode of the machine is possible, under the same operating conditions. A similar model in MATLAB, based on test code environment is also proposed, using the same operating conditions as in the Simulink based model to see the difference. The obtained results are validated by comparing the results of both the models, and with the experimentally obtained results, under single pulse, steady-state, and dynamic modes of the machine operation. The proposed model can handle the measured or computed data of the flux linkage and static torque, respectively.

INDEX TERMS Operating modes, switched reluctance machines, static characteristics.

I. INTRODUCTION

Switched Reluctance Machine is a reliable motor under different environmental conditions. If compared, the machine is simplest of other machines. It is a brushless dc machine, powered from dc source by means of an electronic converter. It has double salient poles, each on stator and rotor. Less copper is used in the motor because rotor does not carry windings. The rotating torque in the machine is produced, as a result of the magnetic attraction of energized stator pole on the bordering rotor pole, resulting, an increased inductance and a decreased reluctance region [1]. Fig.1 shows, the construction, suitable converter, motor connections, and a power supply for a 4-phase (8/6 pole), SR machine. Due to the dual magnetic salient pole structure, and saturation aptitude of the magnetic circuit, the machine displays the nonlinear characteristics. Therefore, the modeling and simulation of SR machine become more distressed. There is a number of simulation models, reported in the literature on basis of different computer software, each has contributed acceptable results and validations.

In this research, an inclusive detail of the existing simulation models is presented. Finally, a simple and flexible mathematical model in Matlab/Simulink (Text based coding and graphical coding) environment is proposed. The results are compared with experimental results, under the same operating conditions. The proposed model addresses, the single pulse, steady-state and dynamic performances of the machine, For the purpose of the sketch, Fig.2 shows, the single pulse operating mode of SR machine in current chopping control and voltage pulse width modulation control [2]. Computer simulation based models are reported in the literature. In reference [3], the dynamic model of a three-phase SR machine, based on time-stepping FEM (Final Element Method) is discussed. Furthermore, the winding end part

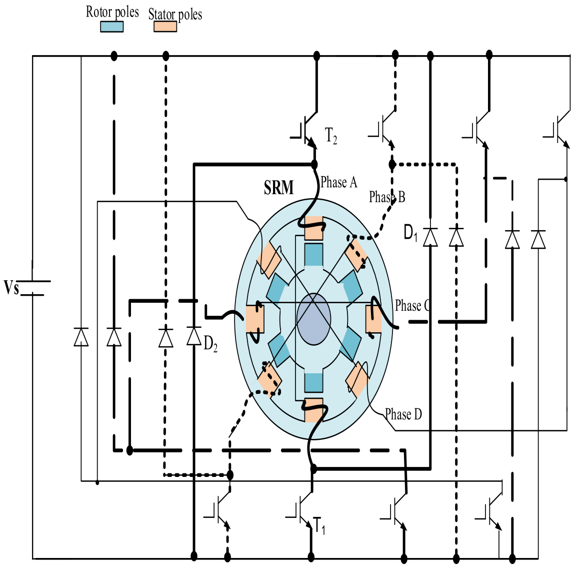


FIGURE 1. A 4-phase, 8/6 pole, switched reluctance machine with motor connections, voltage supply, converter, and energy path [2].

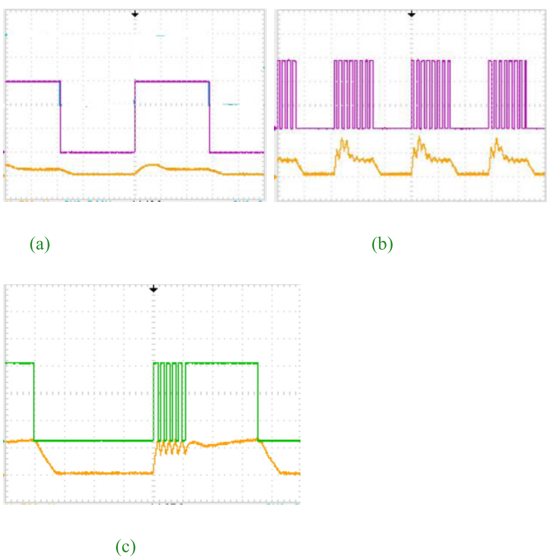


FIGURE 2. Experimental demonstration of machine operating modes (upper waveform-voltage pulse, lower waveform-phase current). (a) Single pulse mode (b) Voltage PWM mode (c) Current chopping mode.

inductance against rotor position is shown. The model [3] has not considered the static characteristic as input data in a single pulse and voltage PWM mode of the machine operation. A direct field-circuit coupled model is used for determination of magnetic field distribution. The obtained results comprise of current rise, torque, and speed. The steady state part is not shown when the transient is over to see the difference.

An electromagnetic force waveforms are shown in Matlab/ Simulink model [4]. In this model, the input data tables are not well-defined. The half bridge (H) converter for a 2-phase machine in Matlab/Simulink, is presented in [5]. For integral parameter calculations, FEMM software, and control circuit model were developed in PLECS software. The phase current and torque profile of a two-phase machine are not produced on the same scale. The instantaneous torque of two phases is also missing in the results. Therefore, the behavior and the trend of obtained results cannot be matched. The static and transient model based on FEM software is discussed in the model [6]. FEM model of a three-phase machine shows the transient behavior under fault in either phase. The results under the dynamic state with and without faults are shown. Total and phase torque results of the machine are not discussed. This model can be helpful for fault simulation. Further that, the obtained results are not kept on the same scale to distinguish the difference. A finite element (Maxwell and Simplorer) based model is presented and the static characteristics are obtained [7]. For lower speed considerations, the current chopping mode is preferred [7]. Furthermore, upper and lower limits required for the current chopping, are set at relatively high limits i.e. 22A and 17A. A FEM based model of switched reluctance machines are developed for a rotary, linear, and a rotary-linear mode respectively [8]. A new structure for a rotary-linear switched reluctance motor (SRM) has been presented in [9]. The motor design was initially presented by theoretical analysis, based on the standard equations. The obtained parameters for the RLSRM are verified by the model analysis, using 3-D-FEA. The dynamic model has shown the results for a linear and a rotary SR machines. The scales are not kept same for the display of results. Also, the torque profile of the machine is missing. A nonlinear dynamic model for the performance of an adjustable speed SRM drive has been proposed [10]. Two systems named, conventional and expert fuzzy system are used. This combination has given better results for performance of the machine. The speed, torque, and inductance waveforms are also shown. The presented work has separately shown results by using a Hybrid Fuzzy Controller, Pi Controller, and a Fuzzy Controller. From torque and inductance results, only steady-state operating mode of the machine is clear, and there is no evidence of the transient. Also, the phase current results in a three-phase machine are also missing. The electric and magnetic simulations on transient analysis are performed with the help of SPICE simulator [11]. The flux distribution is also highlighted in the paper. Furthermore, the phase current, torque, and speed waveforms are shown on the same scale, under the transient operating mode of the machine. However, the waveforms of the flux and total torque are not shown. Electromagnetic transients and DC/Power System Computer-Aided Design (EMTDC/PSCAD) software based model is presented for an SR machine, suitable for the dynamic performance [12]. The simulation results show, the transient and steady-state operating modes. It is notable that there is sharp decrease rate between two states. SPICE software has been suitable for its suitability in the electronic circuit simulations [13], [14]. Therefore, it cannot be efficiently used in SR machines. On the other hand, PSCAD software is comparatively accurate and time-saving [10]. The suitability of this software for SR machines is due to its graphical interface. Shareware software is a progressive vehicle simulator [15]. It takes about 25 hours in dynamic simulation of SR machine. A FEM based model and Equivalent Circuit Simulation, assisted by Maxwell SPICE and Simplorer for an SRM system are presented [16]. The phase currents and applied voltage waveforms are shown. Whereas, the torque and speed waveforms are not shown. Results are validated with the experimental results. Another FEM based model of a tubular linear switched reluctance generator is presented [17]. The dynamic performance of the machine in terms of load current, winding current and force waveforms are shown. A Simulink model, in a single pulse operating mode of SR machine is presented [18]. It uses two data tables. In reference [19], a 12/8 poles, SRM model is developed in Matlab/Simulink, for an optimal turn-off angle, based on [20]. A lookup table based model [21], using Finite Element Method Magnetics (FEMM) software to produce magnetization characteristics of the machine, is presented. The waveforms of the instantaneous phase current, stator pole flux are produced by help of 2D Finite Element (FE) Transient Analysis. Another, FEM model is reported in literature, highlighting the static and dynamic analysis of the SR machines [22]. The dynamic torque profile is shown by using lookup tables. The simulation results are produced for the torque waveforms at different speed range and rotor positions i.e. 8 degrees and 23 degrees. A Matlab-Simulink model is proposed for the dynamic model of a three-phase switched reluctance machine [23]. A model based on FE analysis is presented in [24]. A combination of finite-element technology and PSCAD (Power System Computer Aided Design) circuit simulation provides, an accurate results for the SR motor [24]. In this paper, the different excitation blocks are shown, which are used as part of the simulation model. Furthermore, the results are produced at different load torques. The measured data for lookup tables of flux, torque and inductance is obtained through FEM. A Piecewise Hermite Cubic Spline and Fourier series, data-based dynamic model is presented [25]. The effect of mutual coupling is also considered, and a complete set of results is obtained by comparing dual channel and a single channel modes [25]. Average torque and speed waveforms, in addition to the experimental results are also shown. Adaptive Neural Fuzzy Inference System (ANFIS) is used for the simulation [26]. Two data tables of inverted flux and static torque are also included in the model [26].

II. INPUT DATA TABLES (STATIC CHARACTERISTICS)

Mainly, there are four input data tables: flux linkage $\Psi(\theta, i)$, inverted flux linkage (i, Ψ), co-energy $W'(\theta, i)$, and static torque $T(\theta, i)$. These data tables are commonly known as the static torque characteristics. Of these four data tables, the data of flux linkage is obtained from experiments, on an existing machine, with the help of a suitable computer software. Also, the data of static torque can be obtained from the experiments by using an existing machine from the locked rotor test. Alternatively, this data can also be achievable from the co- energy information, using equation 2. Similarly, an inverted flux linkage data is easy to obtain, once data of flux linkage is available. Third data table is achievable from equation 1.

A procedure of producing these data tables is described in [27].

Co energy is obtained from the relation

$$W'(\theta, i) = \int_0^i \Psi(\theta, i)\, di \tag{1}$$

Static torque is given by the equation

$$T(\theta, i) = \frac{\partial W'(\theta, i)}{\partial \theta} \tag{2}$$

III. THE PROPOSED MATHEMATICAL MODEL OF SWITCHED RELUCTANCE MACHINE

The proposed mathematical model is based on the voltage equations and a mechanical equation, as discussed below. The phase current through a 4-phase SR machine can individually be represented mathematically,

$$\frac{d\Psi_1(\theta, i_1)}{dt} = (v_1 - Ri_1) \tag{3}$$

$$\frac{d\Psi_2(\theta, i_2)}{dt} = (v_2 - Ri_2) \tag{4}$$

$$\frac{d\Psi_3(\theta, i_3)}{dt} = (v_3 - Ri_3) \tag{5}$$

$$\frac{d\Psi_4(\theta, i_4)}{dt} = (v_4 - Ri_4) \tag{6}$$

Where Ψ_{1-4} represents flux linkage for 4-phases of the machine, v_{1-4} denote the supply voltage and R is the resistance of machine windings.

Equations 3-6 can be simplified,

$$v = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \tag{7}$$

$$v = Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\cdot\frac{d\theta}{dt} \tag{8}$$

$$v = Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\cdot\omega \tag{9}$$

where first and second terms on R.H.S of eq.9 are: voltage drop across resistance and inductance, the third term is an induced EMF. Omega (ω) is the rotational speed (rad/sec). The energy flow rate is given as

$$vi = Ri^2 + \frac{d}{dt}\left\{\frac{Li^2}{2}\right\} + \frac{i^2}{2}.\frac{dL}{d\theta}\omega \tag{10}$$

where terms used in equation 10 are separately identified as, power loss in coil caused by its resistance, stored magnetic energy and mechanical output power.

The torque is given by

$$\lambda = i^2\frac{dL}{d\theta} \tag{11}$$

Based on the above equations, a simple and self-explanatory, mathematical model, is developed in Matlab/Simulink in the graphical environment. The proposed model addresses, the single pulse, steady-state and dynamic performances of

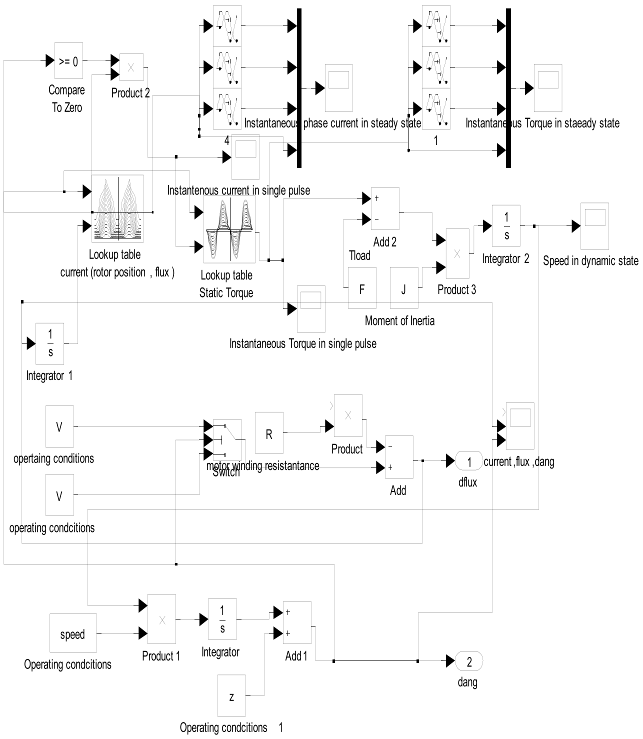


FIGURE 3. The proposed mathematical model for the various operating modes of the SR machine in a graphical environment.

TABLE 1. Operating conditions for the machine operation under different operating modes.

Parameters	Pre set values
Supply voltage	100 V
Switch on angle	-37.12 deg.
Switch off angle	-7.12 deg
Conduction angle	30 deg.
Winding resistance	3.373 Ω
No. of switches per phase	2
No. of diodes per phase	2
Load torque	4Nm
Moment of inertia, J	0.0012 Kg-m^2

the machine for same operating conditions, same input data tables, and same processing time. For the dynamic modeling of the machine, a mechanical equation is added to the set of above equations.

$$\frac{d\omega}{dt} = \frac{1}{J}\left[T - T_L\right] \tag{12}$$

where J indicates the moment of inertia, T is electromagnetic torque, T_L denotes load torque of the machine.

Two input data tables $i(\theta, \Psi)$ and $T(\theta, i)$ out of four input data tables, described in section II, are used in this proposed model. The proposed model is shown in Fig.3. These data table blocks can be easily chosen from the Simulink library, named as; Function Block parameters lookup table for the current in which row index input values indicates rotor position. It is selected from −60 to 60 degrees with the interval of 3 degrees. The column index input values are selected from 0 to 6 with a small interval of 0.041. Similarly, table corresponding to the static torque of the machine in which column index is selected for current range from 0 to 14 amperes with an interval of 1ampere. The values of input data for both the tables are obtained as discussed earlier.

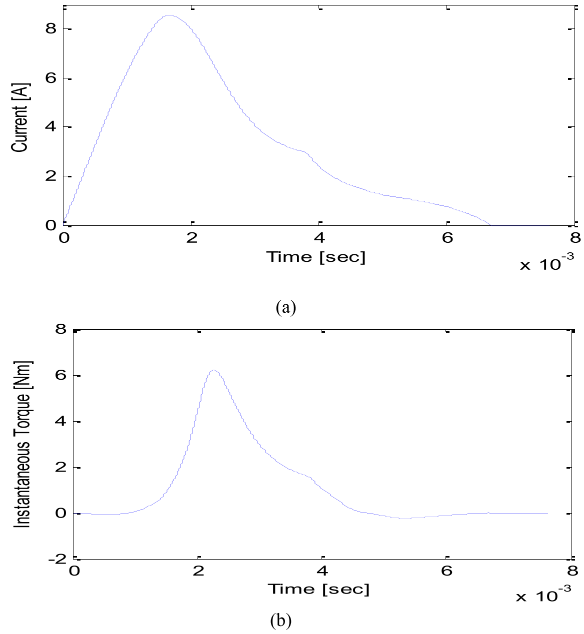


FIGURE 4. (a) Instantaneous phase current (b) Instantaneous torque.

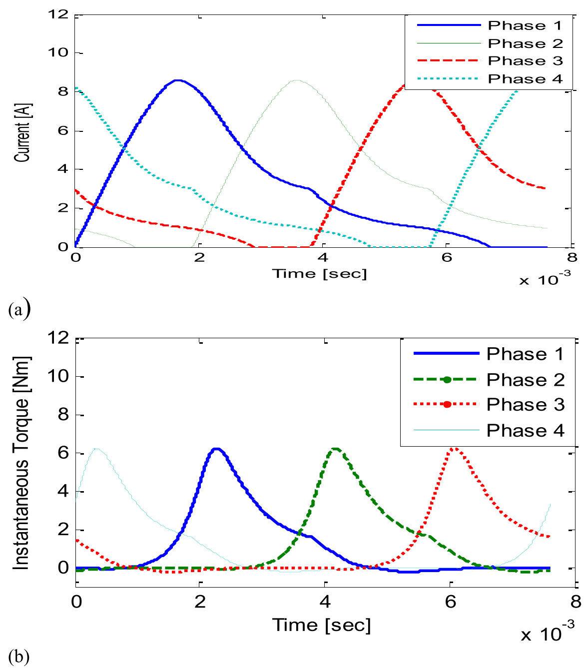


FIGURE 5. The steady-state performance of machine (a) Instantaneous phase current of machine (b) Instantaneous torque.

Other operating conditions are listed in Table 1.

The obtained results consisting of instantaneous phase current and instantaneous phase torque, under the single pulse mode of the machine operation, are shown in Fig.4 (a) and

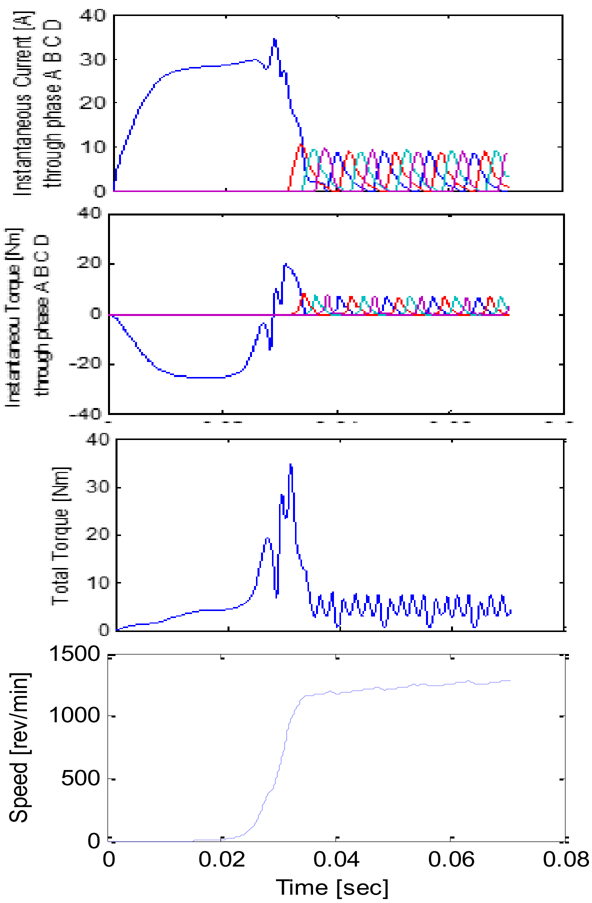


FIGURE 6. Dynamic performance of machine (From top to bottom) • Instantaneous phase current • Instantaneous torque • Total torque • Speed.

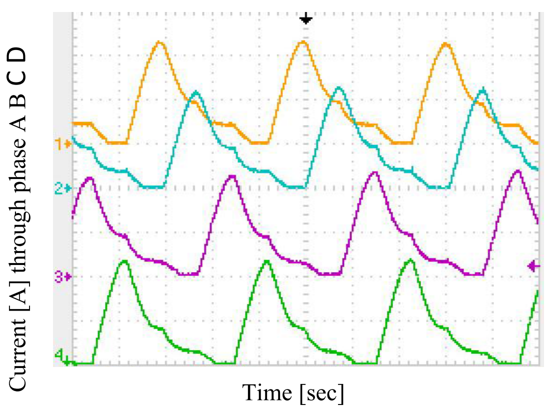


FIGURE 7. Experimental representation of phase current waveforms of a 4-phase machine, under an operating condition, listed in Table 1.

Fig.4 (b). For the comparison, another mathematical model, based on text coding in Matlab, is developed, under the same operating conditions, given in Table 1. The algorithm for the programming, is a self-explanatory, as given in Table 2 [28]. The additional steps are useful in the numerical computations.

Fig.5 is a representation of the phase current and torque waveforms under the steady state operating mode of the machine. Furthermore, the results produced from the dynamic operating mode of the machine are shown in Fig.6, under the same operating conditions and with an addition of total torque and speed waveforms.

Results of instantaneous phase current, instantaneous torque in a single pulse operating mode of the machine, are shown in Fig.4 (a) and Fig.4 (b). These waveforms are reproduced in steady state machine operation for four phases as shown in Fig. 5 (a) and Fig.5 (b). The steady-state representation is actually, the repetition of the single phase, shifted at 15 degrees between each phase to complete one cycle.

Whereas, for the representation of instantaneous phase current, instantaneous torque, total torque and speed waveforms, with more cycles in the dynamic state of the machine operation, are shown in Fig.6.

TABLE 2. Algorithm for the simulation in text code environment.

Steps	Description
Step1	Introduce input data as lookup tables $\Psi(\theta,i)$, $i(\theta,\Psi)$, $W'(\theta,i)$, $T(\theta,i)$ [$T(\theta,i)$ from eq.1, $W'(\theta,i)$ eq. 2] Obtain $i(\theta,\Psi)$ at constant rotor position for equally spaced values $\Psi(\theta,i)$
Step2	While flux (k) =>0 If rotor position θ(k)=< θ(off) Yes, supply $+V_s$ No, supply-V_s Numerically compute current $i(k)$, using lookup table $i(\theta,\Psi)$ Numerically compute torque by using $i(k)$ and $T(\theta,i)$ Numerically compute speed (ω) by using eq.12 End End
Step 3	Computation of current and torque for other phases by phase shift $\delta = \frac{2\pi}{N_r}$ where, N_r denotes the number of rotor poles Computation of average torque and total torque

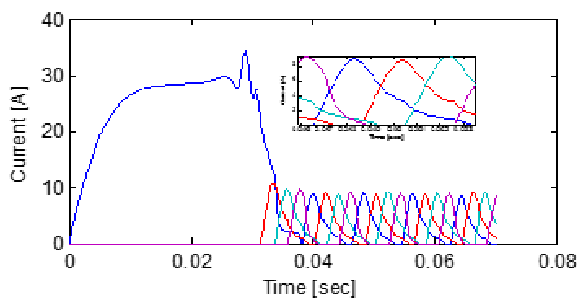


FIGURE 8. Phase current of 4-phase machine under dynamic mode.

IV. VALIDATION OF THE RESULTS

In order to validate the proposed model, the produced results are compared with the experimental results of instantaneous phase current (for one cycle of the machine operation) of a four-phase machine, shown in Fig.7. These results are experimentally obtained, when an existing SR machine with particulars, given in [27] was run under operating conditions, listed in Table 1.

The results obtained from a graphical environment, Simulink based model, shown in Fig.4 (a) and (b) are compared with Fig.5 and Fig.7, keeping one phase in consideration. Fig.6 is compared with experimentally obtained current waveforms shown in Fig.7. A zoom option within the window of Fig.8, in Matlab, was used for a convenience to see the trend.

From the current profile of the machine, the results produced from the proposed model sets a good agreement for the similar trend.

V. CONCLUSION

In this paper, a comprehensive review of the existing simulation models of switched reluctance machine is presented. Comparison of two mathematical models, based on different environments are presented. The produced results are compared and validated with those obtained from the experiments, under the same operating conditions for different performances of a switched reluctance machine. The key point of the proposed model is, an inclusion of three modes of the machine operation within one model, under the same instruction. Whereas, other simulation-based models, discussed above, including the text code based model, developed separately, uses all four data tables. Also, every time, these data tables are repeated and reproduced along with the numerical determination of the equations for the separate performance of the machine. Therefore, other presented models are complex and time taking. Moreover, the possible error can be produced and reaccumulated during the repetition of the code, and computational procedure. Furthermore, other models, including text code approach, are time-consuming due to the revisit and reconstruction of data tables.

This is the reason that proposed model is easy, simpler, and well-defined. It also takes less time in producing results under different performance.

ACKNOWLEDGEMENT

Thanks to Mehran University of Engineering and Technology, Jamshoro, and Higher Education Commission, Government of Pakistan for providing PhD funding. Thanks to Dr. J. Corda for his valuable guidance during PhD at the University of Leeds.

REFERENCES

[1] M. Miller, "Electronic control of switched relcutnce machine," in *Newness Power Engineering Series*. Oxford, U.K., 2001.

[2] M. A. Asghar, U. Yasir, and M. A. Uquali, "Calculation of converter losses for switched reluctance motor," in *Proc. Int. Conf. Elect. Mach. Syst.*, Aug. 2017, pp. 1–5.

[3] X. Yan, D. Xie, Y. Zhang, and C. Yu, "Dynamic performance prediction of switched reluctance motor using field-circuit-torque coupled model," in *Proc. IEEE Autom. Congr. WAC*, Sep./Oct. 2008, pp. 1–4.

[4] C. Hao, X. Wang, P. Nedjeljko, and S. Chao, "Nonlinear dynamic simulation model of switched reluctance linear machine," *Procedia Earth Planetary Sci.*, vol. 1, no. 1, pp. 1320–1324, 2009.

[5] M. Kowol, P. Mynarek, and D. Mrochen, "Construction of a dynamic model for a switched reluctance motors," in *Proc. 2nd Int. Students Conf. Electrodyn. Mechatronics (SCE)*, 2009, pp. 25–26.

[6] V. Kacenka, P. Rafajdus, P. Makys, V. Vavrus, and L. Szabó, "Static and dynamic fault analysis of switched reluctance motor," in *Proc. ELEKTRO*, 2012, pp. 206–211.

[7] X. Li, S. Hexu, G. Feng, D. Yan, and Z. Yi, "Dynamic modeling research on the SRD based on ansoft and simpoloer," in *Proc. 25th Chin. Control Decision Conf. (CCDC)*, 2013, pp. 5165–5167.

[8] M. M. Nezamabadi, E. Afjei, and H. Torkaman, "Design, dynamic electromagnetic analysis, FEM, and fabrication of a new switched-reluctance motor with hybrid motion," *IEEE Trans. Magn.*, vol. 52, no. 4, Apr. 2016, Art. no. 8201708.

[9] R. Krishnan, *Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications*. Boca Raton, FL, USA: CRC Press, 2001.

[10] P. P. Lakshmi and L. Ravisrinivas, "Modeling and simulation of switched reluctance motor double closed loop control system," *Int. J. Innov. Res. Develop.*, vol. 1, no. 8, pp. 546–562, 2012.

[11] K. Nakamura, K. Kimura, and O. Ichinokura, "Electric and magnetic simultaneous transient analysis method of switched reluctance motor for use on SPICE," in *Proc. 5th Int. Conf. Power Electron. Drive Syst. (PEDS)*, vol. 2. Nov. 2003, pp. 1614–1618.

[12] I. El-Samahy, M. I. Marei, and E. F. El-Saadany, "Dynamic simulation of a switched reluctance motor drive on EMTDC/PSCAD software," in *Proc. Power Eng. Soc. General Meeting*, 2005, pp. 2277–2284.

[13] G. Franceschini, S. Pirani, M. Rinaldi, and C. Tassoni, "SPICE-assisted simulation of controlled electric drives: An application to switched reluctance drives," *IEEE Trans. Ind. Appl.*, vol. IA-27, no. 6, pp. 1103–1110, Nov./Dec. 1991.

[14] O. Ichinokura, T. Onda, M. Kimura, T. Watanabe, T. Yanada, and H. J. Guo, "Analysis of dynamic characteristics of switched reluctance motor based on SPICE," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 2147–2149, Jul. 1998.

[15] S. Sadeghi, J. Milimonfared, M. Mirsalim, and M. Jalalifar, "Dynamic modeling and simulation of a switched reluctance motor in electric vehicles," in *Proc. 1st IEEE Conf. Ind. Electron. Appl.*, May 2006, pp. 1–6.

[16] D. Wen, L. Deliang, and C. Zhuping, "Dynamic model and simulation for a 6/4 switched reluctance machine system assisted by maxwell spice and simplorer," in *Proc. Int. Conf. Mechatronics Autom. (ICMA)*, 2007, pp. 1699–1704.

[17] D. H. Wang, X. H. Wang, C. L. Shao, and X. J. Chen, "Modeling and dynamic performance analysis of a high power density tubular linear switch reluctance generator for direct drive marine wave energy conversion," in *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices (ASEMD)*, Nov. 2015, pp. 528–529.

[18] A. A. Memon, I. Hussain, W. Shah, and M. S. Chandio, "Modeling of switched reluctance motor," *Sindh Univ. Res. J.-SURJ (Sci. Ser.)*, vol. 44, no. 4, pp. 571–574, 2012.

[19] S. Saidani and M. Ghariani, "Dynamic behavior of 12/8 switched reluctance motor," in *Proc. 16th Int. Conf. Sci. Techn. Autom. Control Comput. Eng. (STA)*, 2015, pp. 465–470.

[20] F. Soares and P. J. C. Branco, "Simulation of a 6/4 switched reluctance motor based on MATLAB/simulink environment," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 37, no. 3, pp. 989–1009, Jul. 2001.

[21] M. Heidarian and B. Ganji, "A dynamic simulation model based on finite element method for switched reluctance generator," in *Proc. Int. Symp. Power Electron., Electr. Drives, Autom., Motion (SPEEDAM)*, 2016, pp. 1427–1432.

[22] C. Labiod, M. Bahri, K. Srairi, B. Mahdad, M. T. Benchouia, and M. E. H. Benbouzid, "Static and dynamic analysis of non-linear magnetic characteristics in switched reluctance motors based on circuit-coupled time stepping finite element method," *Int. J. Syst. Assurance Eng. Manage.*, vol. 8, no. 1, pp. 47–55, 2017.

[23] M. Nagrial, J. Rizk, and W. Aljaism, "Dynamic simulation of switched reluctance motor using MATLAB and fuzzy logic," in *Proc. 14th Int. Middle East Power Syst. Conf. (MEPCON)*, 2010, pp. 819–824.

[24] K. N. Srinivas and R. Arumugam, "Dynamic characterization of switched reluctance motor by computer-aided design and electromagnetic transient simulation," *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1806–1812, May 2003.

[25] S. Y. Cao and K. J. Tseng, "Evaluation of neighboring phase coupling effects of switched reluctance motor with dynamic modeling approach," in *Proc. 3rd Int. Conf. Power Electron. Motion Control*, Aug. 2000, pp. 881–886.

[26] W. Ding and D. Liang, "Comparison of transient and steady-state performances analysis for a dual-channel switched reluctance machine operation under different modes," *IET Electr. Power Appl.*, vol. 4, no. 8, pp. 603–617, 2010.

[27] A. A. Memon and M. M. Shaikh, "Input data for mathematical modeling and numerical simulation of switched reluctance machines," *Data, Brief*, vol. 14, pp. 138–142, Oct. 2017.

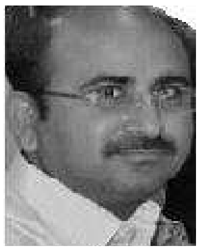
[28] A. A. Memon, "Prediction of compound losses in a switched reluctance machine and inverter," Ph.D. dissertation, School Electron. Elect. Eng., Univ. Leeds, Leeds, U.K., 2012.

ALI ASGHAR MEMON received the B.E. degree from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, and the M.E. degree in power system engineering from the Mehran University of Engineering and Technology, and the Ph.D. degree in electronic and electrical engineering from the University of Leeds, U.K. He is currently a Professor and the Head of the Electrical Machine and Drives Group of Electrical Engineering, Mehran University. He also holds other responsibilities in the same university. He is actively involved in switched reluctance machine and drive system, energy efficient machines, and energy management research. He is a member of the Senate, Departmental Management Review Committee, the Head of Electrical Machines and Drives Group, and a Focal Person for future planning and development of the department. He is also a member of the National Curriculum Revision Committee in electrical engineering for the Universities of Pakistan under the Higher Education Commission, Government of Pakistan.

SYED ASIF ALI SHAH received the bachelor's degree in electrical engineering and the M.E. degree in communication system and networks from IICT, MUET, Jamshoro, in 1993 and 2003, respectively, and the Ph.D. degree in stochastic modeling from the Vienna University of Technology, Austria, in 2010, which is one of the best and leading research universities in engineering and technology of the world, located in the center of Europe. He started his professional career by passing from public service commission examination in 1993. He is currently a Professor with the Department of Electrical Engineering and a member of professional organizations. He is also an approved Ph.D. Supervisor of the Higher Education Commission of Pakistan, an Industrial Coordinator, an IEEE-PES Advisor, a member of the National Curriculum Committee, a member of the Monitoring Team of the affiliated colleges of MUET and a Focal Person to monitor the smooth conduct of practical work and laboratories in the department. He has a vast experience of over 20 years in teaching and research and he traveled extensively throughout Europe. He has supervised and produced over 12 M.E. students and there are over 14 research journal publications, 13 international conference publications, and two international book chapters to his credit. He is extensively involved in research, such as sustainable energy, electrical power transmission and distribution systems, performance modeling of power networks, data networks, distributed generation (micro grids), smart grids and optimization of power generation systems, control engineering, and wireless sensor networks.

WAJIHA SHAH received the bachelor's degree in electronic engineering and the M.E. degree in telecommunication and control engineering from MUET, Jamshoro, in 1994 and 2004, respectively, and the Ph.D. degree in performance modeling of communication systems from the Vienna University of Technology, Austria, in 2010, which is one of the best and leading research universities in engineering and technology of the world, located in the center of Europe. She started her professional career in 1994. She is currently a Professor with the Department of Electronic Engineering and also a Chairperson of the Department of Electronic Engineering. She is also an approved Ph.D. Supervisor of the Higher Education Commission of Pakistan, an Industrial Coordinator, an IEEE-PES Advisor, a member of the National Curriculum Committee, a member of the Monitoring Team of the affiliated colleges of MUET, and a Focal Person to monitor the smooth conduct of practical work and laboratories in the department. She is extensively involved in the research field, including performance modeling of communication system, embedded. She has a vast experience of over 20 years in teaching and research and traveled extensively throughout Europe. She has supervised and produced over 12 M.E. students and there are over 15 research journal publications, 15 international conference publications, and two international book chapters at her credit. She is highly social, straightforward, hard worker, kind, and helping. She is a Lifetime Member of professional organizations, such as the Pakistan Engineering Council, the Mehran University Alumni Association, and the IEEE Robotic and Instrumentation Society.

MAZHAR HUSSAIN BALOCH received the B.E. degree from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, in 2008, the M.E. degree from the Department of Electrical Engineering, Mehran University of Engineering and Technology, in 2013, and the Ph.D. degree from Shanghai Jiao Tong University, China, in 2017, all in electrical power engineering. He is currently an Assistant Professor with the Mehran University of Engineering and Technology, Khairpur Mir Campus. To his credit, he has over 25 National/International research publications. His research interest includes nonlinear control theory and its application in power systems, induction machines, complex dynamic system and modeling and analysis, stability, and control wind power system, including power system protection.



GHULAM SARWAR KALOI received the B.E. degree in electrical power engineering from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, in 2008, and the M.E. degree in electrical power engineering from the Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan, in 2013, and the Ph.D. degree in electrical engineering from Shanghai Jiao Tong University, China, in 2017. He is currently an Assistant Professor with the Quaid-e-Awam University of Engineering Science and Technology. To his credit, he has over 25 national/international research publications. His research interest includes nonlinear control theory and its application in power systems stability and control, induction machines, complex dynamic system, and wind power system, including power system protection.

NAYYAR HUSSAIN MIRJAT received the bachelor's degree in electrical engineering and the M.E. degree in electrical power from Pakistan. He is currently pursuing the Ph.D. in the field of energy system engineering from the Mehran University of Engineering and Technology (MUET), Jamshoro, Pakistan. He joined as a Faculty Member with the Department of Electrical Engineering, MUET. He has extensive field experience of over ten years of working in power generation, distribution, and steel industry. His research interests include energy planning, energy model, renewable energy, and decision analysis.