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Artificial neural network vector controlled common high-side switch asymmetric converter fed switched reluctance motor drive

Ashok Kumar Kolluru, Malligunta Kiran Kumar
Department of Electrical and Electronics Engineering, KoneruLakshmaiah Education Foundation, Guntur, India

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ABSTRACT

The best alternative machine for synchronous and induction machine is switched reluctance machine for various applications. An artificial neural network (ANN) based vector controller is implemented for novel converter to drive switched reluctance motor (SRM) in this paper. To reduce the cost and simplified the controller an effective configuration of converter is proposed with only 4 pulse-withmodulation (PWM) based switches. The 6 pole stator and 4 pole rotor machine is considered in this paper to present results based on MATLAB. The ripples in torque are reduced by proposing vector controller by using novel configuration of converter. Generally SRM machines are having high ripples in torque, hence less number of switches will be feasible solution to drive the machine in order to reduce ripples. The proposed controller can also help to operate system with less ripples in torque since the controller having both torque and flux hysteresis controllers. The extensive results are presented on Simulink platform to validate the proposed method under both steady state as well as transient conditions.

Corresponding Author:

Malligunta Kiran Kumar
Department of Electrical and Electronics Engineering
KoneruLakshmaiah Education Foundation
Vaddeswaram, Guntur-522502, AP, India
Email: kiran.malligunta@gmail.com

1. INTRODUCTION

There is a switched reluctance motor (SRM) for an alternative to the widely used induction and synchronous machines in various applications. Since, it is having simple and low-cost structure, high reliability and better performance at high speeds/torque capabilities [1]-[4]. However, SRM is having some drawbacks due to its double-salient structure, including high torque ripple and acoustic noises. These can be eliminated by proper converter and its controller. The cost effective structure of converter and its vector controller is proposed in this paper to drive the SRM. The proposed configuration of converter having few number of switches comparing to conventional converter. Further for smooth speed operation of controller an artificial neural network (ANN) based speed controller is implemented for vector control. Many researchers are focusing on two areas to reduce the torque ripple those are an optimized structural design for SRMs, and a suitable control strategy [5]-[9].

Many researchers are proposed different types of controllers for SRM for smooth operation of speed controller. In [10], [12], the author pointed out a dip in torque between two subsequent phases dictates the existence of torque ripples. In [13]-[15], the authors where proposed model based dead-beat flux controller. The dead-beat controller proposed in these papers where achieves constant switching frequency and lower sampling rate while maintaining the similar dynamic response as hysteresis controller [16]-[20]. However, the performance of dead-beat controller relies on accurate model and a large gain which may degrade the performance of the dead-beat controller. In [21]-[24], the authors are introduced lyapunov function based controller to solve the mismatch issue in the model. The tracking error is bounded by the parameters of the controller. A sliding mode current controller in proposed in [25]. Parameters of sliding mode controller are carefully selected according to the model mismatch by proposed method in [26]-[28]. These control methods need to store several look-up tables, which increase the storage and computational burden of the digital controller. In order to overcome these problems, a new configuration of converter as well as its controller based on vector controller is proposed in this paper.

2. SYSTEM DESCRIPTION

The proposed system in this paper is shown in Figure 1. The system consists of new configuration of converter which is having only 4 switches, SRM and proper controller of converter. In this paper 6/4 pole SRM is selected. Generally, reluctance machine is consists of variable reluctance magnetic circuits in both rotor and stator, or, it is a double salient machine. The modeling of motor is achieved by [10]-[14].

$$V = \frac{(\lambda_a - \lambda_u)i}{\lambda_u} = \frac{(L_a^s - L_u)i}{t} \tag{1}$$

Where, $t = \frac{\beta_s}{\omega_r}$

$$\sigma_s = \frac{L_a^s}{L_a} \text{ and } \sigma_u = \frac{L_u^s}{L_u}$$

$$V = \frac{\omega_r}{\beta_s} L_a^s i(1 - \frac{1}{\sigma_s \sigma_u}) \tag{2}$$

$$L_a^s i = \phi T_{ph} = B \times A_{sp} \times T_{ph} = B \times D \times L \times \beta_s \times T_{ph} / 2 \tag{3}$$

$$A_s = \frac{2T_{ph} im}{\pi D} \tag{4}$$

$$P_d = K_a K_d V_{in} \tag{5}$$

$$k_d = \frac{\theta_i \, qP_r}{360} \tag{6}$$

$$P_d = k_d k_e \left(\frac{\pi^2}{120}\right)\left(1 - \frac{1}{\sigma_s \sigma_u}\right) BA_s D^2 LN_r \tag{7}$$

$$T = k_d k_e k_3 k_2 (BA_s) D^2 L \tag{8}$$

where, $k_2 = 1 - \frac{1}{\sigma_s \sigma_u}$, $k_3 = \frac{\pi}{4}$, per phase aligned inductance and unaligned inductances are denoted as L_a^s and L_u, the required time of rotor to turn from aligned to unaligned is represented with 't'. The arc of stator pole is expressed as β_s and the aligned unsaturated inductance is L_a^u. The flux which is aligned is represented with parameter 'ϕ' and stator pole area is A_{sp}. The bore diameter and length of stator pole inductance is represented as D and L respectively. The flux density of stator pole is considered as 'B'. The number of turns per pole is T_{ph}. The parameter *m* represents the number of phases conducting simultaneously. For 6/4 pole motor, such as the example being considered only one phase conducts at a time. The duty cycle and current conducting per phase are represents by 'k_d' and θ_i respectively. P_s and P_r are number of poles for stator and rotor respectively.

The proposed converter is also depicted in Figure 1. The proposed converter consists of only one DC source, 4 pulse-with modulation (PWM) based switched and 4 diodes only. This configuration used to produce power in three phases of SRM. Hence, it is very low cost and simple compared to existing converters which are used to drive a SRM. Due to reduction in switched in proposed converter, the converter leads to economical benefits compare to conventional converters.

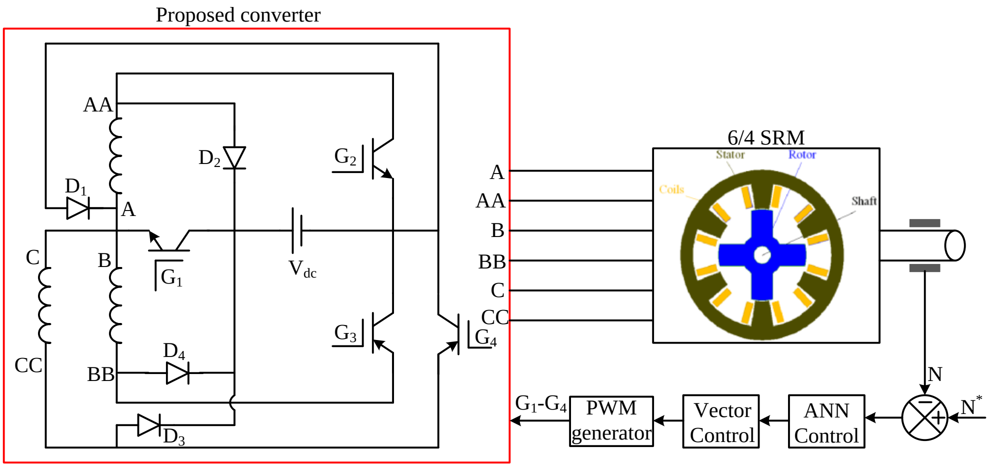

Figure 1. Block diagram for speed control of SRM using proposed converter and vector control

3. SPEED CONTROL OF SRM

The torque hysteresis and flux hysteresis calculations are very important to develop a vector control for any AC motor. Before getting reference electromagnetic torque by motor, the ANN is used to get speed control. The motor speed is compared with reference motor speed as shown in Figure 2. The vector controller is implemented with the help of [5], [15]. The torque hysteresis will generate signal followed by comparing reference torque produced by ANN and electromagnetic generated torque by SRM. Similarly, the flux is estimated by using three phase voltage and current which is depicted in Figure 2. The required pulses are generated by using these two hysteresis signals by using PWM generator.

The modeling of SRM is attempted by synchronous reference frame with the help direct-quadrature (DQ) reference frame of three phase voltage and currents of SRM as shown in (9) and (10):

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos 2\theta & \cos(2\theta - 2\pi/3) & \cos(2\theta + 2\pi/3) \\ -\sin 2\theta & -\sin(2\theta - 2\pi/3) & -\sin(2\theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + \begin{bmatrix} L_{dc} + \frac{L_{ac}}{2}\cos 6\theta & -\frac{L_{ac}}{2}\sin 6\theta & L_{ac}/\sqrt{2} \\ -\frac{L_{ac}}{2}\sin 6\theta & L_{dc} + \frac{L_{ac}}{2}\cos 6\theta & 0 \\ L_{ac}/\sqrt{2} & 0 & L_{dc} \end{bmatrix} p \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$
$$2\omega_r \begin{bmatrix} -L_{ac}\sin 6\theta & -L_{dc} - L_{ac}\cos 6\theta & 0 \\ L_{dc-L_{ac}}\cos 6\theta & L_{ac}\sin 6\theta & L_{ac}/\sqrt{2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{10}$$

The vector control can able to achieve the torque-current linearization when the zero-phase current is controlled at constant value. The generated torque is proportional to the q-axis current.

$$T_e = k_t i_q \tag{11}$$

Where, $k_t = \sqrt{2} P L_{ac} i_d$

The vector controller is designed based on D-Q reference components. The pulse generator is used to generate four pulses for four switches respectively. This modeling of SRM is helps to design the controllers of motor for particular applications. The consumed power by SRM is depends on torque and speed of the SRM. The reference flux is considered as 0.4 to 0.6 per unit to avoid both flux weakening and saturation mode of SRM in Figure 2.

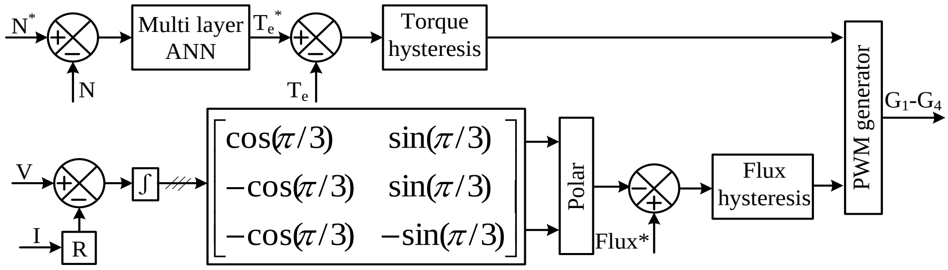

Figure 2. ANN based vector control of SRM

4. RESULTS AND DISCUSSION

The proposed system is implemented and tested under different cases on MATLAB platform. Considered 6/4 pole SRM and presented the results for following case studies.

4.1. Case-1: Ripples on electromagnetic torque

In this case results are presented for ripples in torque. The proposed model and control is limiting the ripples in torque as depicted in Figure 3. The ANN controller plays a vital role in minimizing ripples in torque by generating smooth reference torque of SRM. Hence, the vector controller helps to track the reference torque by generating proper electromagnetic torque of SRM which is also shown in Figure 3. The load torque with value of 25.0 N.m is applied on SRM. In this situation, the ANN is generated reference torque signal by comparing reference and actual speed of SRM (i.e., shown in Figure 2). The load torque, reference torque produced by ANN and torque generated by SRM are depicted in same Figure 2. From Figure 2, it is observed that the ripples content in electromagnetic torque generated by SRM is under limit and allowed. The reference load torque is set to be at 25 and the generated torque is varying between 24.0 to 26.0. Hence the percentage of change in torque is + or – 4 percentage which is allowable ripple in torque. This is achieved by the proposed controller with novel configuration of converter which is shown in Figure 1.

In switched reluctance motor, the basic control issue is production of ripple free torque. Because of the presence of ripple in the torque leads to production of undesirable noise and undesirable vibration during the operation of SRM motor. The proposed controller is helps to reduce the ripples in generated electromagnetic torque as compared with Ghani *et al.* [16]. The percentage of ripples presented in torque of SRM by proposed controller is 8%.

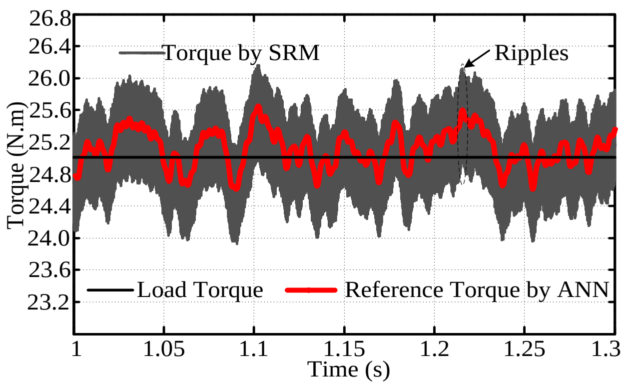

Figure 3. Responses of torque

4.2. Case-2: Response under change in speed

To test the performance of controller, the reference speed is changed from 1000 rpm to 1500 rpm at t=3.0 sec. in this situation, the ANN try to change to reference torque. In order to increasing the speed of motor, the ANN will increase the reference torque under transient condition, since the speed can be increased by increasing electromagnetic torque generated by SRM. The response of speed and electromagnetic torque of SRM is depicted in Figure 4 and Figure 5 respectively. From Figure 4, it is concluded that the vector controller working satisfactory to stabilize the speed of SRM according to reference speed. Similarly, the electromagnetic torque is increased momentarily and gets stabilized to normal value which is equals to load torque once speed get stabilized at its new reference signal which is depicted in Figure 5.

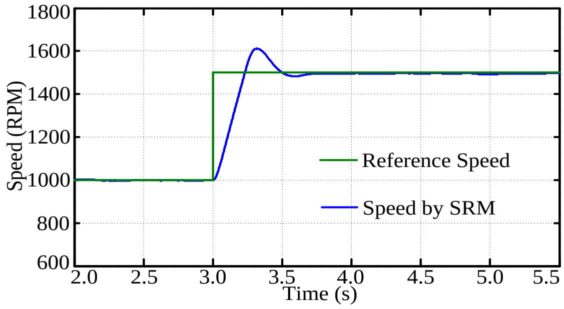

Figure 4. Speed response of SRM under changing reference speed

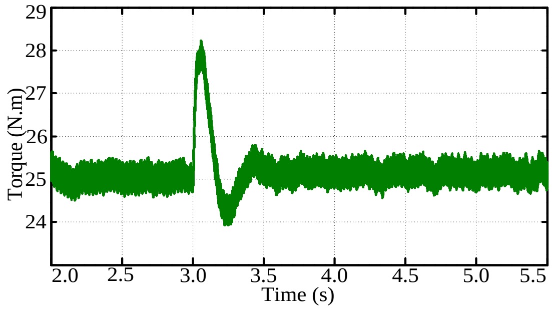

Figure 5. Response of electromagnetic torque generated by SRM under changing reference speed

4.3. Case-3: Response under change in load torque

The proposed system is tested under change in load torque in this case. The load torque is changed from 25.0 to 27.5 N.m at t=2.0 sec. due to increasing load torque, generally speed of SRM will reduce. In order to increase or stabilize the speed of SRM, the ANN increases its output value such as reference electromagnetic torque. Hence, the controller will generate required pulses to converter for increasing electromagnetic torque of motor. The response of electromagnetic torque and speed of SRM is depicted in Figure 6 and Figure 7 respectively. The speed of SRM will momentarily decrease for small time period during the electromagnetic torque reaches to reference load torque. These phenomena are also clearly shows in the Figure 6 and Figure 7. Moreover, considered only change in load torque and not any changes in speed of SRM, hence, the speed reaches its previous value.

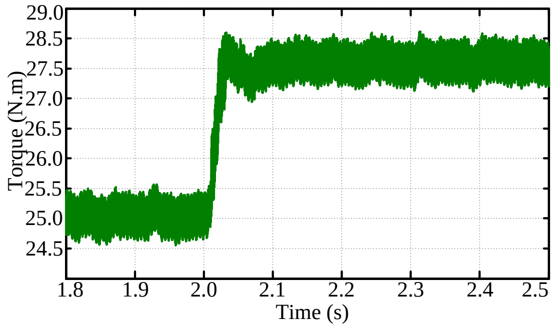

Figure 6. Response of electromagnetic torque under change in load torque

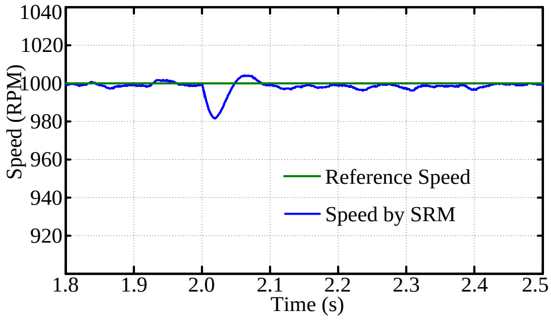

Figure 7. Speed response of SRM under change in load torque

5. CONCLUSIONS

Artificial neural network based vector controller for switched reluctance motor driven by proposed configuration of converter is presented in this paper. The speed controller is achieved under changes in load torques which are presented in results section. The ripples in the torque are minimized by proposed method. The proposed converter having less number of switches compare to conventional converters. Hence, this kind of system is a cost effective solution to drive the SRM. The extension results based on Simulink are presented in this paper to validate the proposed method.

REFERENCES

[1] F. Peng and A. Emadi, "A digital PWM current controller for switched reluctance motor drives," *2014 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2014, pp. 1-6, doi: 10.1109/ITEC.2014.6861765.

[2] E. Bostanci, M. Moallem, A. Parsapour, and B. Fahimi, "Opportunities and Challenges of Switched Reluctance Motor Drives for Electric Propulsion: A Comparative Study," in *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 58-75, March 2017, doi: 10.1109/TTE.2017.2649883.

[3] Z. Yang, F. Shang, I. P. Brown, and M. Krishnamurthy, "Comparative Study of Interior Permanent Magnet, Induction, and Switched Reluctance Motor Drives for EV and HEV Applications," in *IEEE Transactions on Transportation Electrification*, vol. 1, no. 3, pp. 245-254, Oct. 2015, doi: 10.1109/TTE.2015.2470092.

[4] K. Diao, X. Sun, G. Lei, G. Bramerdorfer, Y. Guo, and J. Zhu, "System-Level Robust Design Optimization of a Switched Reluctance Motor Drive System Considering Multiple Driving Cycles," in *IEEE Transactions on Energy Conversion*, vol. 36, no. 1, pp. 348-357, March 2021, doi: 10.1109/TEC.2020.3009408.

[5] M. Ma, Z. Wang, Q. Yang, S. Yang, and X. Zhang, "Vector control strategy of a T-type three-level converter driving a switched reluctance motor," in *Chinese Journal of Electrical Engineering*, vol. 5, no. 4, pp. 15-21, Dec. 2019, doi: 10.23919/CJEE.2019.000023.

[6] J. S. Turner, "New directions in communications (or which way to the information age?)," in *IEEE Communications Magazine*, vol. 40, no. 5, pp. 50-57, May 2002, doi: 10.1109/MCOM.2002.1006972.

[7] N. Yan, X. Cao, and Z. Deng, "Direct Torque Control for Switched Reluctance Motor to Obtain High Torque–Ampere Ratio," *in IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5144-5152, July 2019, doi: 10.1109/TIE.2018.2870355.

[8] C. R. Neuhaus, N. H. Fuengwarodsakul, and R. W. De Doncker, "Predictive PWM-based direct instantaneous torque control of switched reluctance drives," *2006 37th IEEE Power Electronics Specialists Conference*, 2006, pp. 1-7, doi: 10.1109/pesc.2006.1712264.

[9] R. Mikail, I. Husain, Y. Sozer, M. S. Islam and T. Sebastian, "A Fixed Switching Frequency Predictive Current Control Method for Switched Reluctance Machines," in *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3717-3726, Nov.-Dec. 2014, doi: 10.1109/TIA.2014.2322144.

[10] F. Peng and A. Emadi, "A digital PWM current controller for switched reluctance motor drives," *2014 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2014, pp. 1-6, doi: 10.1109/ITEC.2014.6861765.

[11] S. K. Sahoo, S. Dasgupta, S. K. Panda, and J. Xu, "A Lyapunov Function-Based Robust Direct Torque Controller for a Switched Reluctance Motor Drive System," in *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 555-564, Feb. 2012, doi: 10.1109/TPEL.2011.2132740.

[12] J. Ye, P. Malysz and A. Emadi, "A Fixed-Switching-Frequency Integral Sliding Mode Current Controller for Switched Reluctance Motor Drives," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 2, pp. 381-394, June 2015, doi: 10.1109/JESTPE.2014.2357717.

[13] G. Vijay Kumar and J. Somlal, "Design Modelling and Simulation of 6/4 Switched Reluctance Motor," *International Journal of Advanced Scientific Research and Technology*, vol. 2, no. 2, pp. 425-432, 2012.

[14] F. Yi and W. Cai, "Modeling, Control, and Seamless Transition of the Bidirectional Battery-Driven Switched Reluctance Motor/Generator Drive Based on Integrated Multiport Power Converter for Electric Vehicle Applications," in *IEEE Transactions on Power Electronics*, vol. 31, no. 10, pp. 7099-7111, Oct. 2016, doi: 10.1109/TPEL.2015.2510286.

[15] N. Nakao and K. Akatsu, "Vector control specialized for switched reluctance motor drives," *2014 International Conference on Electrical Machines (ICEM)*, 2014, pp. 943-949, doi: 10.1109/ICELMACH.2014.6960294.

[16] M. R. A. Ghani, N. Farah, and M. R. Tamjis, "Field oriented control of 6/4 SRM for torque ripple minimiaztion," *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 4418-4424, doi: 10.1109/ICEEOT.2016.7755554.

[17] B. Y. Reddy, J. S. rao, T. S. Kumar, and A. Nagarjuna, "Fifteen level cross H bridge multilevel inverter fed PMSM," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 11, pp. 1194-1198, 2019.

[18] M. P. Kumar, P. Maheeth, M. S. K. Reddy, and S. R. Teja, "A renewable energy fed non-isolated inverse output voltage DC-DC converter with broad range of conversion," *International Journal of Engineering and Advanced Technology*, vol. 8, no. 5S3, pp. 160-163, 2019.

[19] B. V. Rajanna and M. K. Kumar, "Comparison of one and two time constant models for lithium ion battery," *International Journal of Electrical and Computer Engineering,* vol. 10, no. 1, pp. 670-680, 2020, doi: 10.11591/ijece.v10i1.pp670-680.

[20] B. V. Rajanna and M. K. Kumar, "Dynamic model development for lead acid storage battery, "*Indonesian Journal of Electrical Engineering and Computer Science,* vol. 15, no. 2, pp. 609-619, 2019, doi: 10.11591/ijeecs.v15.i2.pp609-619.

[21] V. Krishna Chaitanya, "Analysis of closed loop control of cascaded three phase grid tied inverter using fuzzy logic controller," *International Journal of Advanced Trends in Computer Science and Engineering*, vol. 8, no. 4, pp. 1123-1127, 2019, doi: 10.30534/ijatcse/2019/19842019.

[22] K. K. Deepika, J. V. Kumar, and G. K. rao, "Time-domain simulations of single-phase enhanced PLL for power converters under distorted grid conditions," *International Journal of Recent Technology and Engineering*, vol. 8, no. 2, pp. 3053-3057, 2019.

[23] B. V. Rajanna and M. K. Kumar, "Chopper-Based Control Circuit for BESS Integration in Solar PV Grids," *Energies*, vol. 14, no. 6, pp. 1-17, 2021, doi: 10.3390/en14061530.

[24] B. V. Rajanna and M. K. Kumar, "Comparison Study of Lead –Acid and Lithium-Ion Batteries for Solar Photovoltaic Applications," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 2, pp. 1069-1082, 2021, doi: 10.11591/ijpeds.v12.i2.pp1069-1082.

[25] N. N. Reddy, J. Somla, and A. Srujana, "Tree structured multi-level control system design based on MPC-EKF for power quality enhancement with selective harmonic elimination," *International Journal of Recent Technology and Engineering*, vol. 8, no. 2S8, pp. 1158-1163, 2019.

[26] Srinivas Pratapgiri, "Effect of Switching Frequency in DTC Based Switched Reluctance Motor Drive," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 12, no. 12, pp. 8085-8091, 2014, doi: 10.11591/telkomnika.v12i12.6718.

[27] N. Mekala, C. Minuraj, and S. M. R. Balaji, "Vibration and Noise Analysis of 4Φ Switched Reluctance Motor Drive," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 14, no. 3, pp. 410-419, 2015, doi: 10.11591/telkomnika.v14i3.7965.

[28] G. Joshi and A. J. P. Pius, "ANFIS controller for vector control of three phase induction motor," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no.3, pp. 1177-1185, 2010, doi: 10.11591/ijeecs.v19.i3.pp1177-1185.

BIOGRAPHIES OF AUTHORS

Kolluru Ashok Kumar received B. Tech Degree in Electrical and Electronics Engineering from Vignan's Engineering College, JNTU, Hyderabad, India, in 2008, M.Tech. Degree in Energy Systems from JNTU College of Engineering anantapur, JNTUA University, Anantapur, India, in 2010 and pursuing Ph. D in Electrical Engineering at KoneruLakshmaiah Education Foundation, Guntur, India. His research interest includes Switched Reluctance Machines.

Malligunta Kiran Kumar received B.Tech Degree in Electrical and Electronics Engineering from Gokula Krishna College of Engineering and Technology, JNTU, Hyderabad, India, in 2007, M.E. Degree in Power Electronics and Drives from SreeSastha Institute of Engineering and Technology, Anna University, Chennai, India, in 2010 and Ph.D in Electrical Engineering at KoneruLakshmaiah Education Foundation, Guntur, India, in 2016. His research interest includes Switched Reluctance Machines, Power Electronics and Control Systems.