Improved Electrical Vehicle Regenerative Braking with a Bidirectional Converter

Nilesh Thorat[1], Gopal Chaudhari[2]

[1]Y. T. I. E.T, Department of Electrical Electronic Engineering, Bhivpuri Road, Karjat
Email: *nileshthorat1686[at]gmail.com*

[2]Department of Electrical Electronic Engineering, Yadavrao Tasagaonkar Institute of Engineering and Technology Chandhai, Karjat
Email: *gsc88[at]rediffmail.com*

Abstract: ***Due to environmental concerns and oil supply instability, electric vehicles are becoming more popular. Regenerative braking increases EV range. This article uses a non-isolated bidirectional converter for electric car regenerative breaking. Motoring uses battery power from the converter. The converter charges the battery with back emf during regenerative braking. Battery storage works. Thus, the battery recovers and reuses a lot of braking energy. Regenerative braking helps batteries. Thus, driving range increases. MATLAB/Simulink simulates the system. A prototype can be used to test simulation findings. This study presents the outcomes of simulation.***

Keywords: Bidirectional Converter, H-bridge (class E-chopper), Regenerative Braking, Soft starting

1. Introduction

The progressive growth in energy consumption has resulted in an increase in fuel burning, which has a negative impact on the environment. Since one unit of energy conserved at the consumption level decreases energy demand by 3 to 4 times, efficient energy usage and preservation are necessary. Furthermore, by strategically utilizing energy, such conservation could be accomplished with less than one-fifth the cost of new capacity production. Energy efficiency can significantly help us fulfill the energy requirements while still reducing the petroleum use.

In electric vehicles, the regular braking systems convert kinetic energy into heat; mainly in the form of friction this wastes a significant amount of energy. Regenerative braking is an energy-recovery method. By converting kinetic energy into a new form, this energy slows down an object or vehicle. Regular braking systems, on the other hand, lose kinetic energy by converting it to heat through friction in the brake linings. Thus, regenerative braking of an electric vehicle implemented with a bidirectional converter can reduce the energy loss and also improve the overall efficiency of the system.

By using a bidirectional DC-DC converter, it is possible to enhance the output voltage of the electrical storage systems to a higher level and hence decreasing the current output. It also enables reverse power flow during regenerative braking, enhancing efficiency. Because of these features, the DC-DC converter is a better alternative for power transfer in electric vehicles, saving the total cost, size, and weight of the system.

Regenerative braking is implemented by operating an induction motor in negative slip region. The method is efficient however it requires complex control algorithms [2]. The design and implementation of a converter with full bridge topology is presented. It allows the regenerative braking in DC motor. This converter presents three operation modes namely, uncontrolled bridge rectifier, boost converter and voltage source inverter.
The main purpose of the converter is transferring the maximum energy from the DC machine to the grid improving the efficiency of the complete system [4]. In a brushless DC (BLDC) motor drive system (used for light electric vehicle propulsion) is modeled by considering non-linear effects. Analytic calculations and simulation results were presented with regenerative braking applied. This study uses BLDC motor that is most favorable in case of electric vehicle, but the amount of energy saved in this process is very less [3].

The system uses an IGBT Buck-Boost converter that is connected to the ultra-capacitor bank at the boost side, and to the main battery at the buck side. This study gives more on the regenerative braking during shorter period that is less than 1 or 2 seconds [5]. The study describes the methodology to use the boost converter and microcontroller to make the output voltage constant. This is helpful in the regenerative braking but it uses expensive and fast microcontroller that increases the cost. From the above, it can be concluded that the complexity of the system and control algorithm depends on the, type of motor selected, inclusion of additional energy storage device, mode of operation etc.

The motivation behind this work is to develop simple and cost-effective system toe) maintain constant voltage across the terminals of the battery and ii) improve the amount of energy saving [6]. A novel methodology utilizing regenerative braking is described. The model comprising of DC machine, feedback-based boost converter and micro-controller is proposed. This work focuses on implementing an efficient, cost effective and simple boost converter for maintaining constant output voltage across the battery terminals [7]. A non-isolated bidirectional DC-DC Converter has been proposed in this paper for charging and discharging the battery bank through single circuit in applications of Uninterruptible Power Supplies (UPS) and the hybrid electric vehicles [8]. This paper refers to an effective model using MATLAB Simulink for Regenerative Braking of a BLDC motor for an Electric Vehicle. In this method the inverter which is used to drive the motor, alone is used.

To attain smooth braking Fuzzy logic controller is used for braking force distribution and PI controller is for controlling the braking current [11]. A review of the bidirectional DC-DC converter (BDC) based on control methodology and switching techniques is presented. The focus of the research is on reducing converter size, weight, cost and losses [14]. The paper analyses two methods of regenerative braking, which become the object of many types of research nowadays, using bidirectional voltage-source inverter. Characteristics of each method and its implementation are presented [15].

2. Specification & design

In system description, a brief introduction about the regenerative braking by using bidirectional converter is given with the literature review. The motivation and objectives are also discussed. This chapter comprises a detailed description of the system with help of block diagram.

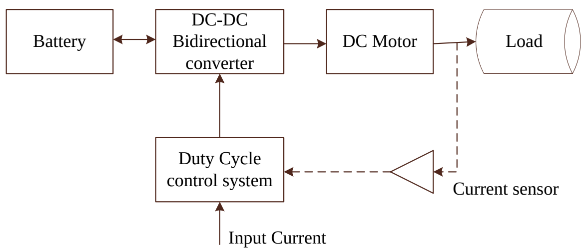

Figure 1: Block diagram of System

Figure 1 shows the block diagram of system. This system needs a rechargeable battery. Rechargeable batteries store energy via reversible chemical process that permits charge to be stored after the battery has been discharged. The entire power requirement means that we need a robust, portable and an efficient source of power.

There are a couple of factors while choosing the type of battery. 12-volt battery can be of many types, sizes, and materials. Depending on their manufacture, batteries come in a variety of shapes and sizes. Lead-Acid, Nickel-Cadmium (NiCad), Nickel-Metal hydride (NiMH), Lithium-Ion (Li-ion), Lithium-Ion polymer (LiPo), and rechargeable alkaline batteries are all common types of rechargeable batteries.

3. Implementation

3.1 Design of System

This circuit comprises of Battery, converter circuit with separately excited DC motor connected in H- Bridge manner. The Gate pulse is given externally from a separate control system designed to control the ON-OFF condition of Switches and monitoring the discharge rate of battery. The discharge rate at various duty cycles like 90 %, 70%, and 50% for the different load conditions is compared.

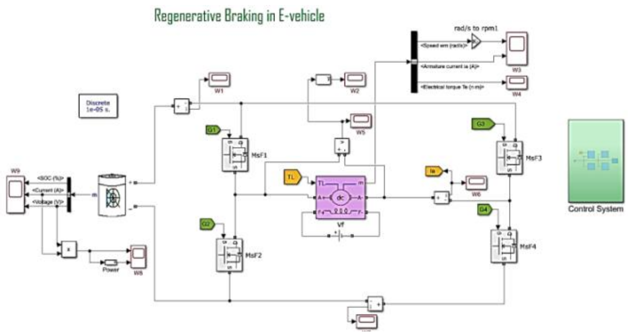

Figure 2: MATLAB System Model

At all this conditions energy delivered to the motor i.e., load from battery is analyzed and the energy required for the motoring is calculated. If motoring action performed continuously the battery will discharge to lower threshold (V_{min}) value and requires recharging.

If motoring is followed by regenerative braking, energy is used for charging the battery partially. This is the aim to extend the time of recharging of the battery.

3.2 Control System

This is the control system designed for controlling the switches by activating their respective pulse ssignal. For giving that signal we have used the pulse generator with 10 KHz (cycle time period 0.1msec) switching frequency and trying to calculate discharge rate of battery by changing the speed at different load conditions.

Each MOSFET and load torque control subsystem has its own subsystem. All MOSFETs are function of Clock while, MOSFET 1 is function of both clock and Armature current (I_a). By sensing armature current respective duty ratio is given to MOSFET 1 to soft-starting of motor. The duty ratio output of the function block is sent to the pulse generator, and the respective duty ratio pulse generated by the pulse generator is given to the gate of the MOSFETs. Internally, the pulse generator is designed using PWM methods, using a square wave as reference signal.

This simulation is used for:

1) Different duty cycles for different operating condition of motor at same and different load conditions.
2) For continuously operated in motoring mode, the discharge rate of battery is checked.
3) Energy supplied from battery to load & to find its rate of discharge.
4) At period of regenerative braking rate of charge of battery is checked.
5) By using regenerative mode, part of energy during regenerative braking is fed back to battery to reduce its recharging time.

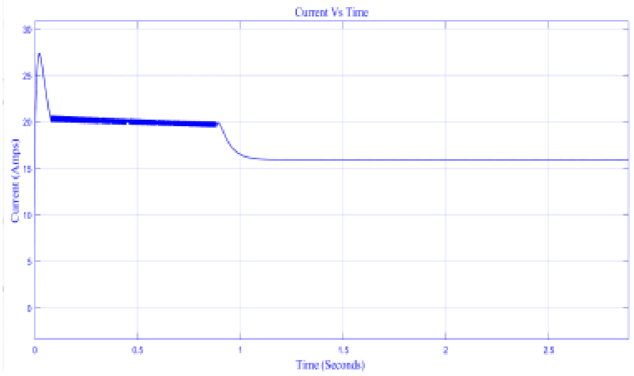

Figure 3 MOSFET 1 control system

Table 1: Motor specifications

Loading	Starting Current	steady state current
Full load	75 A	16.56 A
Half-load	73 A	8.6 A
Loading	Starting Current	steady state current
Full load	27 A	16.56 A
Half-load	27 A	8.6 A

Figure 3 shows the control system designed to reduce starting current, though it increases the time required by motor to attain its rated speed (pickup time) by 0.7 sec. Implying this starting current has been reduced by 64%.

3.3 Calculations

- Calculation at rated condition:

$$I_{FL} = \frac{InputPower(W)}{RatedVoltage(V)} \quad (4)$$

$$I_{FL} = \frac{5 \times 735.5}{240}$$

I_{FL} = *15.32 Amp*

$$E_b = V - I_a R_a \quad (5)$$

= 240-15.32 × 2.58 = 200. 47 V

$$P_{in} = V \times I_a \quad (6)$$

= 240 x 15. 32
= 3677 Watt

$$P_{out} = E_b \times I_a \quad (7)$$

= 200.47 × 15.32
= 3071 Watt

$$P_{out} = T_e \times \omega \quad (8)$$

$$\omega = \frac{2\Pi N}{60}$$

$\omega = \frac{2\Pi 0 \times 1750}{60}$ = 183.25 rad/sec

$$T_e = P_{out} / \omega \quad (9)$$

= 3071 × 183.25
T_e*= 16.75 N-m…. (Full load torque)*

- Calculation for duty cycle of MOSFET 1

In matlab/simulink models, the switching loss is absent (ideal). Reverse Fall Time (*tRH*) & Forward Rise Time (*tFH*) are ideally zero. So, considered 90 % duty cycle of DC-DC for motor operation on practical basis

- Calculation for Battery voltage

$$V_s = V_{rated}/0.9$$

$$V_s = 240/0.9$$

= 266.67 ≅ 270 V

To obtain rated voltage at motor terminal the battery voltage required is 270V.

- MOSFET 2 duty ratio Consideration :

Table 2: Shows results are taken at different duty ratio of MOSFET 2.

Duty Ratio [Ton]	Energy recovered	Braking Current
40	195 J	17 A
50	258 J	25 A
60	292 J	33 A
70	323 J	41 A
80	218 J	50 A
90	142 J	57 A

From Table2 result table, itis concluded that maximum energy is recovered at 70% duty ratio.So, for MOSFET 2 duty cycle applied is 70%. when the duty ratio is increased braking current increases which leads to increased braking torque.

4. Results & Evaluation

The earlier discussed design of the system is implemented. After the implementation the following results and evaluation is done as discussed in this chapter.

Two cases are implemented; they are as follows:
Case 1: Motor Operated with Full Load Condition with

- 2 sec motoring operation followed by braking
- 4 sec motoring operation followed by braking

Case 1: Motor Operated with Full Load Condition

Results Calculated for 15.69 N-m full load at 16.5 Amp, speed for full load is 1936 rpm for analysis purpose and calculations done for motoring operation without regenerative braking and with regenerative braking.

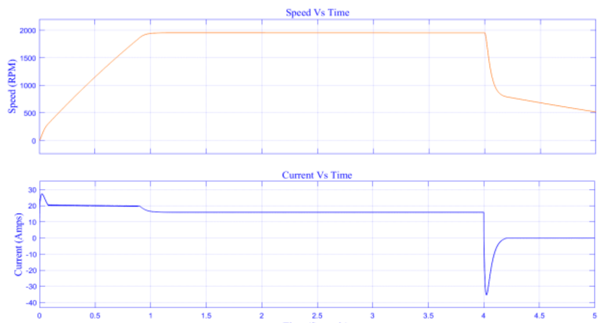

Figure 4: Speed & Current waveforms at full load with 0.9 duty ratio

Energy in rotating mass = $\frac{1}{2} j\omega^2$= $\frac{1}{2} \times 0.02215 \times$ *(202.73)2*= 455.20 J

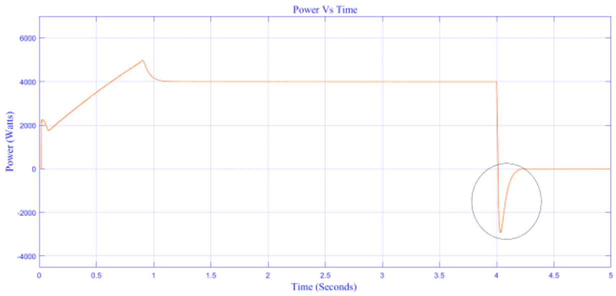

Figure 5: Power waveform at full load 0.9 duty ratio

Energy recovered by braking = 183 J
Percentage energy Recovered of rotating mass = 39.49 %
Energy required at starting = 2651 J
Energy required at starting + Motoring= 7325 J
Percentage energy Recovered of Starting = 6.88 %

The continuous motoring time is used as 2 sec and 4 sec before braking.

1) Performing **2 sec motoring operation** following calculation are carried out,

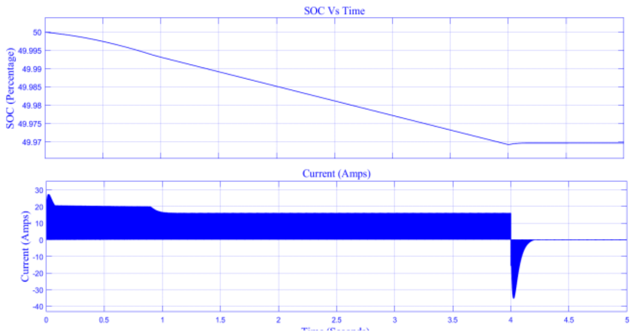

Figure 6: SOC & Current waveforms at source side at full load 0.9 duty ratio

Figure 6 shows SOC characteristics of battery. By finding slop of SOC during motoring and braking rate of discharge and charge are calculated respectively.

Rate of Discharge= 8.2×10^{-3} %/sec
= $100/(8.2 \times 10^{-3})$
= 12195 sec

Time required to full discharge without regenerative braking= 3.38 Hrs.

Rate of charge during braking = 3×10^{-3} % / sec

Total Rate of charge during braking for 0.25 sec
= $0.25 \times 3 \times 10^{-3}$ % / sec
= 0.75×10^{-3} %

No of Cycles required for 100% Discharge = $100/(2 \times 8.2 \times 10^{-3})$= 6098 Cycles

Total Braking charge in % = $6098 \times 0.75 \times 10^{-3}$= 4.57 %

Time extended before recharging of Battery due to regenerative braking= 4.57 % of 3.38 Hrs.= 9.26 min

Time required to full Discharge = Time required to full Discharge without regenerative braking +of battery Time extended before recharging of Battery due to regenerative braking= 3.38 Hrs. + 9.26 min= 3.53 hours

2) Performing **4 sec motoring operation** following calculations are carried out,
Time required to full Discharge = 3.46 Hrs.
No of Cycles required for 100% Discharge = $100/(4 \times 8.2 \times 10^{-3})$= 3049 Cycles
Total Braking charge in % = $3049 \times 0.75 \times 10^{-3}$= 2.285 %
Time extended before recharging of Battery due to regenerative braking= 2.285 % of 3.38 Hrs.= 4.63 min
Time required to full Discharge = Time required to full Discharge without regenerative braking +
Time extended before recharging of Battery due to regenerative braking= 3.38 Hrs. + 4.63 min= 3.46 Hrs.

Table 3: Full load Torque = 16.75 N-m

	Case 1	Case 2	Case 3
Duty Cycle	0.9	0.7	0.5
Speed in rpm	1936	1415	897
Energy in rotating mass	455 J	243 J	98 J
Energy recovered by braking	182.5 J	118 J	48.19 J
Percentage energy Recovered of rotating mass	39.49%	48.55%	49.17%
Percentage energy Recovered of Starting	6.88%	6.30%	4.47%
Rate of Discharge in %/sec	8.2 × 10-3	6.4 × 10-3	4.4 × 10-3
Rate of Charge in %/sec	3 × 10-3	2 × 10-3	1 × 10-3
Time required to full Discharge without Regenerative braking	3.38 Hrs.	4.34 Hrs.	6.31 Hrs.
Time required to full Discharge with Regenerative braking	3.53 Hrs.	4.49 Hrs.	6.45 Hrs.

Table 3 shows the Results for 8.37 N-m Full load Torque with variation of duty cycles like 0.9, 0.7 and 0.5 are presented with 4 sec motoring operation.

Results from Table 3 indicates speed of motor is increased at half load compared to full load because torque required is less in half load and back emf is increased so percentage of recovered energy is more so life of battery is extended is by 70% more than full load and hence regenerative braking is more efficient in half load.

At higher duty cycle, with higher motor speed the energy stored in rotating mass is higher and vice versa. So, by comparing all the duty cycles, at 0.9 duty cycle speed of motor is high so, Time required to full Discharge of battery with Regenerative braking is high.

5. Conclusion

The MATLAB modeling for motoring as well as regenerative braking mode was performed and the results were confirmed using theoretical calculations. If the motor is operated in continuous motoring mode at 0.9 duty cycle the time required for complete discharging of battery is 3.38 hour sat full load. Model was tested for different duty cycles and loading conditions with variation of motoring and braking patterns.

Time extended before recharging of battery due to regenerative braking at full load. At higher duty cycle (0.9) speed is maximum so tapped energy in rotating mass is more and time extended before recharging of battery due to regenerative braking is also more.

References

[1] M. Ceraolo, et al.,"A general approach to energy optimization of hybrid electric vehicles," *IEEE Trans. Veh. Technol*., vol/issue: 57(3), pp. 1433–1441, 2008.

[2] A. A. Mahapatra and S. Gopalakrishna, "Regenerative Braking in Induction Motor Drives in Applications to Electric Vehicles", *IEEE Students Conference on Electrical, Electronics and Computer Science (SCEECS),Rourkela, India*, Mar. 1-2, 2014

[3] O. C. Kivanc, O. Ustun, G. Tosun and R. N. Tuncay, "On Regenerative Braking Capability of BLDC Motor", *42nd Annual Conference on Industrial Electronics Society (IECON), IEEE*, Oct. 23-26, Italy, 2016.

[4] O.F.R. Martinez, A.G. Rodriguez, R.S. Cabrera et. al, "Single Phase Regenerative Rectifier for a DC-motor Drive", *12th International Power Electronics Congress (CIEP), 2010, Mexico*, Aug. 22-25, 2010.

[5] J. W. Dixon, M. Ortzar and E. Wiechmann, "Regenerative Braking for an Electric VehicleUsing Ultracapacitors and a Buck-Boost Converter", *Department of Electrical Engineering Catholic University of Chile*.

[6] S. Masri, P. W. Chan, "Design and development of a DC-DC boost converter with constant output voltage", *International Conference on Intelligent and Advanced Systems (ICIAS)*, Jun. 15-17, Malaysia, 2010.

[7] Amit Kumar, Krupa Shah, "Practical Model of Regenerative Braking using DC Machine and Boost Converter",*2020 IEEE International Conference for Innovation in Technology (INOCON) Bengaluru*, India. Nov 6-8, 2020

[8] M. Aamir, et al., "High-Gain Zero-Voltage Switching Bidirectional Converter with a Reduced Number of Switches," *IEEE Trans. Circuits Syst. II, Express Briefs*, vol/issue: 62(8), pp. 816–820, 2015.

[9] Q. Zhao, and F. C. Lee, "High Efficiency, High Step-Up DC-DC Converters, " *IEEE Trans. Power Electron*., vol. 18, pp. 65-73,Jan. 2003.

[10] F. L. Tofoli, et al., "Survey on non-isolated high-voltage step-up dc–dc topologies based on the boost converter," *IET Power Electron*., vol/issue: 8(10), pp. 2044–2057, 2015.

[11] Aswathi E. R.,Prathibha P. K.,Jayasri R. Nair, "Regenerative Braking of BLDC Motor using Fuzzy Control for Electric Vehicles", 2nd International Conference on Inventive Communication and Computational Technologies (ICICCT 2018) *IEEE Xplore Compliant* - Part Number: CFP18BAC-ART; ISBN:978-1-5386-1974-2

[12] J. Yao, et al., "Steep-gain bidirectional converter with a regenerative snubber," *IEEE Trans. Power Electron.*, vol/issue: 30(12), pp. 6845–6856, 2015.

[13] C. C. Lin, et al., "Study of a non-isolated bidirectional DC–DC converter," *IET Power Electron*., vol. 6, pp. 30–37, 2013. "Study of Bidirectional DC-DC Converter:Control Schemes and Switching Techniques"

[14] Waghmare, T., & Chaturvedi, P. (2020). Study of Bidirectional DC-DC Converter: Control Schemes and Switching Techniques. *2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC).*

[15] Rini Nur Hasanah, Victor Andrean, Soeprapto, HadiSuyono, and R AriefSetyawan, "Bidirectional VSI as a Regenerative-Braking Converter for BLDC Motor – Analysis on a Plug-in Electric Vehicle Application", *International Journal of Power Electronics and Drive Systems (IJPEDS)*

[16] T. J. Liang, et al., "Analysis, design, and implementation of a bidirectional double-boost DC-DC converter," *IEEE Trans. Industry Applications*, vol/issue: 50(6), pp. 3955-3962, 2014

[17] G. Hua and F. C. Lee, "An overview of soft-switching techniques for PWM converters," EPE J., vol. 3, no. 1, Mar. 1993

[18] D. Sable, F. C. Lee, and B. H. Cho, "A zero-voltage-switching bidirectional battery charger or discharger for the NASA EOS satellite," in *IEEE Appl. Power Electron*. Con$ Proc., 1992

[19] N. K. Mydham, A. Vijayakumari and S. R. Mohanrajan, "Enhanced Regenerative Braking System for Electric Vechile with High Power Density Storage," *2021 International Conference on System, Computation, Automation and Networking (ICSCAN), Puducherry*, India, 2021, pp. 1-7, doi: 10.1109/ICSCAN53069.2021.9526369.

[20] C. Asok and D. M. U, "IPMSM Drive with Interleaved Bidirectional Converter for Electric Vehicle Application," 2022 *IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES),THIRUVANANTHAPURAM, India, 2022*, pp. 268-273, doi: 10.1109/SPICES52834.2022.9774142.

[21] Y. -S. Lin, K. -W. Hu, T. -H. Yeh and C. -M. Liaw, "An Electric-Vehicle IPMSM Drive With Interleaved Front-End DC/DC Converter," *in IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, pp. 4493-4504, June 2016, doi: 10.1109/TVT.2015.2435040.

[22] Z. Geng, D. Gu, T. Hong, K. Qi, K. Zhang and J. Ambrosio, "Modularized High Power Density Bidirectional Buck-Boost DC-DC Converter for EV Battery Management," 2018 *IEEE Transportation Electrification Conference and Expo (ITEC)*, Long Beach, CA, USA, 2018, pp. 164-167, doi: 10.1109/ITEC.2018.8450230.

[23] A. Gupta, R. Ayyanar and S. Chakraborty, "Novel Electric Vehicle Traction Architecture With 48 V Battery and Multi-Input, High Conversion Ratio Converter for High and Variable DC-Link Voltage," in *IEEE Open Journal of Vehicular Technology*, vol. 2, pp. 448-470, 2021, doi: 10.1109/OJVT.2021.3132281.

[24] T. K. Haritha, S. S. Kumar, P. Jayaprakash and O. V. Asokan, "Regenerative Braking System for Fuel Cell-Battery Hybrid Sources," *2022 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)*, Trivandrum, India,

2022, pp. 1-6, doi: 10.1109/PESGRE52268.2022.9715858.

[25] Thakre, Mohan and Bhartiy, Jayesh and Gawde, Sunil and Pagar, Om and Darekar, Mangesh and Deshmukh, Bhupendra, Performance Analysis of Lithium-Ion Battery Based on State of Charge and State of Health for EV Applications (July 8, 2021). *Proceedings of the International Conference on IoT Based Control Networks & Intelligent Systems - ICICNIS 2021*, Available at SSRN: https://ssrn.com/abstract=3882516 or http://dx. doi.org/10.2139/ssrn.3882516

[26] Butale, V., Thakre, M., Gaikwad, V., Mahadik, Y., Jadhav, T. (2022). An Evaluation of Wireless Charging Technology for Electric Vehicle. In: Majhi, S., Prado, R.P.d., DasanapuraNanjundaiah, C. (eds) *Distributed Computing and Optimization Techniques. Lecture Notes in Electrical Engineering*, vol 903. Springer, Singapore. https://doi.org/10.1007/978-981-19-2281-7_18