ENERGY STORAGE SYSTEM IN AN ELECTRICALLY PEAKING HYBRID (ELPH) VEHICLE

Chandra Prakash Jain[1], Amrit[2], Panchan Kumar[3], Karimullah Ansari[4]
E-Mail Id: cpjain1983@gmail.com
Geetanjali Institute of Technical Studies, Udaipur, Rajasthan, India

Abstract- Advantages like high reliability, long cycle life, high energy storage capacity and deep discharge of an Flywheel Energy storage system (FESS) can potentially enhance the performance of the hybrid vehicles. This paper the study related to integration of Flywheel Energy storage system (FESS) to an already available model of parallel hybrid vehicle with retransmission torque coupling, i.e., replacing the conventional chemical battery with an equivalent mechanical battery. FESS employed for the analysis comprises an integrated flywheel homopolar inductor machine with High frequency drive. The simulation results of an Electrically Peaking Hybrid (ELPH) are used as a base work in the present analysis. The ELPH model uses a control strategy to optimize the vehicle performance with a major concern for battery performance. The paper analyzes the performance of considered FESS model under the same control strategy and driving conditions. A MATLAB/SIMULINK model is used for the analysis of the vehicle for both urban and highway drives. Finally a comparison is drawn between the performances of the chemical battery, working in its best efficiency range, as a result of the applied control strategy, to that of the considered FESS. It is inferred from the simulated results that the performance of employed FESS is satisfactory in comparison to chemical batteries. It is therefore expected that FESS can be effectively employed in hybrid vehicles.

Keywords: FESS, Hybrid, MATLAB/SIMULINK.

1. INTRODUCTION

Electric battery powered vehicles have some advantages over ICE powered vehicles, but their shorter range is a major drawback in their performance. Traditional internal combustion engine (ICE) vehicles suffer from poor fuel economy and environmental pollution. Poor fuel economy is based on perating the engine in the low efficiency region for most of the drive cycle and (ii) dissipation of the vehicle's kinetic energy during braking. Both of these shortcomings can be overcome by the use of Hybrid Electric Vehicle (HEV). An HEV combines a conventional propulsion system with an onboard rechargeable energy storage system (RESS) to achieve better fuel economy than a conventional vehicle as well as greater range than an electric vehicle. HEVs prolong the charge on the RES by capturing kinetic energy through regenerative braking, and some HEVs also use the engine to generate electricity through an electric generator (M/G) to recharge the RES. HEVs have smaller engines and can run at different speeds, providing higher efficiency. HEVs allow greater fuel economy and lower emissions than conventional ICE vehicles:

- Allowing the engine to stop under vehicle stop condition,
- Downsizing the engine for same peak load requirements, as the motor will assist the engine for such higher loads, and
- Allowing regenerative braking, not possible in conventional vehicle. In urban drive conditions, about 30% of the fuel can be saved through regenerative braking because of the frequent stop and go conditions.

HEVs come in two main configurations: series and parallel hybrids. Even within parallel hybrids, there are multiple ways to arrange the engine, motor, and transmission for optimal performance. This can be done through speed coupling, where speeds of the engine and motor are combined, or torque coupling, where torques are summed using a torque coupler. The parallel hybrid is preferred for its advantages over series hybrids, including lower emissions, improved efficiency, simpler setup, and better performance. The focus of analysis is on the 'pretransmission torquecoupled parallel hybrid drivetrain'. However, batteries in HEVs have drawbacks like limited cycle life and modest power densities. To address these, alternative Energy Storage Systems (ESS) like Flywheel Energy Storage Systems (FESS) are being researched. Flywheels offer high reliability, long cycle life, and higher energy storage per kilogram than batteries, meeting peak power demands. The FESS used in the analysis is the 'Integrated Flywheel Energy Storage System with Homopolar Inductor Motor/Generator and High Frequency Drive', providing benefits such as reduced weight, lower costs, and simpler manufacturing.

2. SYSTEM DESCRIPTION

The system analysis focuses on an Electrically Peaking Hybrid Electric propulsion system with a parallel configuration. Compared to conventional ICE vehicles, this setup downsizes the engine, using a smaller one approximately equal to the average load power. An AC induction motor supplements power needs beyond what the engine provides, while also absorbing excess engine power when load demands are low. This surplus power, combined with regenerative braking, charges the Flywheel Energy Storage System (FESS) to maintain its State of Charge (SOC) at an optimal level.

The operation of the vehicle is meticulously managed by a sophisticated vehicle controller, which serves as the central hub for communication between various subsystems including the motor controller, engine controller, and FESS controller. These subsystems receive and respond to input signals originating from the accelerator and brake pedals, allowing for precise control and coordination of the vehicle's propulsion system. To optimize performance under different driving conditions, two distinct control strategies are implemented: "MAXIMUM BATTERY SOC" ensures that the battery maintains a specific range of state of charge (SOC), thereby maximizing efficiency especially during urban driving where frequent acceleration and deceleration occur. On the other hand, the "ENGINE TURNON AND TURNOFF" strategy intelligently manages the engine's operation based on the SOC of the RESS, making it particularly suited for highway driving scenarios.

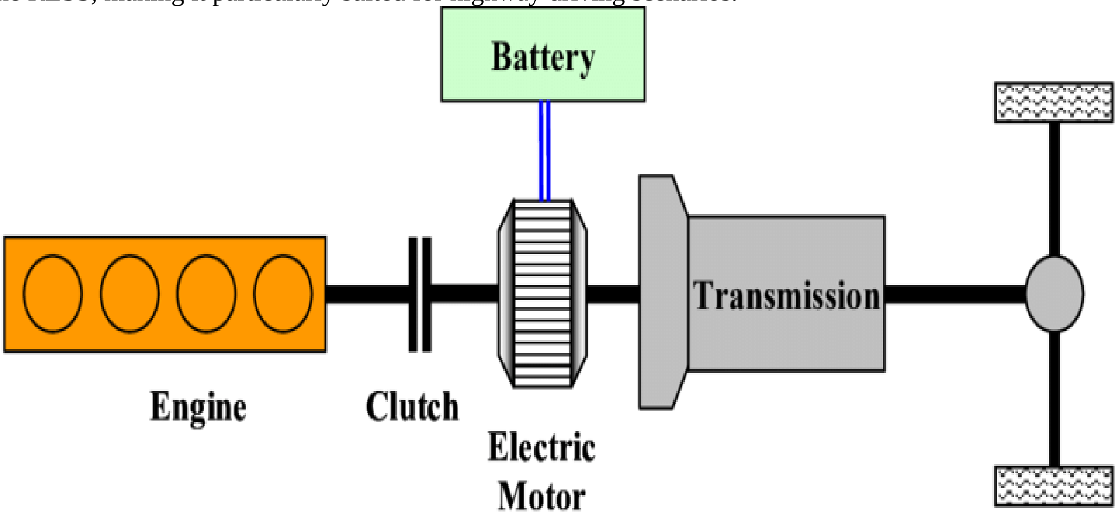

Fig. 2.1 Pretransmission Torque Coupled ELPH

In addition to the implementation of control strategies, the vehicle is equipped with an innovative integrated flywheel system, which represents a significant advancement in energy storage technology. This system seamlessly combines the energy storage accumulator and rotor into a single, cohesive unit, resulting in a highly streamlined design. By integrating these components, the system achieves not only a reduction in weight and volume but also an enhancement in overall system efficiency. This streamlined design optimizes space utilization within the vehicle while simultaneously improving its performance characteristics. Furthermore, the decision to utilize homopolar inductor motors instead of traditional PM motors for FESS applications offers several notable advantages. These advantages include increased reliability, thanks to the simpler construction and reduced number of moving parts, which inherently decreases the likelihood of mechanical failure. Additionally, homopolar inductor motors exhibit reduced sensitivity to temperature variations compared to their PM counterparts, ensuring consistent performance across a wide range of operating conditions. This strategic choice underscores a commitment to maximizing the robustness and longevity of the vehicle's propulsion system, ultimately contributing to its overall effectiveness and reliability in real world driving scenarios.

The primary objective of the study is to conduct a thorough comparison of the performance attributes of Flywheel Energy Storage Systems (FESS) and chemical batteries within the context of hybrid vehicles. This research endeavor is motivated by the overarching goal of addressing prevalent research gaps in the field and elucidating the relative strengths and weaknesses of each energy storage technology. To achieve this objective, the study employs a meticulous approach that involves the analysis of simulation results derived from the Electrically Peaking Hybrid Electric (ELPH) propulsion system. These simulations are carried out utilizing a sophisticated SIMULINK model, which enables the accurate representation of the vehicle's behavior under various operating conditions. By subjecting the system to simulations emulating both urban and highway drive cycles, the study aims to extract valuable insights into the performance dynamics of FESS and chemical batteries. Moreover, the study goes a step further by generating lookup tables based on the simulation results, which serve as invaluable tools for conducting in depth analyses and comparisons. Through this comprehensive methodology, the research contributes significantly to the ongoing advancement of hybrid vehicle technology, offering valuable guidance for researchers, engineers, and stakeholders in the automotive industry.

The initial SOC of the battery is assumed to be at a level of 50%. Thus the instantaneous energy of the battery E_{batt}, will become

$$E_{batt} = E_{0(batt)} + \Delta E_{batt}$$

where $E_{(batt)}$ is the assumed initial energy level of the battery and ΔEbatt is the change in the energy of the battery at any instant with respect to the initial energy of the battery. Then the instantaneous power level of the battery Pbatt, can be determined by simply differentiating the instantaneous energy of the battery with respect to time.

$$P_{batt} = \frac{dEbatt}{dt}$$

The plot between the efficiency of the battery η_{batt}, and its SOC i.e. the efficiency of the chemical battery at any instant as a function of its instantaneous SOC has been determined by drawing lookup tables in SIMULINK model. The instantaneous power of the vehicle interacting with the RESS i.e. basically the instantaneous electrical machine power of the vehicle, can be determined as follows:

$$P_{veh} = P_{batt}.\eta_{batt} \quad \text{if } P_{batt} < 0$$

$$P_{veh} = P_{batt}/\eta_{batt} \quad \text{if } P_{batt} \geq 0$$

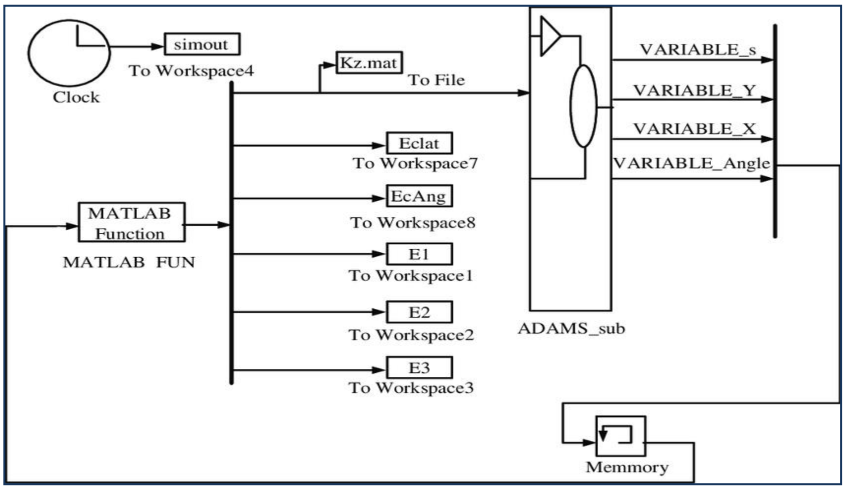

Fig 2.2 MATLAB/SIMULINK Model used for the Analysis

where positive and negative values of P_{batt} corresponds to the charging state and discharging state of the battery respectively, and

$$f(SOC) = \eta_{batt}$$

When the chemical battery in the system is replaced with a mechanical battery, specifically a Flywheel Energy Storage System (FESS), it introduces a new dynamic in the interaction of instantaneous power at the vehicle's end. Reference [5] provides a comprehensive plot illustrating the efficiency of the FESS across different power levels. These efficiency values are crucial for understanding the FESS's performance under varying power demands. To incorporate this into the simulation model, a lookup table is meticulously generated using the data from the efficiency plot. This lookup table is then integrated into the SIMULINK model, allowing for the determination of the instantaneous efficiency of the overall FESS, denoted as ηFESS, as a function of its instantaneous power, represented by the equation ηFESS = f(PFESS). Importantly, this calculation is averaged over the speed range of the flywheel, ensuring that the model accurately represents the FESS's behavior across its operational spectrum. By adopting this meticulous approach, the simulation framework can provide valuable insights into how the FESS interacts with the vehicle's power requirements, thereby contributing to a comprehensive understanding of its performance characteristics and informing future advancements in hybrid vehicle technology.

Now the instantaneous power of the FESS, P_{FESS} can be determined as follows:

$$\Delta E_{FESS} = \int_0^t P_{FESS}.dt$$

ΔE_{FESS}, the initial energy of the FESS i.e. at the start of the drive cycle is added to this change in energy to get the instantaneous energy level of the FESS. Then the quantity is divided by the total energy capacity of the FESS ($E_{max(FESS)}$), to get the instantaneous State Of Charge of the FESS, *FESS SOC.*

$$SOC_{FESS} = \frac{(E_{0(FESS)} + \Delta E_{FESS})}{E_{max(FESS)}}$$

In a similar manner the instantaneous SOC of the battery, SOC_{batt} can be determined, and finally a comparison between the two is drawn to establish the satisfactory performance of an FESS in a parallel hybrid drive train.

$$SOC_{batt} = \frac{(E_{0(batt)} + \Delta E_{batt})}{E_{max(batt)}}$$

3. RESULTS AND DISCUSSION

The numerically simulated results comparing the performances of the chemical battery and the Flywheel Energy Storage System (FESS) are meticulously generated for the entirety of the drive cycles, specifically the FTP75 Urban and FTP75 Highway, using the elaborated SIMULINK model. Fig. 3 visually presents the results of the comparison, specifically focusing on the State Of Charge (SOC) of the flywheel (SOCFESS) in contrast to that of the chemical battery (SOCbatt) over the FTP75 urban drive cycle. These results are derived from simulations covering a cycle duration of 1400 seconds, offering a comprehensive assessment of the system's performance under typical urban driving conditions. The control strategy implemented for the urban drive cycle is the 'MAXIMUM BATTERY SOC,' which prioritizes maintaining the battery's SOC within a specific range for optimal efficiency. By visualizing and analyzing these results, researchers and engineers gain valuable insights into how the FESS performs relative to the chemical battery across varying driving scenarios, thus informing further refinements and advancements in hybrid vehicle technology.

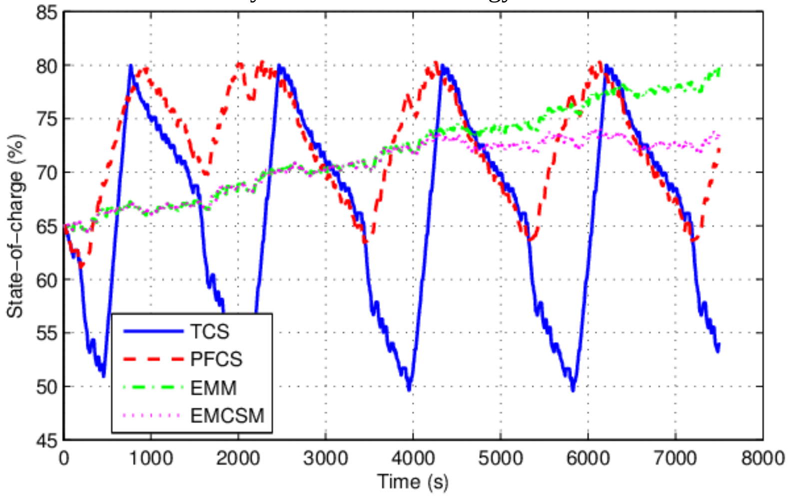

Fig. 3.1 Plot between SOC of the FESS and the Time for FTP75 Urban Drive Cycle

The analysis of the plotted data reveals that even under conditions of deep discharge, such as those observed around the 200second mark, the performance of the Flywheel Energy Storage System (FESS) remains satisfactory. Moreover, across the entirety of the drive cycle, the FESS performs comparably well to the chemical battery. Fig. 4 illustrates the relationship between the State Of Charge (SOC) of the FESS (SOCFESS) and the chemical battery (SOCbatt) over the complete FTP75 Highway drive cycle. The control strategy employed for this specific drive cycle is the 'ENGINE TURNON AND TURNOFF' strategy. Upon closer examination of the plot, it becomes evident that during instances of very deep discharge, approximately around the 350 and 650second marks, the FESS effectively supplies the required power in accordance with the vehicle's traction demands. Furthermore, during vehicle deceleration, particularly during regenerative braking, the FESS demonstrates an impressive ability to capture a substantial amount of energy, as facilitated by the motor/generator set. This phenomenon is clearly illustrated in the plot, notably around the 550second mark, where a notable increase in FESS charging occurs. These findings underscore the FESS's performance parity with the best performing chemical batteries during highway driving scenarios. It is worth noting that for both drive cycles, the final SOC level of the FESS at the conclusion of the drive cycle is approximately 2.5% lower than that of the chemical battery. However, this observation pertains to the optimal performance of a chemical battery, suggesting room for significant enhancement in the FESS's performance.

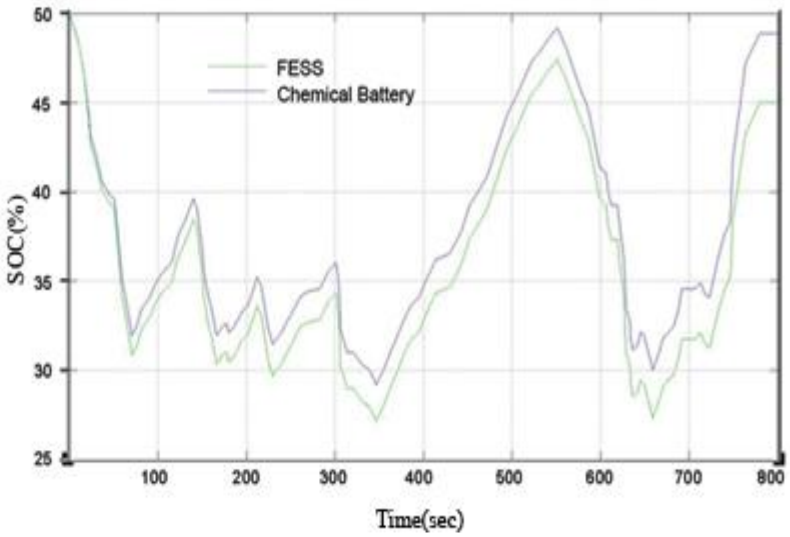

Fig. 3.2 Plot between SOC of the FESS and the Time for FTP75 Highway Drive Cycle

CONCLUSIONS

Based on the comprehensive analysis of the numerically simulated results and the detailed discussions presented in the preceding sections, it can be inferred that the integration of Flywheel Energy Storage Systems (FESS) holds significant promise for the effective enhancement of hybrid vehicles. The findings suggest that FESS exhibits satisfactory performance levels when compared to chemical batteries operating within their optimal efficiency ranges. Notably, the results indicate that not only does the FESS demonstrate performance comparable to that of chemical batteries, but its incorporation also has the potential to elevate the overall performance metrics of hybrid vehicles. This conclusion underscores the viability and potential benefits of integrating FESS technology into hybrid vehicle platforms, offering a compelling alternative to traditional chemical battery systems. Furthermore, these insights provide valuable guidance for further research and development efforts aimed at optimizing and advancing the utilization of FESS in the realm of hybrid vehicle technology.

REFERENCES

[1] Mehrdad Ehsani, Yimin Gao, Sebastien E. Gay, Ali Emadi, “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design,” CRC Press, 2004.

[2] Katrasˇnik Tomazˇ, “Hybridization of powertrain and downsizing of IC engine – A way to reduce fuel consumption and pollutant emissions Part 1, Energy Conversion and Management,” Vol. 48, 2007, pp. 14111423.

[3] Ali Emadi, “Handbook of Automotive Power Electronics and Motor Drives,” CRC Press, 2005.

[4] Haichang Liu, Jihai Jiang, “Flywheel energy storage—An upswing technology for energy sustainability,” Energy and Buildings, Vol. 39, May 2007, pp. 599604

[5] P. Tsao, M. Senesky, and Seth R. Sanders,” An Integrated Flywheel Energy Storage System With Homopolar Inductor Motor/Generator and High Frequency Drive,” IEEE Trans. On Industry Applications, Vol. 39, Nov/Dec. 2003,pp. 17101725.

[6] M. Aarif; D. Joshi; R. Jangid and S.S. Sharma, “Grid Power Smoothing Management for Direct Drive PMSG Variable Speed Wind Energy Conversion System with Multilevel Converter”, IEEE 7th International Conference on ICT for Sustainable Development, Organized by Global Knowledge Foundation during 29-30, July 2022 at Goa, India.

[7] Y. Joshi; J.k Maherchandani; V.K Yadav; R. Jangid; S. Vyas and S.S Sharma, “Performance Improvement of Standalone Battery Integrated Hybrid System” IEEE 7th International Conference on Electrical Energy Systems (ICEES), Organized by Sri Sivasubramaniya Nadar College of Engineering during 11-13 Feb. 2021at Chennai, India.

[8] R. Jangid; J.k Maherchandani; R.R. Joshi and B.D Vairagi, “Development of Advance Energy Management Strategy for Standalone Hybrid Wind & PV System Considering Rural Application”, IEEE 2nd International Conference on Smart Systems and Inventive Technology, Organized by Francis Xavier Engineering College during November 27-29, 2019 at Tirunelveli, India.

[9] R. Jangid et al., “Reducing the Voltage Sag and Swell Problem in Distribution System Using Dynamic Voltage Restorer with PI Controller”, International Journal of Soft Computing and Engineering, ISSN: 2231-2307, Vol.-3, Issue-6, January 2014.

[10] R. Jangid; J.k Maherchandani; V.K Yadav and R.K Swami, “Energy Management of Standalone Hybrid Wind-PV System”, Journal of Intelligent Renewable Energy Systems (John Wiley & Sons, Inc.) Pages 179-198, 2022.

[11] H. Kumawat and R. Jangid, “Using AI Techniques to Improve the Power Quality of Standalone Hybrid Renewable Energy Systems”, Crafting a Sustainable Future Through Education and Sustainable Development, IGI Global, Pages 219-228, 2023.

[12] H. Kumawat; R. Jangid, “Performance and Investigation of Two Drive Train Interfaced Permanent Magnet Synchronous Generator for Wind Energy Conversion System”, Journal of Emerging Technologies and Innovative Research, ISSN:2349-5162, Volume 7, Issue 1, January 2020.

[13] R. Jangid et. al., “Smart Household Demand Response Scheduling with Renewable Energy Resources”, IEEE Third International Conference on Intelligent Computing and Control System, Organized by Vaigai College of Engineering during May 15-17, 2019 at Madurai, India.

[14] S. Kumar et al., “Comparative Performance Analysis of Adaptive Neuro-Fuzzy Inference System (ANFIS) & ANN Algorithms Based MPPT Energy Harvesting in Solar PV System.” International Journal of Technical Research and Science, vol. 8, Issue 3, March 2023.

[15] S. Sharma; R. Jangid and K. Parikh “Development of Intelligent Control Strategy for Power Quality Improvement of Hybrid RES Using AI Technique” International Journal of Technical Research and Science, vol. VIII, Issue II, Feb. 2023.

[16] M. Ehsani, Yimin Gao, and Karen L. Butler, “Application of Electrically Peaking Hybrid (ELPH) Propulsion System to a Full Size Passenger Car with Simulated Design Verification,” IEEE Trans. On Vehicular Technology, Vol. 48, Nov. 1999,pp. 17791787.

[17] Zhou, Yuliang Leon, "Modeling and Simulation of Hybrid Electric Vehicles,” M.A.Sc. Thesis, University

of Victoria, December 2007.

[18] Sasanka Sekhor Sharma, RR Joshi, Raunak Jangid, Shripati Vyas, Bheru Das Vairagi, Megha Vyas., 2020, MITIGATION OF TRANSIENT OVER-VOLTAGES AND VFTO EFFECTS ON GAS INSULATED SUBSTATION. Solid State Technology, Volume 63, Issue 5/

[19] Vyas, M., Yadav, V.K., Vyas, S., Joshi, R.R. and Tirole, R. (2022). A Review of Algorithms for Control and Optimization for Energy Management of Hybrid Renewable Energy Systems. In Intelligent Renewable Energy Systems (eds N. Priyadarshi, A.K. Bhoi, S. Padmanaban, S. Balamurugan and J.B. Holm-Nielsen). https://doi.org/10.1002/9781119786306.ch5

[20] Vyas, Megha & Yadav, Vinod & Vyas, Shripati & Joshi, R.. (2021). Voltage Sag Mitigation Using Distribution Static Compensator. 10.1007/978-981-15-8586-9_24.

[21] Tirole, R., Joshi, R.R., Yadav, V.K., Maherchandani, J.K. and Vyas, S. (2022). Intelligent Control Technique for Reduction of Converter Generated EMI in DG Environment. In Intelligent Renewable Energy Systems (eds N. Priyadarshi, A.K. Bhoi, S. Padmanaban, S. Balamurugan and J.B. Holm-Nielsen). https://doi.org/10.1002/9781119786306.ch4

[22] S. V. . . et. al., "Life Extension Of Transformer Mineral Oil Using AI-Based Strategy For Reduction Of Oxidative Products", TURCOMAT, vol. 12, no. 11, pp. 264–271, May 2021.

[23] Kumar P, Kumar V. Economic Analysis of Rural Distribution System with DER and Energy Storage System. Proceedings of International Conference on Computational Intelligence and Emerging Power System. Springer Singapore; 2021 Dec 14;235–44. http://dx.doi.org/10.1007/978-981-16-4103-9_20.

[24] Prashant Kumar, Vinod Kumar "Energy storage options for enhancing the reliability of Power system in the presence of Renewable Energy Sources" 2nd International Conference on Inventive Research in Computing Applications (ICIRCA 2020), IEEE Conference, 15-17, July 2020. https://doi.org/10.1109/ICIRCA48905.2020.9183349

[25] H. Agrawal, P. Kumar and P. Singh, "Revolutionizing EV Charging stations through IoT," 2024 3rd International conference on Power Electronics and IoT Applications in Renewable Energy and its Control (PARC), Mathura, India, 2024, pp. 356-360. https://doi.org/10.1109/PARC59193.2024.10486546.

[26] Prashant Kumar, Pushependra Singh, Akash Talwariya "Allocation of Charging Stations in Kota City using Data Analysis" has been published in the Energy Sources, Part B: Economics, Planning, and Policy (TAYLOR & FRANCIS INC). https://doi.org/10.1080/15567249.2024.2360437.