Intelligent Power Flow Control in Renewable Energy-Based Charging Stations Using Optimization Algorithms

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Abstract: Given the rapid growth of electric vehicles, building effective and sustainable charging infrastructure has become inevitable. Conventional charging stations are grid-electricity dependent, as most regions still produce it from fossil fuels, thus canceling the climatic benefits of electric vehicles. The study focuses on the integration of renewable energy sources, such as solar and wind, with advanced power flow control mechanisms to optimize the performance of EV charging stations. A hybrid charging station model, including Permanent Magnet Synchronous Machines (PMSM) and battery-based energy storage solutions, is proposed for optimal DC bus voltage stability. The study applies AI-assisted power management strategies and optimization techniques like Genetic Algorithms (GA) and Model Predictive Control (MPC) for better energy distribution and minimized losses. Simulations are done based on MATLAB/SIMULINK to exhibit improved power quality, reduced voltage fluctuations, and efficient utilization of energy storage. These indicate that renewable integration at EV charging stations is decisive for the further improvement of transport ecosystems in regard to stability, efficiency, and ecological compatibility.

Keywords: electric vehicles (EVs), Permanent Magnet Synchronous Machines (PMSM), Genetic Algorithms (GA), Model Predictive Control (MPC), flywheel energy storage system (FESS).

I. Introduction

Charging stations for electric vehicles contain facility equipment that supplies electric power to recharge batteries of electric vehicles. They include Level 1 (which is the slowest, using standards outlets for charging), Level 2.fast AC charging, and finally, DC Fast Charging (meant for quick fuelling action on the go). They are either sited in public locations, workplaces, or at home, facilitating EV adoption by rendering charging convenient and efficient. Many of these stations have in-built smart options like mobile app connectivity, payment solutions, and real-time availability updates, further upping the user convenience. As the demand for EVs goes up, the expansion of charging networks goes global [1]. Concerns of climate change, air pollution, and the depletion of fossil fuels have sped up the world's shift toward electric vehicles-(EVs). Governments and industries around the world are bringing electric vehicles to the forefront as sustainable alternatives to traditional internal combustion engine vehicles [2].

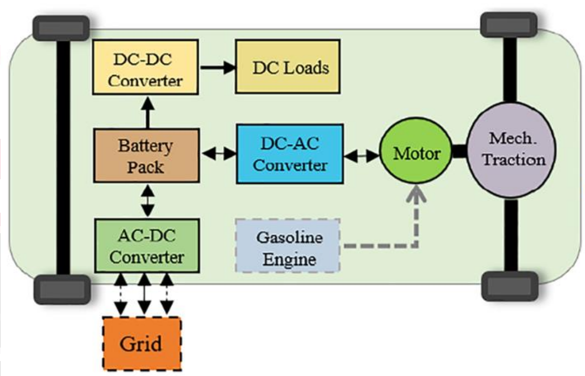

Figure 1 Block diagram of a typical electric vehicle [3]

This figure 1 shows how power flows in a hybrid or electric vehicle. The battery is charged from the power grid by an AC-DC converter that then sends power via a DC-AC converter to a motor for propulsion. Finally, auxiliary DC loads are powered by a DC-DC converter. The motor drives the wheels, and the gasoline engine may be used to assist propulsion or recharge the battery (depending on whether a hybrid system is adopted). This framework allows for efficient energy management in an appropriate operating mode of the vehicle [3]. But to support such large-scale use of EVs, well-developed and efficient charging infrastructure becomes imperative. Conventional charging stations are wholly dependent on grid electricity for their operation; grid electricity is, in turn, produced in some parts of the globe with the use of coal or natural gas. Such dependency is actually in contradiction with the environmental benefits of EVs, as it causes carbon emissions and energy inefficiency indirectly [4]. Consequently, there is a gradual shift to renewable energy integration-especially in solar and wind-into EV charging stations to develop a sustainable and eco-friendly transportation ecosystem.

A. Advantages of Renewable Energy-Powered Charging Stations

Incorporating renewable energy sources into EV charging stations presents various advantages. Notably, solar PV systems and wind energy systems reduce the dependence on fossil-fuel-based grids as they create clean, sustainable and decentralized power generation [5]. The reduction in the carbon footprint and enhanced energy security derives from the lesser dependence on the externally supplied energy. In addition, hybrid renewables offer enhanced reliability, combining solar and wind energies into one hybrid system, thus ensuring the performance of charging stations under fluctuating environmental conditions. Renewable-powered charging stations also contribute to easing power grid congestion through peak load reduction, as this is of significant benefit in the urban context, in which the low capacity for the power distribution network might be stressed [6]. The augmentation of energy storage systems (flywheels and batteries) will enable these charging stations to store energy produced in excess and supply it when the demand is greater than its supply, thereby improving their efficiency and reliability.

B. Challenges in Implementing Renewable Charging Stations

The growing need for renewable-powered EV charging stations brings both opportunities and challenges. While the initial costs for installing solar panels, wind turbines, and energy storage systems can be high, these expenses are gradually decreasing thanks to technological advancements and economies of scale. Another hurdle is the inconsistency of renewable energy sources; solar power relies on sunlight, and wind energy is subject to variations in wind speed. To tackle these issues, advanced energy management systems, smart grids, and optimization methods like Genetic Algorithms (GA) and Artificial Intelligence (AI) are being incorporated into power distribution networks to improve efficiency and maintain a stable energy supply [7]. Additionally, governments and private companies are providing incentives, subsidies, and policy support to encourage the use of renewable-powered EV charging stations. This means that the continued advancement of technology and decline in costs will usher in the transformation toward a totally green, decentralized, and smart charging infrastructure to be used within the context of a global plan for the attainment of sustainable, carbon-neutral transportation.

C. Power Flow Stability Issues in Hybrid Charging Stations

Hybrid energy-based charging stations combining solar, wind, and other renewable sources with ESSs pose major difficulties in maintaining a stable power flow [8]. In contrast to the steady and predictable electricity supply available for traditional grid-powered charging stations, renewable energy sources are naturally variable. The power generation through solar panels is variable with changes in the weather, cloud cover, and seasonal variation; the output of wind energy depends on the wind speed and direction, thus producing unpredictable power. Variation may cause a change in the DC link voltage and may lead to instability in a charging station. This often becomes complicated if multiple sources of energy are in use, as coordinating their outputs for continuous, balanced power flow into the loads becomes a complex challenge [9]. Effective control mechanisms are not in place, and instant changes to power supply may cause voltage fluctuations, frequency imbalances, and even power interruptions, affecting the total performance of the charging station.

D. Efficiency Challenges Due to Energy Conversion and Storage Losses

A significant challenge faced by hybrid charging stations is achieving high energy efficiency, as the presence of multiple conversion stages and storage components result in energy losses. Electric vehicles require DC power for charging, but sources of energy such as wind and solar can come in both DC and AC formats, thus requiring multiple conversion processes, including DC/DC, AC/DC, and DC/AC. Each of these stages contributes to energy losses, which ultimately lower the system's overall efficiency [10]. Further, ESS, that is, batteries and flywheel energy storage systems, for instance, suffer from losses in charging as well as in discharging because of inherent issues such as internal resistances, heat generation, or degradation of the aging process. In due course, their efficiency decreases, and they lose performance or waste energy. In addition, the energy management systems should be designed to utilize direct power whenever possible rather than storing it, hence reducing unnecessary losses in energy and ensuring proper distribution of energy between loads and storage components.

E. Role of Energy Storage in Hybrid Charging Stations

Energy storage is fundamental for hybrid charging stations because it will stabilize the supply of electricity with reliability and efficiency in case the source is based on intermittent energy such as solar or wind power. Typically, the extra energy generated at peak times can be stored through a BESS and then fed into the power supply grid during demand exceeding supply conditions, using an FESS. This process helps stabilize power flow, maintain a constant DC link voltage, and reduces the dependency on the grid [11]. Moreover, energy storage improves charging efficiency by delivering power directly to electric vehicles (EVs) when renewable generation is low, which minimizes voltage fluctuations and load imbalances. Hybrid charging stations can improve energy distribution, prolong battery life, and enhance overall system performance by using advanced energy management techniques such as Genetic Algorithms (GA), Machine Learning (ML), and Predictive Control Systems [12]. Energy storage is also important for peak load management, allowing stations to store energy during off-peak hours and release it during peak times, thus relieving grid congestion and enhancing cost efficiency. In the final analysis, integration of energy storage solutions will ensure that hybrid charging stations are reliable, sustainable, and efficient. This is sure to support a wider-scale penetration of electric vehicles within a cleaner and more resilient energy framework.

II. Literature Review

The demand for electric cars (EVs) has been increasing in recent years due to rising fossil fuel prices and rising carbon dioxide (CO2) emissions, according to **Savio Abraham, D. et al. (2021) [13].** The current utility power grid systems are used to power these EV charging stations, which has put additional strain on the utility grid and raised load demand at the distribution side as well. Because of its greater dependability, power conversion efficiency, ease of integration with RESs, and integration of energy storage units into ESU, DC grid-based EV charging is significantly more efficient than AC distribution. An alternate method for controlling utility grid demand is to use RES-generated power storage in local ESUs. Additionally, energy management and control strategies need to carefully power the EV battery charging unit in order to sustain the microgrid levels of EV charging demand. Furthermore, charging stations must adhere to specific levels and standards, use specialized converter topologies, and employ control mechanisms. To guarantee optimal operation at the EV-charging point, many forms of microgrid architecture and control methodologies are employed, depending on the accessibility of EVs, ESUs, and RES. This review paper describes several RES-connected architecture and control methodologies used in EV-charging stations based on the aforementioned qualities. With the existing power converter topologies suggested in the literature, it emphasizes the significance of various charging station architectures. Furthermore, a comparison of the energy management, control techniques, and charging converter controls of microgrid-based charging station design is provided. Along with the controls and connectors utilized, the various tiers and kinds of charging stations utilized for EV charging are also covered. For the efficient use of generated renewable electricity, an energy management strategy based on experiments was created to regulate power flow between the available sources and charging terminals. Maximizing the use of RES consumption is the primary goal of the EMS and its control. The difficulties and possibilities of EV charging are also covered in this review, along with criteria for choosing suitable charging stations.

According to research by **Hu, J. et al. (2021) [14],** microgrid development is a beneficial way to include quickly expanding renewable energy sources. However, a number of issues have been brought about by the stochastic nature of renewable energy sources and fluctuating power demand, including unstable voltage and frequency, complex power management, and intricate utility grid interaction. Predictive control has recently shown enormous promise in microgrid applications due to its quick transient reaction and adaptability to various restrictions. Model predictive control (MPC) in standalone and networked microgrids is thoroughly reviewed in this research, covering converter-level and grid-level control strategies implemented on three tiers of the hierarchical control architecture. According to this survey, MPC is just getting started in microgrid applications and is starting to compete with traditional techniques in power flow management, voltage regulation, frequency control, and economic operation optimization. Additionally, some of the most significant developments in MPC have been emphasized and examined from a prospective future standpoint.

Bevrani, H. et al. (2021) [15] described how the growing use of renewable energy sources, the development of new storage systems, programmable loads, and power electronics technologies, as well as changes in system structure, have made frequency management of power grids an important area of study. Technological developments in computation, communication, and control also aid in the creation of novel methods and solutions. Applied modern control systems, current obstacles for the integration of renewable energy sources, and the most significant frequency stability concerns are reviewed in this study. Additionally, the article highlights previous successes, emerging research avenues, and current trends.

Integration of renewable energy sources, like wind and solar, into co-located hybrid power plants (HPPs) has drawn a lot of attention as an inventive way for plant developers to address the intermittency and variability inherent in renewable systems due to technological advancements, economies of scale, and governmental policies, according to **Bade, S. O., Meenakshisundaram, A., & Tomomewo, O. S. (2024) [16].** As previously said, the design stages of creating any large-scale hybrid plant provide a significant difficulty; the most crucial concerns center on matters like energy management, sizing optimization, and putting an ideal control method into practice. As a result, the article presents a significant analysis of utility-scale wind-solar hybrid power plants that are co-located, paying particular attention to sizing optimization and issues related to energy management. This is followed by the best methods for energy strategies and energy management controls. The authors created a review methodology that involved compiling an article database, creating inclusion and exclusion standards, and carrying out in-depth analyses. More study is needed, particularly in comparative studies, as the review highlights the dearth of peer-reviewed studies on utility-scale HPPs. Furthermore, it will be argued that combining artificial intelligence, machine learning, and sophisticated optimization algorithms for real-time decision-making is a potential approach to address challenging energy management issues. In order to create a power system that is cleaner, more economically feasible, efficient, and dependable, researchers will find great value in the ideas provided in this publication.

Energy storage devices (ESDs) offer solutions for autonomous electric vehicles, uninterrupted supply in remote areas, and flexibility in generation and demand in grid-connected systems, but each ESD has technical limitations to meet high-specific energy and power simultaneously **Reveles-Miranda et al. (2024) [17].** The combination of energy-power-based storage, enhanced technical features, and extra advantages is made possible by the complement of supercapacitors (SC) and batteries (Li-ion or Lead-acid) in a hybrid energy storage system (HESS). HESS's ability to improve quality of power (PQ), optimize battery performance, optimize sizing, and provide non-technical profits from cost reduction, environmental effect, and efficiency raises its worth. The study suggests a HESS-main categorization with ancillary services subclassified into (i) energy management, (ii) non-technical advantages, and (iii) power quality support and power systems protection. The services-oriented review takes into account the objectives and scope of each application. It also examines the ancillary services that are covered directly and indirectly as a means of assessing and offering insight into the value of HESS implementation and opening the door to a possible decrease in investment costs that could make this storage technology more profitable. In order to research and create new HESS, it concludes by summarizing the existing state of HESS and examining the storage requirements of upcoming electronic devices, large-scale power systems, and the growth forecast of isolated renewable energy (RE) systems.

Table 1 Comparison of Research Studies on Renewable Energy Integration and Power Flow Optimization

Author	Focus Area	Key Challenges	Proposed Solutions	Future Research
Savio Abraham, D et al. (2021)	EV charging stations powered by renewable energy sources, impact on utility grid, energy management strategies	Increased stress on utility grids, need for optimized charging station architectures and power converters	Energy Storage Units (ESU) for load balancing, advanced converter topologies, improved energy management	Improvement in energy management and control strategies, standardization of charging station architectures
Hu, J et al. (2021)	Microgrid development, power management challenges, Model Predictive Control (MPC) for stability	Unstable voltage/frequency, complexity in power management and microgrid-grid interaction	Model Predictive Control (MPC) for enhanced power flow stability and grid interaction	Advancements in predictive control techniques, integration with AI for better microgrid performance
Bevrani, H et al. (2021)	Frequency stability issues in power grids, modern control strategies for renewable integration	Integration of renewables affecting frequency stability, need for modernized control strategies	Modern control techniques leveraging advances in communication and computation technologies	New research in control strategies for high renewable penetration, development of smart grids
Bade, S. O. et al. (2024)	Hybrid Power Plants (HPPs) integrating wind and solar, optimization and energy management challenges	Challenges in optimization, sizing, and control strategies for large-scale hybrid renewable plants	Machine Learning and AI-driven optimization for real-time decision-making in hybrid plants	Comparative studies on different HPP configurations, AI-driven optimization techniques
Reveles-	Hybrid Energy	Limitations of	Hybrid Energy Storage	Expansion of HESS

Miranda et al. (2024)	Storage Systems (HESS), combining supercapacitors and batteries for energy-power balance	individual energy storage devices, need for hybrid systems for efficiency improvements	Systems (HESS) for power quality enhancement, efficiency improvement, and cost reduction	applications in large-scale power systems, cost reduction strategies, new storage materials

III. Objectives

- Setting up a hybrid charging station that harnesses both solar and wind energy, combined with a hybrid energy storage system incorporating PMSM and battery-based storage solutions to ensure optimal DC bus voltage stability.
- Designing a hybrid control algorithm to regulate DC/AC converters at the station, enhancing PMSM performance and enabling seamless integration with the power grid.
- Analysing the overall charging infrastructure under varying input conditions for both solar and wind energy sources to assess system efficiency and reliability.

IV. Research Methodology

The growing popularity of electric and plug-in hybrid vehicles is having a significant impact on the power grid, increasing energy demand and putting strain on the electrical infrastructure. While fast charging helps address the range limitations of these vehicles, it also amplifies power consumption, making efficient energy storage solutions like flywheel energy storage systems (FESS) crucial for enhancing grid stability and efficiency. This study proposes an AI-assisted power management scheme for EV charging stations, utilizing metaheuristic algorithms to optimize power electronics, real-time control, and energy distribution. The AC/DC controller within a d_{q^0} reference frame enables adaptive regulation, reducing energy losses and improving system reliability. By integrating optimization techniques with classical control methods, the system ensures better power quality, enhanced converter efficiency, and a more sustainable EV charging infrastructure.

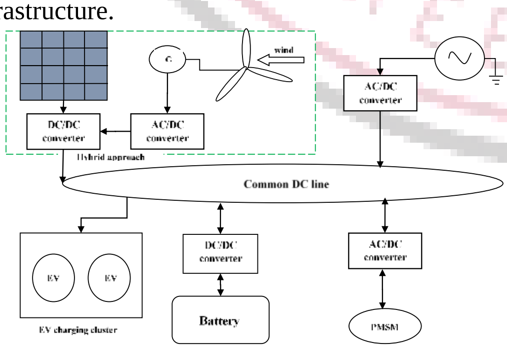

Figure 2 Hybrid approach at the charging station

A. Simulation of Flywheel Energy Storage System Using MATLAB

Equivalent circuit modelling is an essential method for analysing motor performance, helping engineers grasp how motors behave under different operating conditions and develop customized control strategies. In the case of a synchro-driven permanent magnet motor with a wheel-type design, the electromagnetic torque is represented in the d-q rotating reference frame, facilitating the examination of motor dynamics in relation to the vehicle and power supply. Important parameters include pole pairs (p), permanent magnet flux (Ψ_{PM}), and the motor's inductance components (L_d,L_q), with i_q and $i_d$denoting the quadrature and direct axis currents, respectively. This analytical method enhances motor efficiency, torque output, and overall vehicle performance. Furthermore, the MATLAB can be used to model flywheel energy storage systems with kinetic energy represented in an analytical form based on rotational dynamics.

$$KE = \left(\frac{1}{2}\right) I\omega^2 \text{L} \quad (1)$$

The power generated by the flywheel can be expressed as follows:

$$P_{out} = -I \cdot \omega \cdot \frac{d\omega}{dt} \quad (2)$$

- P_{out} is the output power,
- I is the moment of inertia,
- ω is the angular velocity, and
- $\frac{d\omega}{dt}$ is the angular acceleration.

B. Control Strategies for Power Electronics in EV Charging

In EV charging stations, AC/DC and DC/DC converter topologies play the key role, which can transform and regulate the power with very high efficiency. The AC/DC converter would change AC received from the grid to DC needed for charging an EV battery, whereas the DC/DC converter fine-tunes the voltage as well as the current level so that the special needs of any particular vehicle regarding charging can be fulfilled. Proportional-Integral (PI) control system, which is being used to sustain stable voltage, effectively manage the reactive power for charging. A control approach keeps monitoring the output and reduces deviation by adjusting parameters of the system, thus enhances the efficiency in charging, supports voltage stability, and optimizes the performance related to power factor in the charging station.

$$T_e = p\left[\lambda_f I_q + \left(L_d - L_q\right) I_d I_q\right] \quad (3)$$

Where:

- T_e = Electromagnetic torque
- p = Number of pole pairs
- λ_f = Permanent magnet flux linkage
- $I_d I_q$ = Direct and quadrature axis currents
- L_d, L_q = Inductance in direct and quadrature axis

$$V_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q \quad (4)$$

$$V_q = R_s I_q + L_q \frac{dI_q}{dt} + \omega L_d I_d + \omega \lambda_f \quad (5)$$

Where:

- V_d, V_q = Stator voltage components
- R_s = Stator resistance
- L_d, L_q = Direct and quadrature axis Inductance
- $I_d I_q$ = Direct and quadrature axis currents
- ω = Angular velocity

C. Renewable Energy System Modelling for EV Charging

The integration of solar and wind energy into electric vehicle charging stations will promote sustainability because it reduces dependence on fossil fuels and provides a cleaner source of energy. Renewable energy from solar panels and wind turbines can be used immediately for charging or stored in batteries for later use, thus improving the availability of energy and reducing reliance on the grid. MATLAB/Simulink is employed to simulate energy generation, storage, and distribution dynamics in assessing and improving integration. Simulation results are used for the evaluation of system performance, forecasting energy variation, and creating effective power management strategies that allow EV charging to be both reliable and environmentally friendly.

$$V_{out} = V_{mp} - I_{sc} R_s \quad (6)$$

Where:

- V_{out} = Output Voltage
- V_{mp} = Maximum Power Point Voltage
- I_{sc} = Short- Circuit Current
- R_s = Series Resistance

$$P_{wind} = \frac{1}{2} \rho A C_{p v^3} \quad (7)$$

- P_{wind} = Wind turbine power output
- ρ = Air density
- A = Rotor swept area
- C_p = Power coefficient
- v = Wind speed

D. AI-Based Optimization for Energy Management

Genetic Algorithm (GA) Optimization is applied in the EV charging stations to optimally enhance the power flow control for efficient energy distribution with minimum losses. GA is a bio-inspired metaheuristic algorithm that fine-tunes system parameters iteratively by selecting, mutating, and evolving solutions toward optimum performance. In this scenario, metaheuristics are particularly useful for optimizing the switching control of power converters, which handles the voltage and current levels through which energy is transferred efficiently. The algorithms dynamically change switching patterns to enhance the efficiency of conversion, reduce power losses, and make the overall charging infrastructure of the EV more stable and reliable.

$$F(x) = \sum_{i=1}^{n} w_i \left(x_i - x_{opt}\right)^2 \quad (8)$$

- $F(x)$ = Fitness function
- w_i = Weight coefficients
- x_i = Parameter being optimized
- x_{opt} = Optimal parameter value

AI-powered management of power and integration of renewable energy are essential to increasing the efficiency of the grid, reducing losses from power distribution at charging stations for EVs, and leveraging machine learning and predictive analytics to improve energy distribution, demand response, and storage in batteries. In addition, real-time AI-based energy forecasting can help balance loads and resource planning, reducing reliance on fossil fuels. Further research should focus on blockchain-based energy trading: decentralized and transparent transactions between the producers and consumers of energy while allowing peer-to-peer (P2P) energy exchange for EV charging. This will further enhance grid resilience, increase renewable energy utilization, and provide a more sustainable and cost-effective EV charging environment.

V. Results and Discussion

A 25 kW solar-powered charging station has been designed using MATLAB/SIMULINK, integrated with a flywheel energy storage system of 5 kW as well as the battery system. This station can feed power both to DC of 5 kW and AC, which are divided into two different sections of 5 kW. The DC/AC inverters are controlled through a genetic algorithm-based controller. The two control strategies used for the management of converters are Standard Voltage Modulation Control (VMC) and Optimized Power Flow Genetic Algorithm (OPGA). This paper aims to optimize power flow distribution with a stable 600V DC link voltage. Furthermore, the model also incorporates a wind energy system for evaluating different power distribution strategies. Findings show that solar radiation and temperature have a significant effect on solar cell efficiency, which in turn impacts the overall performance of the system. The OPGA method improves power quality and system stability by fine-tuning the parameters of the DC/AC converters, ensuring effective energy use in the charging station.

A. Performance Analysis of Power Flow Control

A standard regulator controller is utilized to analyse the system in charge of a 5 kW electric vehicle and provides 15 kW of power to multiple AC and DC loads. The relevant figure 3 shows the DC link voltage that allows power to flow in the charging station. Observations reveal disturbances in the DC link voltage as power flows through System 1. Observations reveal disturbances in the DC link voltage as power flows through System 1.

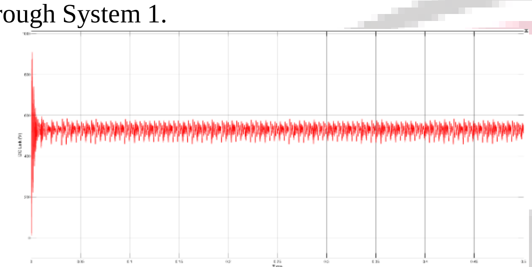

Figure 3 DC link management in the system with constant voltage regulation control

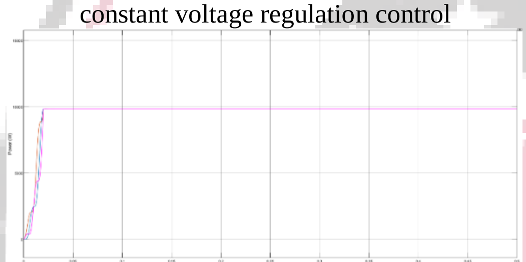

Figure 4 Active Power Drawn at the AC terminal of system 1 with solar fed CS

The Figure 4 shows the active power drawn at Ac load terminal in system1 and is found to be approximately 5 kilowatt. For AC loads resistive loads are used and hence the reactive power drawn in the AC load line of system 1 is zero.

B. Impact of Optimization on Energy Storage Utilization

The percentage state-of-charge of the battery, which stores excess input from the line, is graphically represented in this figure 5. The observations indicate that as surplus power becomes available, the battery absorbs the excess energy, gradually increasing the SOC from its initial value of 60%.

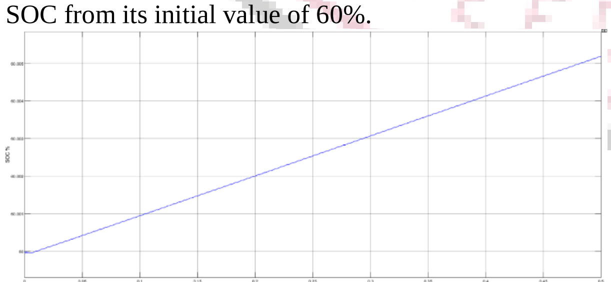

Figure 5 SOC% of the storage battery in system 1

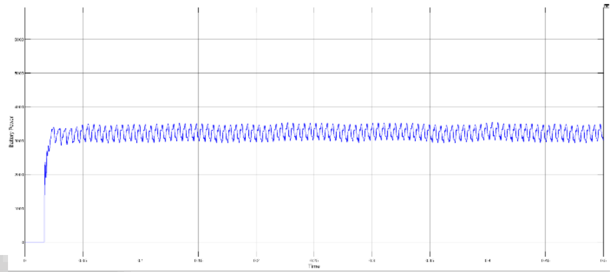

Figure 6 Power of the storage battery in system 1

The charging current of the battery storage system appeared on the corresponding figure 5. It should be noticed that the charging current is nearly 15 amperes and causes a gradual increase in the state of charge (SOC) starting from its initial value. The power available in battery storage system is shown in figure 6 which is the product of available battery voltage and the current charging the battery to store the power in system 1. The Flywheel Energy Storage System (FESS) is a part of an analysis for a system that employed a simple method of voltage regulation. For the conversion from DC/AC, a bidirectional controller was utilized, allowing the system to store kinetic energy based on the available power in the system. The Flywheel is observed to be rotating at a speed of 1500 rpm as shown in figure 7.

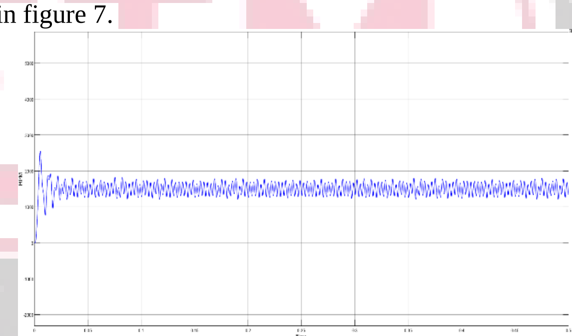

Figure 7 Speed of the PMSM based Flywheel energy storage in system 1

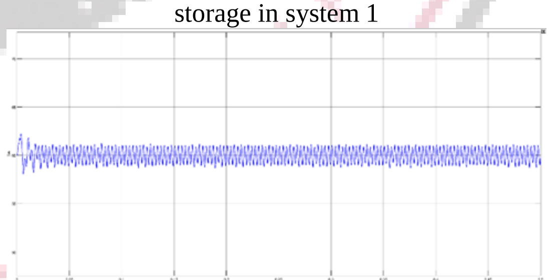

Figure 8 Torque of the PMSM machine working as Flywheel energy storage in system 1

During this case the excessive power is being stored in the Flywheel energy storage system and hence the power is positive and is measured to be approximately of 4.2 KW. The rotational torque generated in the system with management with basic voltage regulation control is shown in figure 8. The nature of torque generated in the machine is highly variable which effects the nature of output power and machine rotation speed.

C. Evaluation of Voltage Stability and Load Distribution

DC load which is of 5KW is directly connected to the DC link of the charging station and draws power form the line directly whose flow is controlled by the standard voltage regulation based controllers for the converters. The Voltage available at the DC line of the 5KW Dc load in system having voltage regulation based controller is shown in figure 9 which is same as that of the DC link 600V approximately and is unstable.

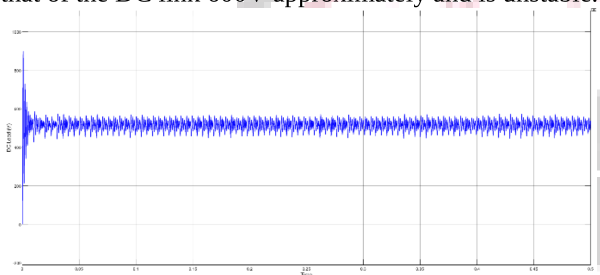

Figure 9 DC voltage at the Load terminal in system 1

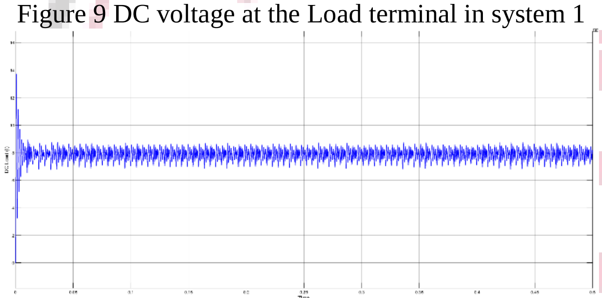

Figure 10 Current drawn at the DC Load terminal in system 1

When the DC load is connected to the system one it draws a current of approximately 8 amperes to drive the load which is shown in figure 10. The load current is highly unstable due to the fact that power flow across the DC link is not well examined stabilised. Load connected is of 5 kilowatt power and is shown figure in system 1 where all the controllers which maintain the power across the load and the storage systems are controlled by the standard voltage regulation based control systems.

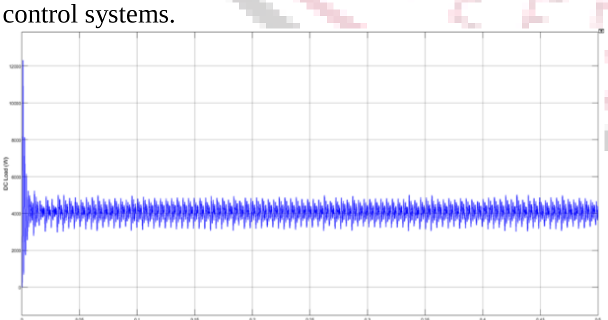

Figure 11 Power at drawn at the DC load terminal in system 1

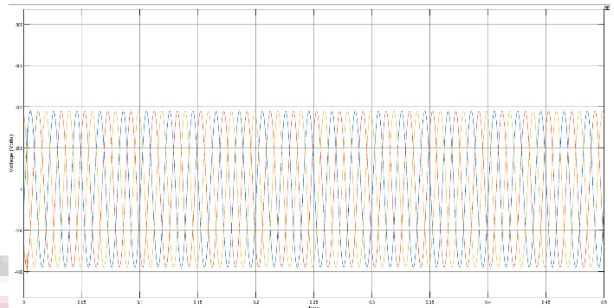

Figure 12 AC voltage in the line of system 1 with solar fed CS

During the analysis of the power flow the DC link, two AC loads of 5 kilowatt connected to the charging station via DC to AC converters and the power is transferred to these loads in the form of AC after conversion through the control system. The figure 12 shows the voltage at the AC load line of the Solar based charging station having controllers driven by standard voltage regulation based control. The output voltage is approximately 380V.

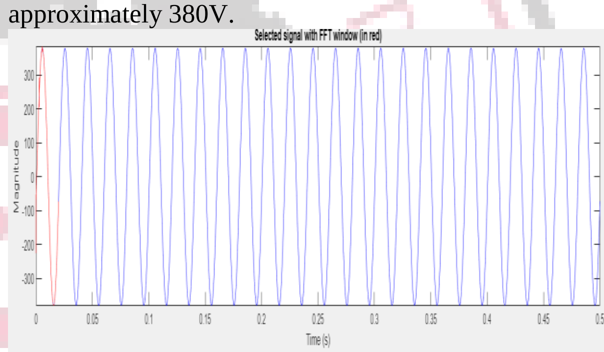

Figure 13 FFT analysis of AC voltage in the line of system 1 with solar fed CS

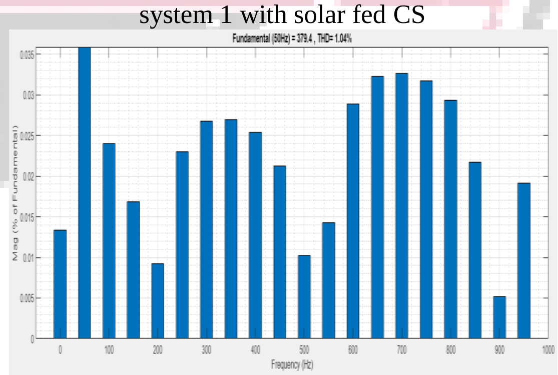

Figure 14 THD% in AC voltage in the line of system 1 with solar fed CS

The figure 13 shows fast Fourier transform analysis of the AC voltage in system 1 at the AC load line carried out in MATLAB which is them utilised for analysing the distortion levels present in the AC voltage available at the load. The figure 14 shows the distortion percentage in the AC voltage in system 1 which is found to be approximately 1.04%. The three phase current drawn at the AC load line of the system one is shown in figure 15. This current is drawn at the low terminal is 24 Ampere. It is driving two loads of 5KW each after conversion from DC/AC converters. The figure 16 shows fast Fourier transform analysis of the AC current in system 1 at the AC load line carried out in MATLAB which is then utilised for analysing the distortion levels present in the AC current drawn at the load terminal.

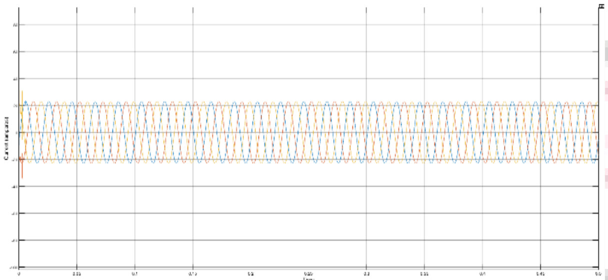

Figure 15 AC current drawn in the line of system 1 with solar fed CS

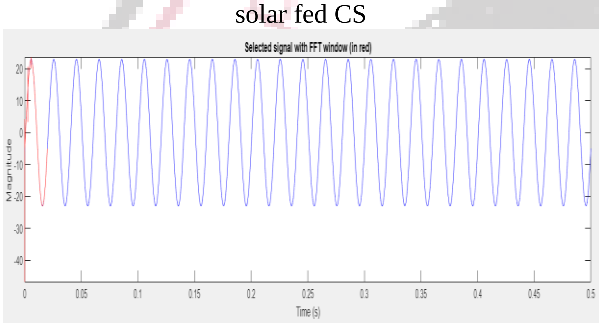

Figure 16 FFT analysis of AC current drawn in the line of system 1 with solar fed CS

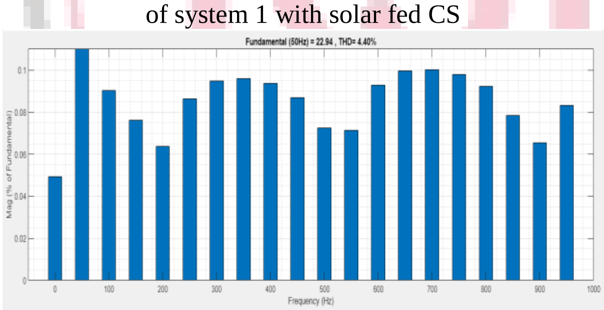

Figure 17 THD% in the AC current drawn in the line of system 1 with solar fed CS

Figure 17 as for the system 1, the distortion percentage of the AC current is found to be about 4.40%. The input provided to the DC/AC converters as well as the control system driving them do affect the distortion levels. In this case, the system is controlled by standard voltage regulation based controllers.

Table 2 Comparative analysis of CS with solar as inputs and DC/AC converter having two controllers

Parameters	**System with standard voltage regulation control**	**System with standard proposed OPGA control**
DC load line power	unstable	stable
AC load current distortion	4.40%	1.28%
Ac load voltage distortion	1.04 %	0.29%

VI. Conclusion

The study focuses on integrating renewable energy into electric vehicle charging stations, which can help stabilize power flow, reduce dependence on grid electricity, and enhance sustainability. With hybrid renewable energy sources such as solar and wind power and advanced energy storage systems, these charging stations can achieve greater reliability and efficiency. These hybrid systems will be helpful in managing power supply fluctuations and help stabilize and make the energy distribution process more predictable. This would also be particularly useful in helping to reduce the dependence on the traditional grid power, which, in most cases, is a fossil fuel-based product, hence aligning with the environmental goals that EV usage is associated with. These are AI-based optimization techniques, like Genetic Algorithms and Model Predictive Control, applied to power distribution management and optimal energy usage to improve system performance. The algorithms control the energy flow in real-time within the charging stations and reduce inefficiencies and losses by ensuring that power supply meets demand. The MATLAB/SIMULINK simulations yield the following findings: the optimization strategies are effective in improving DC link voltage stability, reducing harmonic distortions, and enhancing energy efficiency. The results show that a well-designed, renewable-integrated charging infrastructure is not only practical but also advantageous for improving the operational efficiency and reliability of EV charging stations. Challenges persist, especially on the side of energy conversion losses and the inherent intermittency of renewable energy sources. The fluctuations in the availability of solar and wind energy make power generation unpredictable, and it requires sophisticated energy management techniques to ensure stability. Energy conversion losses at different stages of power conversion are still significant issues, since these losses have a direct impact on the performance and economic feasibility of renewable-based charging stations. Tackling these issues will necessitate ongoing research into advanced control systems, enhanced battery technologies, and efficient power electronics. Looking forward, future research and technological advancements are anticipated to propel further progress in this area. The incorporation of blockchain-based energy trading systems could facilitate decentralized and transparent energy transactions, enabling peer-to-peer (P2P) energy exchanges between EV users and renewable energy producers. Such innovations have the potential to strengthen grid resilience, foster energy independence, and create new economic models for energy distribution. In addition, optimization of hybrid energy storage systems through advanced materials and machine learning-driven predictive analytics can improve energy retention, enhance power balancing, and extend battery life cycles. In summary, the shift towards renewable-powered EV charging infrastructure is a vital step in achieving a sustainable and carbon-neutral transportation system. Despite the challenges, integration of AI-driven optimization techniques, advancements in energy storage, and decentralized energy trading mechanisms will continue to aid in realizing an intelligent, self-sufficient, and resilient EV charging network. Continuous development in this domain is a great promise for shaping the future of green mobility, making electric transportation more accessible, reliable, and environmentally friendly.

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