Hybrid Renewable Microgrid-Based Smart EV Charging Stations with AI-Enhanced Energy Management

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Abstract: Rapid growth in the deployment of electric vehicles (EVs) has fuelled the demand for sustainable, efficient, and intelligent charging infrastructures. This work presents a smart EV charging station model interfaced with a hybrid renewable microgrid formed by solar and wind energy systems and supported by dual energy storage, namely battery and flywheel. The model under testing was built in the MATLAB/SIMULINK environment and has a centralized DC bus with an AI-based control strategy using multi-stage genetic algorithm (MS_GA) with the fuzzy logic interface. The hybrid approach has the additional benefit of enhancing system stability through DC link voltage regulation, total harmonic distortion (THD) minimization, and optimal power flow management, adapted to the best possible under constant or variable irradiation conditions. The charging station consists of unidirectional DC/DC converters for EV charging and AC/DC inverters for AC loads, allowing for real-time adjustments in reactive and active powers. The comparison between classical voltage regulation and the proposed AI-based control strategy showed excellent gains in grid reliability, voltage stability, and energy utilization. Load forecasting, V2G integration, and dynamic control through artificial intelligence will provide an adaptable and robust solution for smart cities of the future. The model also adapts under lower renewable efficiencies, proving the flexibility and viability of the proposed hybrid energy management.

Keywords: Electric Vehicle Charging Station, Hybrid Renewable Energy System, Solar Energy, Wind Energy, Energy Storage Systems, Flywheel Energy Storage (FESS), Battery Energy Storage (BESS), DC Microgrid, Smart Charging, Artificial Intelligence, Genetic Algorithm, Fuzzy Logic Control, Total Harmonic Distortion (THD), Voltage Stability, Vehicle-to-Grid (V2G), Energy Management System (EMS), MATLAB/SIMULINK Modelling, Load Forecasting, Smart Grid Integration.

I. Introduction

Smart charging is a contemporary technology and an advanced method for considering the pricing, availability of electricity, and needs of the driver in optimizing the time and mode for electric vehicle (EV) charging [1]. For this process, a data link is required between the EV, the charger, the cloud management platform, and the grid; it allows the operator to control energy application for the sake of regulation [1]. Cloud-based solutions allow easy tailoring of services to individual needs, provide support for vehicle-grid integration, and assist in preventing overload on the grid [2]. When the charging cable is plugged in, an interactive communication session or driver identification will commence automatically to provide charging management, battery tracking, and billing of the driver [3]. The charger also acts as a mediator between the infrastructure and the grid through a central platform that oversees energy resources [4]. Smart charging lowers the cost of charging and alleviates stresses on the grid by promoting the charging of electric vehicles during off-peak periods or intervals in which renewable energy generation is abundant [5]. Through communication with vehicles, grids and users, smart EV charging stations make intelligent management of charging for vehicles, thus optimizing efficiency, cost and convenience. The escalating popularity of EVs necessitates extensive charging infrastructure [6]. Advancements in Level 2 and DC fast chargers have enabled rapid battery replenishment specifically along major routes [7]. Such features as real-time monitoring and auto transactions contribute to even more reliability and end-user enjoyment.

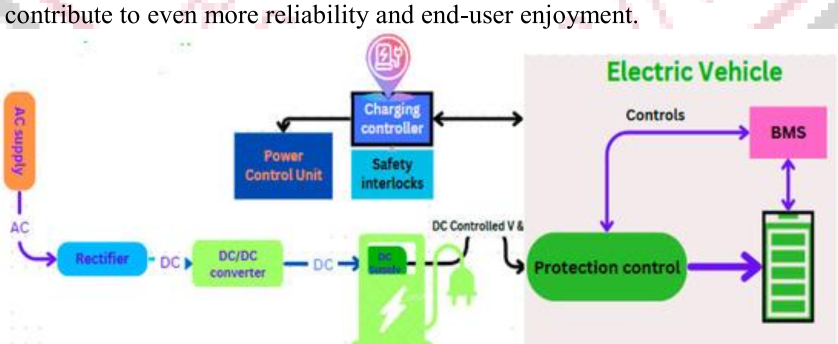

Fig. 1 Block diagram of an electric vehicle charging station [8]

Fig. 1 thus shows the basic EV charging system from where an electric-powered source connects: for example, Alternating Current power can be converted into direct current supply by using a rectifier and DC/DC converter, which is then finally pumped into the EV with control procedures from charging unit and battery management system BMS for safety and battery monitoring [9]. Smart charging ensures that cost is optimized, as operations would mostly occur when demand is at its lowest, while relaying user preferences to the cloud platform through 3G/4G/5G, Ethernet, or Wi-Fi. IoT SIM cards are also commonly used because they charge much less and allow monitoring from remote places but are far better than Ethernet and Wi-Fi regarding ease and reliability in real-time applications [11].

A. Wireline Communication for Smart EV Charging Stations

The high reliability and long-distance data communication possibilities make wireline communication technologies ideal for smart EV charging installed in large cities. Power Line Communication (PLC) is the widely accepted protocol, employing existing power lines for simultaneous power and data transmission. PLC is characterized by its robustness and interference resistance, having standards established based on it such as HomePlug 1.0, HomePlug AV, HD PLC, and UPA [12][13]. Optical fiber and Digital Subscriber Line (DSL) also provide this solution, allowing for high data rates, long ranges, and low-cost deployment at high voltages [14]. But wireless interaction allows the real-time interaction of EVs with charging stations, enabling energy management, billing, and V2G services in a smart way. These wireless networks are often arranged as hierarchical mesh systems, offering scalability, resilience, and low data loss, presenting the best environment for operational efficiency and user experience [15][16]. Fig. 2 Smart electric vehicle charging system integrated with renewables, storage, and vehicle-to-grid technology that allows bidirectional energy flow and real-time coordination with the grid [17]. Smart electric vehicle charging systems pave the way to tremendous benefits in the energy sector, effectively improving the efficiency of energy use and bringing resultant values to most stakeholders. For example, smart charging systems are quite beneficial for drivers of electrical vehicles (EVs) as they provide convenience and safety from various factors, including financial aspects through mobile applications designed to locate stations, current pricing, fast charging access, and most automated billing [18] [19].

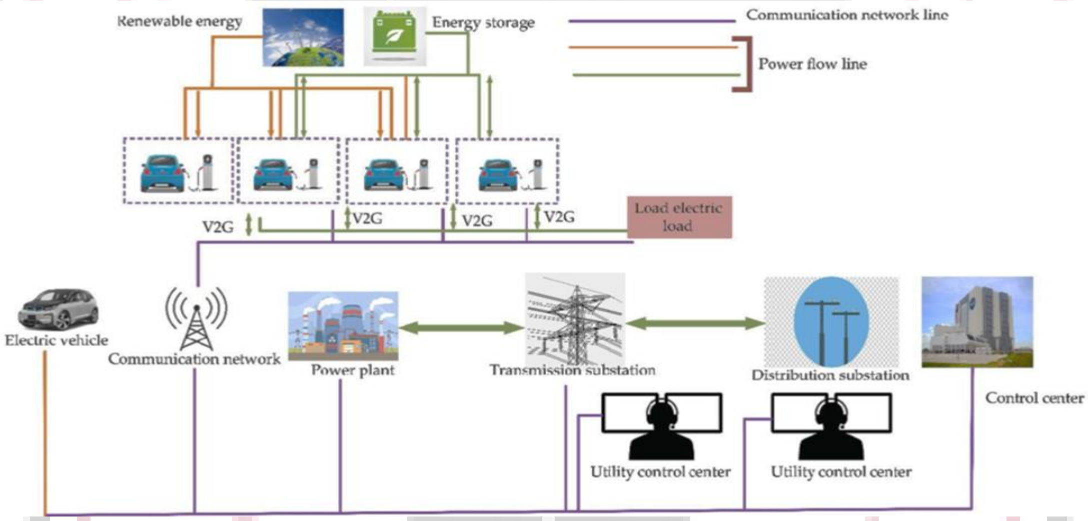

Fig. 2 Smart EV Charging System with Renewable Energy, Storage, and V2G Integration [17]

In addition, it can facilitate off-peak charging, resulting indirectly in reduced electricity costs and environmental impacts, as well as possible incentives such as grid backup services. For businesses, smart charging allows centralized station control across numerous sites, efficient billing, and energy use optimization without overcharging the electric grid. Other advantages include remote troubleshooting, flexible pricing, and operational autonomy, which allow businesses to concentrate on their principal functions while enjoying control and visibility of operations [20].

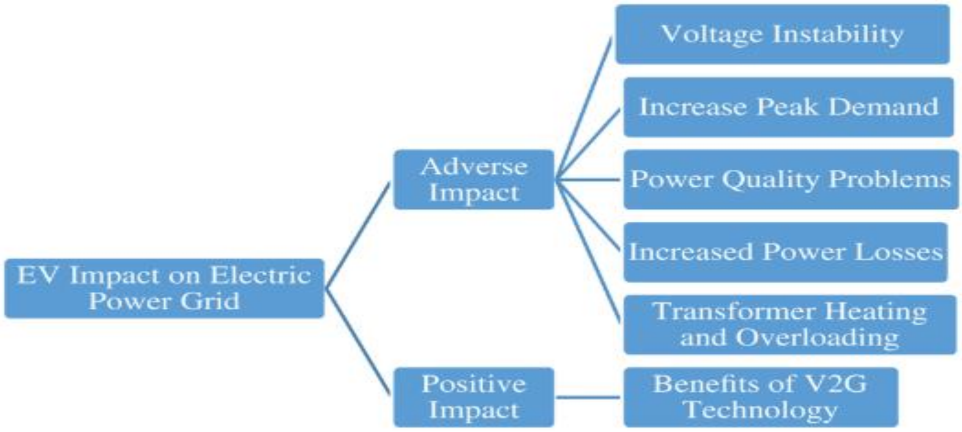

Fig. 3 EV impacts on the electric power grid.

Electricity generation and charging network operators can enhance grid stability through smart charging-real time demand-response and energy optimization. These systems enable remote upgrades, scalability, and data-driven decisions via dashboards that show station activity and user behaviour while adaptive service models and demand response programs provide new revenue opportunities [21]. As shown in Fig. 3, EV charging has both advantages and disadvantages regarding grid issues. Peak load increases--up to 43% in uncoordinated charging scenarios in Australia--bring up issues for which tariff-based strategies, especially concerning high-demand fast-charging stations, will have to be developed: even though no voltage instability took place under varying EV penetration levels [22]. EV charging also plays a role in power quality through harmonics and voltage sags, requiring Total Harmonic Distortion (THD) control for reliable grid operation [23]. In addition, thermal stress increases with uncontrolled charging, and the transformer ages more quickly. This captures the reason why coordinated charging is good for the long-term health of the grid [24].

B. Renewable Hybrid Microgrid Systems

With increasing global demand, energy becomes an engine for both national growth and global development, thus necessitating sustainable energy management from one region to the other, and into the future [25]. This has had to turn people towards alternative renewable energy sources (RESs), like solar and wind, which are known to be eco-friendly and unlimited in availability [26]. Applications of RESs to the electric grid cover all varieties-from residential to industry, and EV charging infrastructure; thus, hybrid renewable energy systems (HRESs) along with microgrids are receiving even more attention to bring about energy security, efficiency, and sustainability [27]. The increased adoption of EVs drives an increased focus on optimizing performance and evaluation from technical and economic perspectives-aspects that can be further bolstered by assessing based on various prediction scenarios. Many benefits have been seen from this trend in power grid operation: reduced generation costs, increased voltage stability, reduced power losses, and less generation of carbon dioxide from fossil fuels. Thus, the need to modernize conventional grids to integrate both RES and EVs becomes strong [29]. Fig. 4 shows such a hybrid configuration, which enables wind, solar, and conventional sources through an AC connection complemented by storage solutions like batteries and hydro-pumped systems to deliver a reliable, flexible, and sustainable power supply for residential and EV loads.

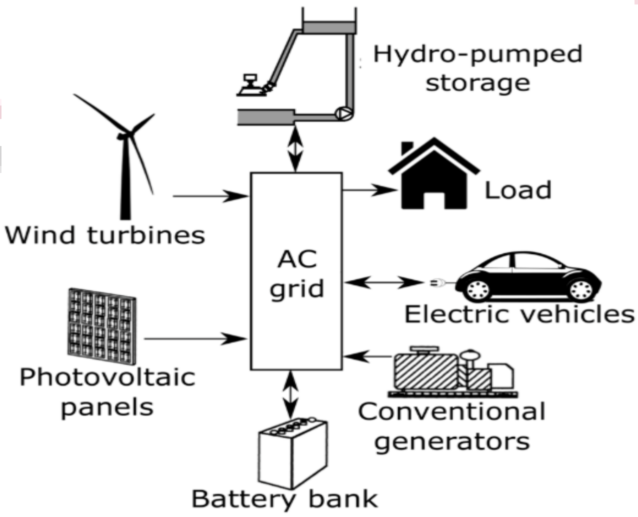

Fig. 4 Hybrid Energy System Integrated with AC Grid [30]

C. Artificial Intelligence in EV Energy Management

Artificial intelligence is necessary in electric vehicles (EVs) energy management optimization because of machine learning (ML), neural networks (NN), and reinforcement learning (RL). These technologies enhance EV performance, efficiency, fault detection, life cycle assessment, among others, predictive maintenance, and user preferences [34]. In addition, these EVs can also provide backup power when charged using solar PV systems [35]. The AI-based EMS enables energy forecasting, route optimization, and load balancing in battery, fuel cells, and hybrid systems, which promotes cost-and-energy efficiency in EV-microgrid applications [36][37]. Fig. 5 shows AI's contributions to optimizing charger placement for EVs, decongesting the network, and facilitating smart real-time interaction with the grid.

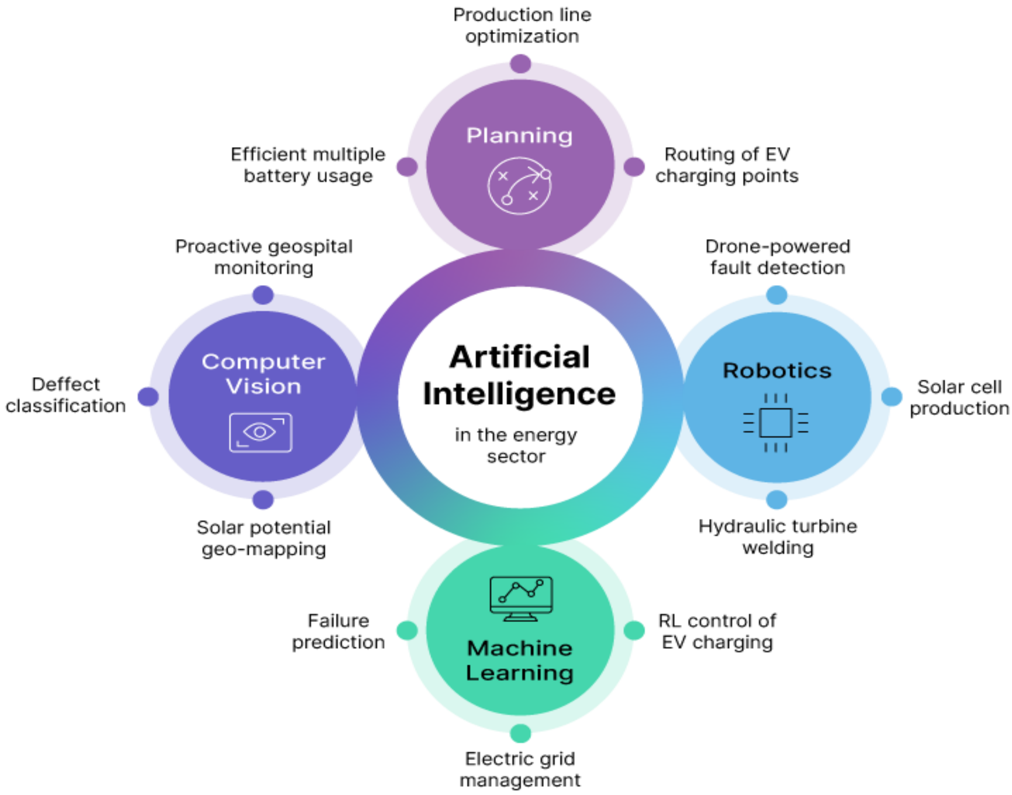

Fig. 5 Applications of Artificial Intelligence in the Energy Sector [38]

AI is necessary for an accurate load forecast and a subsequent charging schedule optimization. The analysis of massive datasets, nowadays employed by AI, helps predict energy demand, adjust patterns of charging, and use user behaviour modelling for load balancing in real time and reduced waiting times [39][40]. Smart algorithms dynamically split energy to the user according to priorities, like grid stability, pricing, and renewable availability, and should consequently create a better and user-friendly-charging experience [41]. Advanced optimization technologies would combine EMS easily into changing conditions for improvised grid integration and lowered operational costs [42]. Leveraging smart sensor data gathered from EV systems, AI helps to detect the presence of faults early on so that maintenance can be scheduled in a proactive manner to ensure safety and prevent the occurrence of breakdowns [43]. This further enhances the accuracy of diagnosis over time through deep learning and reinforcement learning [44]. AI is responsible for optimizing energy consumption in fleet management while simultaneously minimizing downtime, while charging systems for EVs are being scheduled by AI to predict demand and coordinate several charging stations [45][46]. Generally, AI improves efficiencies, grid stability, and sustainability to support the mass adoption of electric mobility [47].

II. Literature Review

A comprehensive research work on the charging technologies for electric vehicles (EVs) has been conducted and reported in the literature on environment benefits of shifting from fuel-based transport modes, with key barriers to adoption listed to include: changing from fuel modes to electric, charging time, speed, costs, reliability, and effects on grid impact [48]. Unidirectional and bidirectional AC-DC/DC-DC charging topologies of charging technologies have been studied in terms of efficiencies and limitations for slow and fast charging of EVs. The study also focused on conductive and wireless methods for charge transfer such as battery swapping; with mention of inductive, capacitive, and optical technologies; and concluded further investigation on grid-related issues such as distorted waveform and fluctuating voltage and load management. Another investigation proposed a whale-optimized neuro-fuzzy-classification-based deep learning control system that achieved a success accuracy of 99%in charging administration concerning power input from the grid according to users' requirements [49]. The random utility model will portray behaviour in which EV drivers are incorporated with improved smart grid charging services [50]. Research in electric vehicle smart charging (EVSC) shows a 30% cost saving, 10% operation saving, and up to 40% mitigation of curtailments due to aggregator, forecasting, and integration strategies [51]. For example, cloud-based infrastructure in studying charging is proven to be beneficial in management and cybersecurity [52]; IoT-cloud systems for optimal solar powering of mobility and optimally locating EVCS network [53]; and sustainable solar-EV integration across regulatory and economic barriers [54]. The office charging scenario regarding charging through WPT, IoT, and solar is also considered [55]. It studies the effect of plug-in EVs on distribution reliability and the necessity for energy management in variable renewable conditions. [56]. Work done in microgrids emphasizes energy storage, V2G technology, and support of policy initiatives for grid resilience [57]. Hydrogen fuel cell electric vehicles were studied for determining the control strategy that these optimization approaches likely rely on data and artificial intelligence [58]. LSTM shows it being more accurate in short-term prediction on EV demand by load forecasting using AR, SVR, and LSTM [59]. Many AI techniques could also be used in EV powertrain fault detection systems where reliability and future performance improvements will include system maintenance [60]. Finally, smart charging models incorporating driver data while addressing uncertainty of demand in EVs can be seen as scale-up low maintenance solutions to grid optimization [61].

Table 1 Analysis of Integrated Smart Charging Solutions for Sustainable E-Mobility

Reference	Model Parameter	Method Used	Key Findings	Outcomes
Mohammed Masud Rana et al. (2025) [48]	Charging techs, grid impacts	Topology & method review	EVs support grid balance, need for efficiency	Highlights integration challenges and gaps
T. Senthilkumar et al. (2025) [49]	DL + Whale-Optimized Neuro-Fuzzy	Deep learning, fuzzy logic, WOA	High prediction accuracy (99%), grid-aware control	Validated robust AI model for smart cities
Nicolò Daina et al. (2025) [50]	Utility model for EV behaviour	Random utility modelling	Behavioural insights into smart grid integration	Useful for EV charging policy design
Omid Sadeghian et al. (2025) [51]	EVSC with aggregator role	Analytical assessment	EVSC reduces cost, curtailment, and grid stress	30% cost & 10% operational savings
N. Sumanth Chowdary et al. (2024) [52]	Cloud infrastructure for EVCS	Descriptive study	Cost-effective, efficient cloud-based EVCS	Cloud boosts energy management efficiency
Yousra Abdul Alsahib S. Aldeen et al. (2024) [53]	IoT-CC based EVCS model	IoT and cloud modelling	Improved EVCS with IoT, solar, and payment systems	Sustainable, user-friendly EVCS
Muhammad Usman Nawaz et al. (2024) [54]	Solar-EV integration aspects	Technical, economic, policy review	Solar-EV charging feasible but faces barriers	Proposes supportive policies and models
Sheeraz Iqbal et al. (2024) [55]	WPT + IoT + Solar for offices	Integrated system design	IoT-enabled WPT enhances office EVCS	Office EV charging automation
A. Rajapandiyan et al. (2024) [56]	PEV grid impact, cost optimization	Simulation analysis	Controlled charging boosts grid stability	Recommendations for grid cost-efficiency
Yingking Mitra Prianka et al. (2024) [57]	RES-microgrid-EV interaction	Review and strategy analysis	Microgrids optimize energy and RES usage	Supports DERs and grid stability
Mojgan Fayyazi et al. (2023) [58]	Fuel cell EV energy control	Data-driven AI methods	AI critical in managing hydrogen vehicles	Future trend direction for fuel cell EVs
Gayathry Vishnu et al. (2023) [59]	EV load forecasting models	AR, SVR, LSTM comparison	LSTM superior in short-term EV forecasting	Accurate EV demand prediction metrics
Xiaotian Zhang et al. (2023) [60]	AI in EV powertrain diagnostics	AI-based condition monitoring	AI improves safety and reliability in EVs	Promotes AI for powertrain monitoring
T. Rigaut et al. (2022) [61]	Smart charging demand uncertainty	Smart charging architecture with simulation	Demand forecasting reduces grid uncertainty	Validated low-maintenance, scalable model

III. Objectives

1. Development of a common DC link bus and its Central management scheme driving DC loads and charging of E-vehicles.
2. Designing of a hybrid solar-wind based charging station in combination with hybrid storage system comprising of battery and PMSM based energy storage devices in order to optimize the DC bus voltage balance.
3. Development of Modified Power Quality control strategy in combination with optimization algorithms guided by Artificial Intelligence in bi-directional DC/AC converter.
4. Development of hybrid algorithm to improve the performance at the PMSM point.

IV. Methodology

The increasing share of electric and hybrid vehicles is enhancing their impact on grid load. They are gradually becoming the primary means of personal and commercial transportation. As their market share increases, so therefore does their impact in terms of electrical demand. Although hybrids primarily circumnavigate the range issue, the original EVs are still riddle with constraints that most often necessitate an expensive high-capacity battery. Fast charging facilitations tackle the issue of range anxiety, increasing demand for electricity, hence further pressurizing the grid. It is here that the EES plays an important role in diminishing peak demand, optimizing demand-supply matching, and augmenting system efficiency. Among the EES types, flywheel energy storage suitable for short-duration high-power applications is gaining ground with changing technology, proving more and more feasible across various sectors.

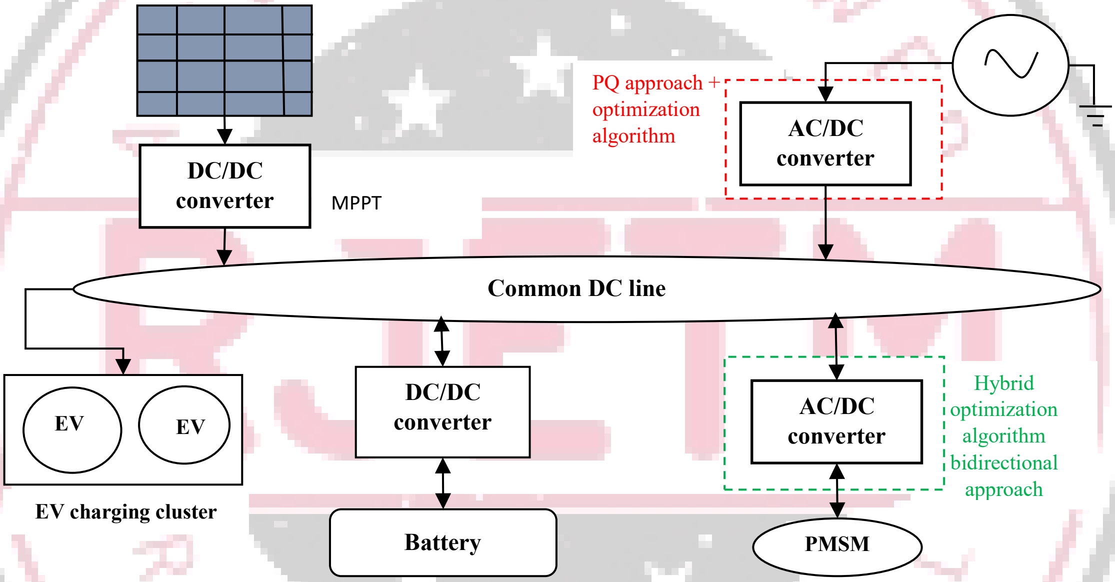

Fig. 6. Proposed controls at the AC/DC conversion system in the EV model at the DC micro grid

This study investigates the optimization algorithm-centric approaches to conventional methods for power system control during EV charging station development. The inherently distinct nature of rapid control tuning and sensitive condition monitoring requirements of power electronics means that the forms of optimization applicable in this field will be fundamentally different from those in other "traditional" engineering areas.

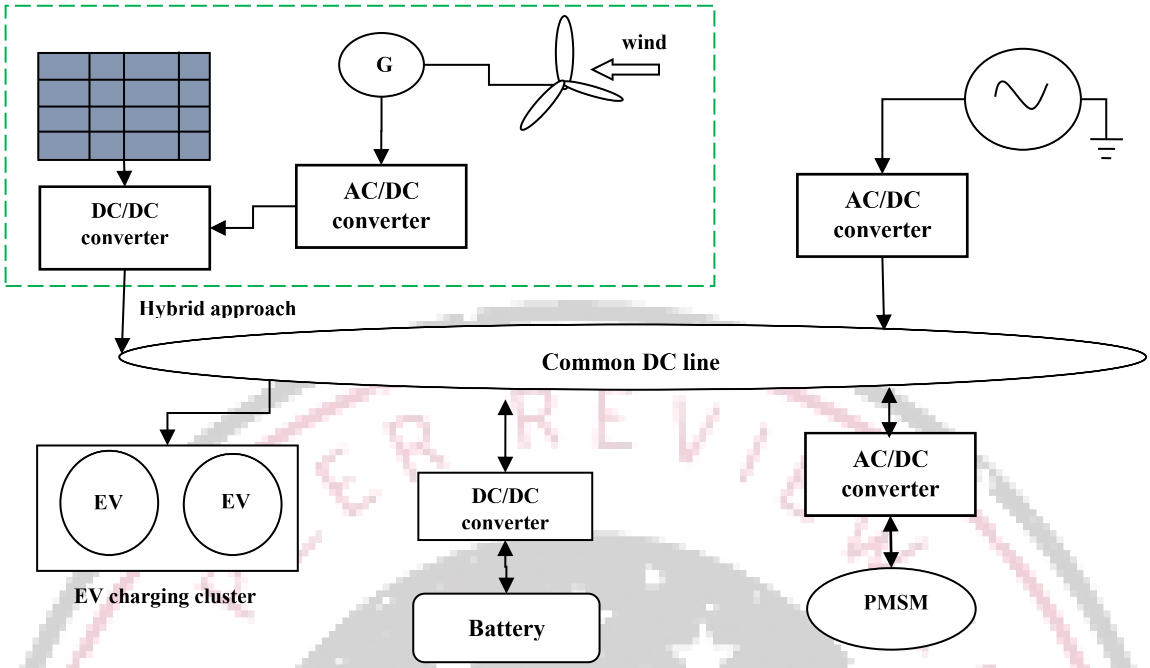

Fig. 7 Hybrid approach at the charging station

The AC/DC control at the grid termination is designed using a PQ based optimization technique towards further improving grid-side performance in dq0 reference frame for an easy analysis. The controller monitors the parameters of the grid, load, and inverter output and adjusts the active and reactive powers accordingly. Current reference control determines the use of phase shifting for reactive power, and balances load requirements through PI controller gain tuning, finally adding harmonic correction before the generation of the PWM signal. A second controller governs the bidirectional power flow associated with an energy storage device based on PMSM, wherein the AC/DC converter behaves like a DC source, driving the PMSM by controlling angular speed under varying load torques. Thus, focus will be on the functionality of the converter, battery discharge control, PMSM speed regulation, and overall energy management. Proper converter design is crucial for system safety and minimal driveline losses in the efficient operation.

A. Modelling of flywheel energy storage system in MATLAB

Equivalent circuits of the motors are used for study and simulation of motors. From the d-q modelling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Since the wheel motor is a synchronous permanent magnetic machine (PMSM), the electromagnetic torque expressed in the d-q rotating frame is given by:

$$T_e = \frac{3p}{2}[\Psi_{PM} i_q + i_q i_d (L_d - L_q)] \qquad (1)$$

Where p is the number of pole pairs; Ψ_{PM} is the flux produced by the permanent magnet; L_d and L_d are respectively the direct and quadrature components of the wheel motor inductance. i_q is the quadrature axis current and i_d is the direct axis current.

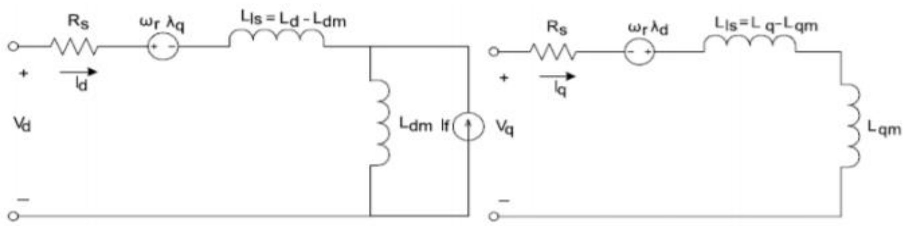

Fig. 8 Equivalent d-q Axis Model of a PMSM (Permanent Magnet Synchronous Motor) in the Rotating Reference Frame

$$KE = (1/2) * I * \omega^2 \qquad (2)$$

where KE is the kinetic energy, I is the moment of inertia of the flywheel, and ω is the angular velocity of the flywheel. The rate of change of kinetic energy with respect to time is the power input to the flywheel, which can be expressed as:

$$P_{in} = d\,(KE)/dt = I * \omega * d\omega/dt \qquad (3)$$

The power output from the flywheel is given by:

$$P_{out} = -I * \omega * d\omega/dt \qquad (4)$$

where the negative sign indicates that power is being extracted from the flywheel.
The net power input to the flywheel is the difference between the power input and the power output:

$$P_{net} = P_{in} + P_{out} = I^{*}\omega^{*}\, d\omega/dt - I^{*}\omega^{*}\, d\omega/dt \quad (5)$$

The flywheel energy storage system (FESS) is modelled using a Permanent Magnet Synchronous Machine (PMSM), during which energy is presumed constant with reference to time. The model includes a back-to-back power converter, consisting of two three-leg inverters, each of which is modelled using six force-commutated IGBT power switches in a bridge layout. These converters have been simulated using the well-detailed equations within a simulation environment. The control construct has an inner current loop and an outer speed loop, with constant voltage regulation in one of the approaches and a genetic algorithm-based method of gate signal control for the DC/AC converter. The FESS system consists of Inverters with control logic with PMSM-based flywheel that receives the stored energy in the flywheel as indicated in Equation 6.

$$E = \frac{1}{2}J\omega^2 \quad (6)$$

where J is the wheel inertia and ω is the angular speed
The d_q model of PMSM can be represented as follows:

$$v_q = R_s i_q + \frac{d}{dt}\lambda_q - \omega_e \lambda_d \quad (7)$$

$$v_d = R_s i_d + \frac{d}{dt}\lambda_d - \omega_e \lambda_q \quad (8)$$

where variables v_d and v_q are d_q stator voltage components, i_q and i_d are d_q stator current components. ωe is the angular velocity of the electrical magnet field in the rotor. Rs is the stator resistance. Flux Linkages are given by:

$$\lambda_q = L_q i_q \quad (9)$$

$$\lambda_q = L_q i_q + \lambda_f \quad (10)$$

where λ_f is the PM flux linkage, L_d and L_q are dq axes inductance. The electromagnetic torque (Te) can be given by:

$$T_e = \frac{3}{2}P(f i_q - (L_d - L_q) i_d i_q) \quad (11)$$

where p is the number of pole pairs. but since $L_d = L_q$, the applied Torque becomes:

$$T_e = \frac{3}{2}P(\lambda_f i_q) \quad (12)$$

B. Converter Control system DC/AC Architecture control Designing

Motor drive conversion systems are composed of three main parts: power converters, motors, and control systems. The converters undertake the task of transforming DC input voltage into three-phase AC output voltage for driving the motor, which in turn converts electrical energy into mechanical energy for the purpose of driving a load. Voltage Source Inverters (VSIs) are generally employed for adjustable speed drives and are designed to produce a switched voltage waveform for controlling both the amplitude and phase of the stator current, thus representing the high-band and width inner loop in the whole motion controller. The control system operates by determining the output voltage and frequency using a mathematical model taking into account the dynamics of both the DC side and the AC side in safe operation. Then the feedback control system adjusts the switching signals in an area called Pulse Width Modulation (PWM) to have certain outputs. The three-phase inverter bridge comprises three pairs of switches between the given DC source and output phases, triggered according to the PWM technique to obtain a three-phase AC waveform. By alternating the switching states of its power devices between ON and OFF, an inverter is capable of providing the required AC output. The block diagram of a three-phase grid-connected DC-AC inverter is shown in Fig. 9.

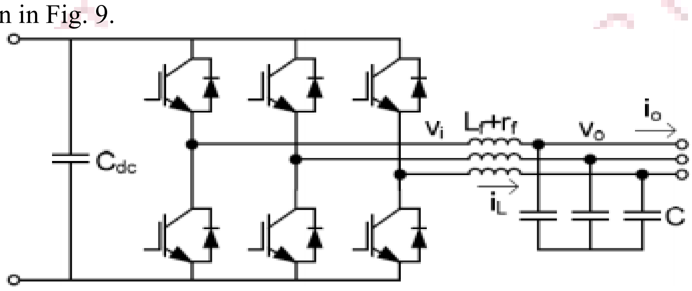

Fig. 9 Block diagram of three phase inverter.

Table 2 Inverter Parameters

Power electronic device	IGBT/Diodes
Snubber resistance	5000 ohms
Forward voltages	0
Ron	1x10^{-3} ohms

C. Multi stage Genetic Algorithm Description for Converter Control

In a conventional scheme, the controller parameters are fixed. These fixed parameters are not suitable for dynamic references. Unsuitable parameter specifications will sometimes cause the system to become unstable. Thus, it is important to select suitable parameters for the scheme. The optimization algorithms based on artificial intelligence is widely used to solve optimal problems because of its excellent optimization efficiency and global search capabilities. These algorithms are programmed to imitate nature's selection process and obtain the optimal solution based on several bio-inspired operators.

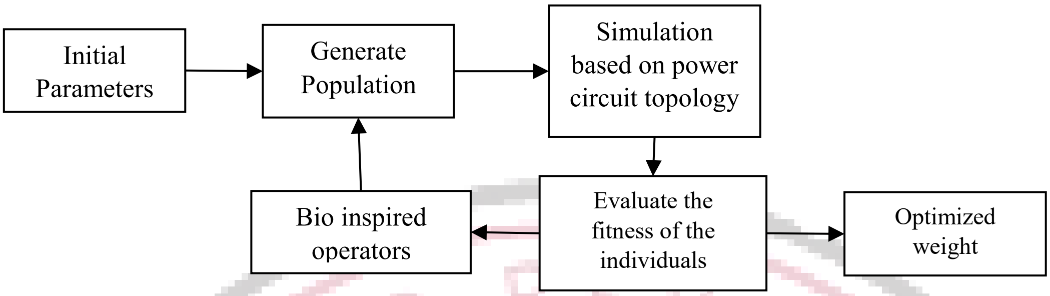

Fig. 10 Operation of the optimization scheme

After an iterative calculation, the optimal result can be obtained. the aim of the optimization problem is to find a group of initial weights that can minimize the suppression/evaluation time and overshoot. This means that the optimization process should shorten the suppression time as much as possible and limit the amplitude of the overshoot. the performance of the converter could be improved to a greater extend by selecting an optimum PID gain which guarantees a better dynamic and steady state response. With the aim of optimizing the systems dynamic and steady state behaviour under disturbances, the objective function is selected for minimization and the PID gains are tuned so as to minimize/maximize the objective function, thus guaranteeing the desired dynamic performance.

V. Results and Discussion

A 25 KW solar-powered charging station developed in MATLAB/SIMULINK consisted of two coupled storage systems such as a 5 KW flywheel energy storage system and batteries at about 60% initial SOC. The station supplies 5KW DC loads plus two offloads: one to be used by 5KW AC loads, using DC/AC inverters controlled by a genetic algorithm-based logic controller, while unidirectional DC/DC converters manage EV charging. The system analysis focuses on stabilizing 600V DC link and minimizing total harmonic distortion of the AC loads. While comparing traditional voltage regulation control under an altered MS_GA with fuzzy interface system for driving the DC/AC converters for EV charging, the extension of the model would further accommodate the wind energy in addition to solar energy and also analyse power distribution mechanisms subject to two different control systems, where one control employs standard controllers and the other employs a multi-stage genetic algorithm with fuzzy rules, optimizing parameter converters and improves power quality as well as stabilizing DC voltage.

A. Analysis of the solar based CS when the irradiation is kept constant at 1000 W/m^2

Charging stations (CSs) deploy photovoltaic (PV) modules, which utilize solar radiation intensity and cell temperature as inputs to produce the I-V and P-V characteristics. Analysis has shown that the changes in the field of irradiation significantly affect the current that is generated by the photon but do not affect significantly the voltage in open-circuit conditions. The solar cell is modelled and simulated for measuring the various characteristics so that it reveals that an increase in temperature serves to lessen the efficiency of the solar cell, while increase in solar radiation boosts the output power at the same voltage. In this model, twenty by five cells are connected to an array.

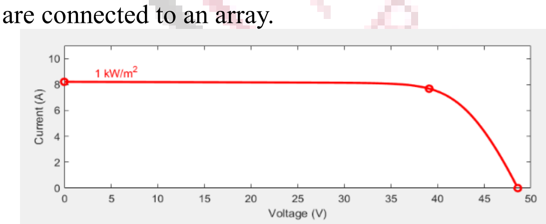

Fig. 11 I-V characteristic of the solar module at 1000 W/m^2

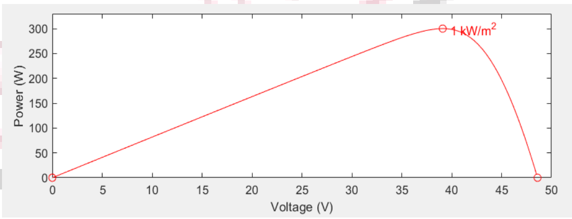

Fig. 12 P-V characteristic of the solar module at 1000 W/m^2

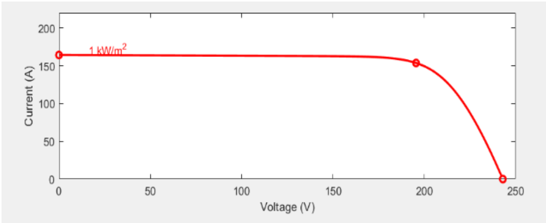

Fig. 13 I-V characteristic of the solar array at 1000 W/m^2

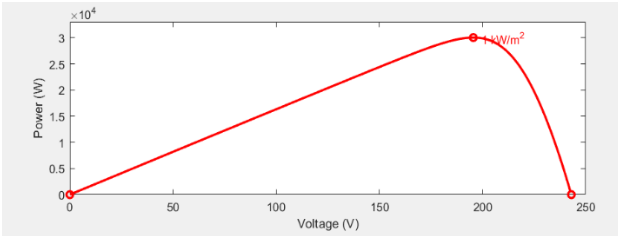

Fig. 14 P-V characteristic of the solar module at 1000 W/m^2

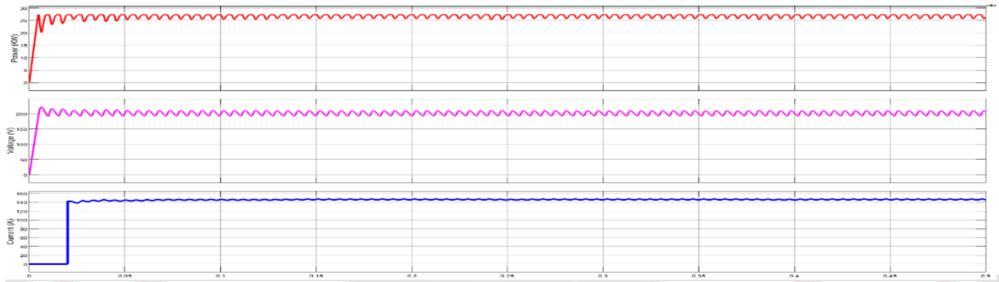

Fig. 15 Output from the solar array with 1000W/m^2 feeding in the charging station (a) Power Output in KW (b) Voltage (c) Current Output

This fig. 11 illustrates the I-V characteristics of a solar photovoltaic (PV) module, gained under an irradiation of 1 kW/m². From the curve, it can be seen that the current remains almost constant with the increasing voltage until a peak, beyond which it begins to decrease drastically, indicating the maximum power point and the general behavior of a solar cell. Fig. 12 shows the corresponding P-V characteristic curve at 1 kW/m² for the same PV module. It shows how the output changes with voltage and reaches the peak before dropping. The peak value is called the maximum power point (MPP) of the PV system and is very important for efficient energy harvesting. Now, I-V characteristics of a larger array or of a PV setup with higher capacity under 1 KW/m² is shown in this fig. 13. Again, it looks like that in the previous fig.13, where current is high and kept at a constant level for quite a number of voltages, but scale is much beyond the 200A mark, which is used by systems generating much more power. The plot illustrates the P-V characteristic curve of the larger PV plant shown in Fig. 14. It indicates that with the voltage increasing, output power rises up to an approximately maximum of about 30,000 W (30 kW), after which the power levels decline again, denoting the maximum power point of the array. This is the dynamic system performance of the charging station or energy storage system. Fig. 15 shows top plot (red) represents stabilization resulting from the power output. Next on the list is the plot in the middle which displays voltage regulation (presumably approximately a target of 600V), while the lowest plot (blue) shows state of charge (SOC) stabilization as a function of time. All parameters stabilize quickly and remain in steady condition, indicating good control and performance.

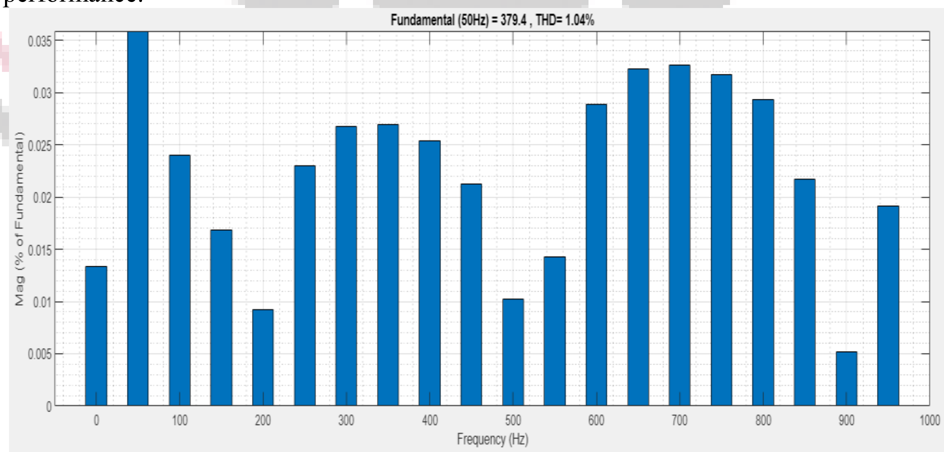

Fig. 16 THD% in AC voltage in the line of system 1 with solar fed CS

This fig. 16 represents the harmonic spectrum for the output voltage/current in respect of the different harmonic components' magnitudes as a percentage of the fundamental frequency (50 Hz). Thus, the Total Harmonic Distortion (THD) at 1.04% signifies very low distortion and a high-quality output waveform. With the bars representing different harmonic frequencies up to 1000 Hz, it indicates that most harmonic magnitudes are still quite small relative to the fundamental, confirming good harmonic mitigation and stable inverter performance.

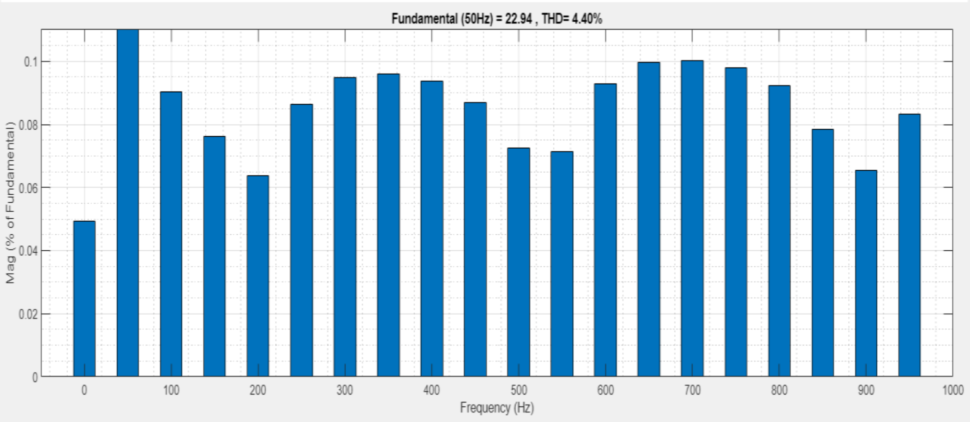

Fig. 17 THD% in the AC current drawn in the line of system 1 with solar fed CS

The fig. 17 shows the distortion percentage in the AC current in system 1 which is found to be approximately 4.40%. the distortion levels are affected by the input provide to the DC/AC converters and the control system driving them. In this case the system is controlled by standard voltage regulation based controllers.

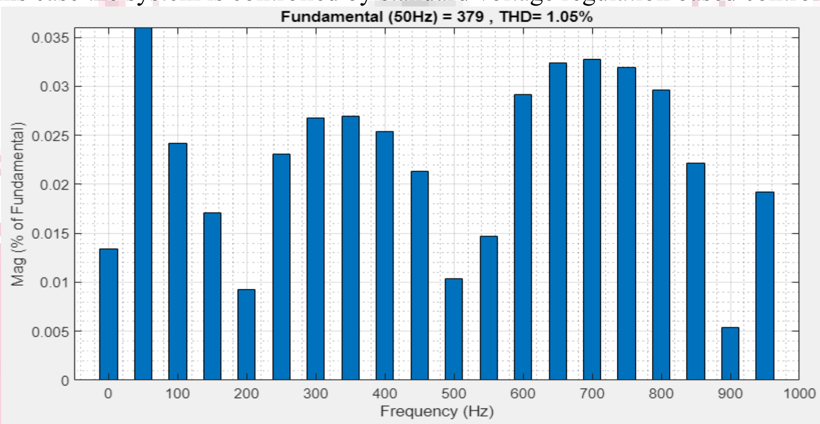

Fig. 18 THD% in AC voltage in the line of system 1 with solar fed CS with variable input

Fig. 18 shows the distortion percentage in the AC voltage in system 1 which is found to be approximately 1.05%.

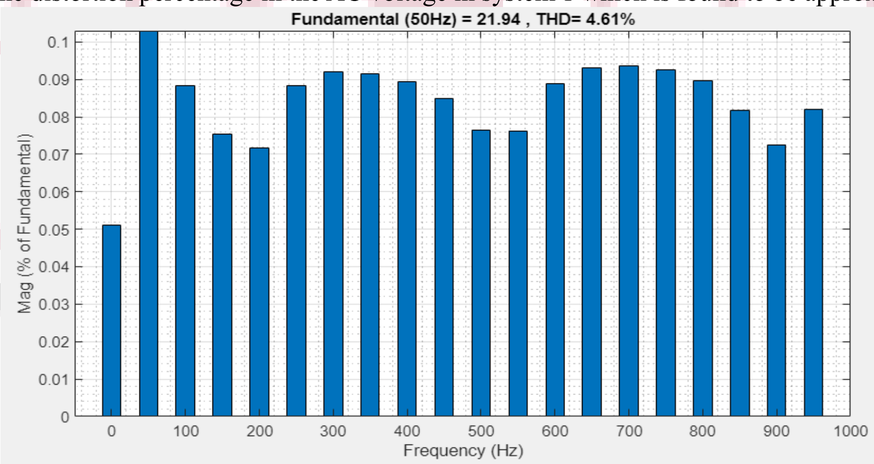

Fig. 19 THD% in the AC current drawn in the line of system 1 with solar fed CS with variable input

Fig. 19 shows the distortion percentage in the AC current in system 1 which is found to be approximately 4.61%. the distortion levels are affected by the input provide to the DC/AC converters and the control system driving them. In this case the system is controlled by standard voltage regulation-based controllers in solar fed CS with variable input

Table 3 Impact of Irradiation Variations on System Performance under Voltage Regulation

Parameters	**System with standard voltage regulation control**	
	Constant Irradiation	Variable Irradiation
DC load line power	unstable	unstable
AC load current distortion	4.40%	4.61%
Ac load voltage distortion	1.04 %	1.05%

B. Analysis with Reduced Efficiency Operating Conditions

In this case, the solar energy and wind energy systems have been intentionally operated below maximum efficiency in order to deliver lesser power outputs. At time equal to 0.2 s, the solar plant, receiving 600 W/m² irradiation, reduces power output to 15 kW, and the wind plant, having operated under a rather reduced wind speed for wind turbine running, dispatches 5 kW after 0.2 seconds. The electric vehicle load is 10 kW, with other loads drawing 15 kW (5 kW DC and 10 kW AC), making the total hybrid system load equal to 25 kW. Given that only 20 kW is generated by solar and wind combined, 5 kW of deficiency from storage is equally provided by the energy storage systems BESS and FESS.

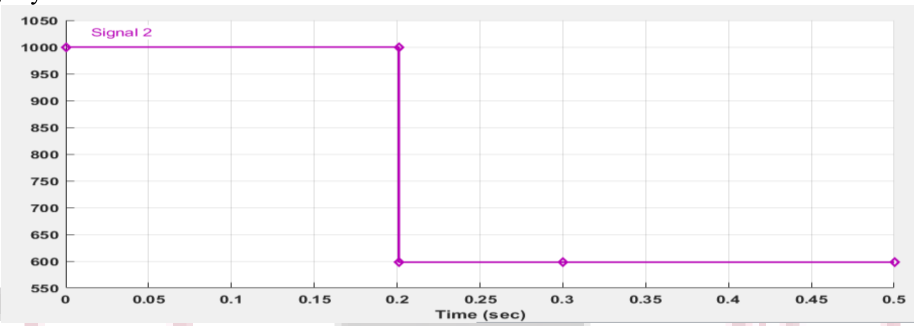

Fig. 20 Variation in the irradiation level provided to the solar system

The irradiation input provided to the Solar Energy in hybrid charging station is shown in fig. 20. It can be observed that at 0.2 seconds the irradiation level is reduced from 1000 W/m^2 to 600 W/m^2

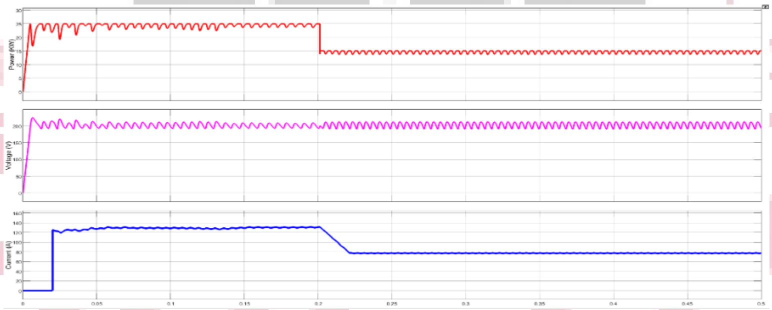

Fig. 21 Power outputs from the solar system at variable inputs in hybrid CS (a) Power Output in KW (b) Voltage (c) Current Output

The fig. 21 shows changes in the power output in the solar system due to changes in the irradiation level. The power is reduced from 25 kilowatt to 15 kilowatt at 0.2 seconds when the radiation level is reduced as an input to the solar energy module.

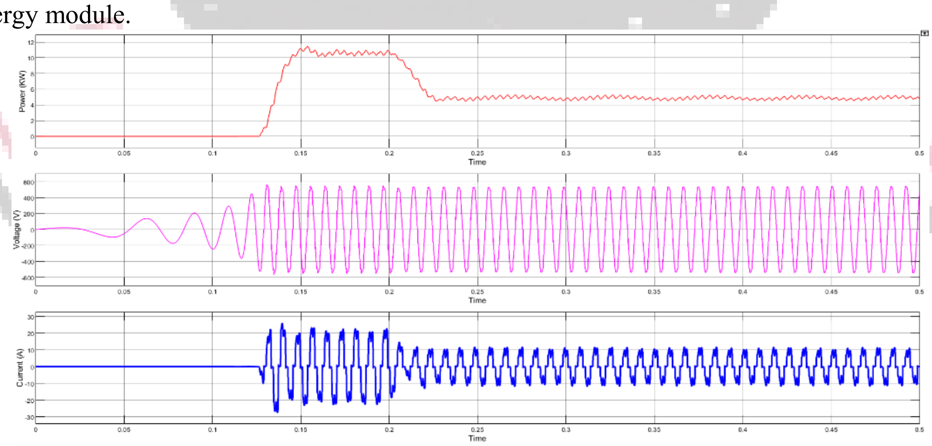

Fig. 22 Power outputs from the solar system at variable inputs in hybrid CS (a) Power Output in KW (b) Voltage (c) Current Output

The fig. 22 shows changes in the power output in the wind system due to changes in the speed level. The power is reduced from 11 kilowatt to 5 kilowatt at 0.2 seconds when the there is changes in the input parameters to the generator

VI. Conclusion

This study has accomplished the design of a hybrid renewable energy-based charging infrastructure for electric vehicles (EV), with intelligent control methods for efficiency, scalability, and stability. The hybrid model combines solar and wind sources with a dual energy storage system of battery and PMSM-based flywheel to provide a continuous power supply irrespective of variable renewable generation conditions. The centralized DC link bus allows load management and energy distribution between EVs, DC, and AC loads. The combination of a multi-stage genetic algorithm and fuzzy logic increases the converter control performance considerably with a focus on reducing THD and stabilizing the DC link voltage compared to the conventional voltage regulation techniques. The simulation results showed that power quality and voltage stability have been improved compared to the status quo, stressing the importance of these improvements under both constant and variable input scenarios. The AI-embedded control system's ability to operate in adverse conditions like low irradiation and wind speeds is a testimony to the resilience and effectiveness of the system. Thus, the architecture is a modern sustainable solution for EV charging, in the making, and is in line with the objectives of smart grid modernization in tackling energy optimization, cost-effectiveness, and environmental sustainability.

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