FOPID-BASED CONTROL OF A GRID-CONNECTED SOLAR-BATTERY SYSTEM FOR EV CHARGING STATION

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Abstract:
The grid-connected EV charging station integrating a photovoltaic (PV) array and battery energy storage system (BESS) to enhance energy reliability and efficiency. A Fractional-Order Proportional-Integral-Derivative (FOPID) control strategy is employed to optimize power flow, ensuring stable grid interaction and effective energy management. In this project, a charging station for electrical vehicle (EV) integrated with a battery energy storage (BES) is presented with enhanced grid power quality. The positive sequence components (PSCs) of the three phase grid voltages are evaluated for the estimation of the unit templates (UTs) and the reference grid currents. The EV and BES are connected at dc link using a bidirectional buck-boost converter. During the daytime, EV takes power from the solar array, while in its absence, it consumes the power from the grid. The proposed system mitigates grid dependency by maximizing renewable energy utilization and leveraging battery storage for peak load management. Simulation results demonstrate the effectiveness of the FOPID-based control in improving system stability, voltage regulation, and overall performance compared to conventional controllers. This research contributes to the advancement of smart and sustainable EV charging solutions. Tests are conducted on a software developed in the MATLAB/SIMULINK for the validation of the satisfactory response under different dynamics conditions.

Key Words-- Photovoltaic (PV) Array, Battery Energy Storage (BES), Voltage Source Converter (VSC), Bidirectional DC–DC Converters, Digital Signal Processor, Fractional order PID controller (FOPID)..

I.INTRODUCTION

The rapid growth of electric vehicles (EVs) has created an urgent need for efficient and sustainable charging infrastructure. Conventional EV charging stations primarily rely on the grid, increasing stress on the power network and raising concerns about peak demand and energy costs. To address these challenges, integrating renewable energy sources, such as photovoltaic (PV) arrays, with battery energy storage systems (BESS) has emerged as a viable solution for sustainable EV charging. A grid-connected PV-based EV charging station with energy storage can enhance system reliability, reduce dependency on fossil fuels, and optimize energy management.

However, integrating renewable energy with the grid introduces challenges such as voltage fluctuations, power quality issues, and intermittent energy supply. To overcome these limitations, advanced control strategies are essential for managing power flow between the PV system, battery storage, and the grid. Among various control techniques, the Fractional-Order Proportional-Integral-Derivative (FOPID) controller has gained attention due to its superior dynamic performance, robustness, and flexibility in handling system uncertainties. Unlike traditional PID controllers, FOPID provides additional tuning parameters, enabling better optimization of control response and improving system stability.

This paper proposes a grid-connected EV charging station that incorporates a PV array and BESS, managed by an FOPID-based control strategy. The primary objectives of the proposed system are to ensure efficient energy utilization, stabilize power flow, and enhance voltage regulation while reducing grid dependency. The performance of the FOPID controller is analyzed and compared with conventional PID control through simulations to demonstrate its effectiveness in improving system efficiency and stability.

The key features of the present work are as follows.

1) The PV array is used for EV battery charging and the surplus power is fed to the grid and BES.
2) In the absence of PV source, BES charges the EV battery, so that minimum power is exchanged from the grid and no additional burden is exerted on the grid.
3) In this topology, PV array is directly connected at dc link. Therefore, the overall efficiency of system is improved.
4) The nonlinearities are introduced in grid since EV charging/discharging is taken care by voltage source converter (VSC) control.
5) The capability of the system for the smooth and seam less synchronization between the grid disconnection and reconnection operating mode.

II.LITERATURE SURVEY

[1] N. Chen, B. van Arem, T. Alkim, and M. Wang, "A hierarchical model-based optimization control approach for cooperative merging by connected automated vehicles," IEEE Trans. Intell. Transp. Syst., vol. 22, no. 12, pp. 7712–7725, Dec. 2021.

This paper puts forward a hierarchical control approach for Connected Automated Vehicles (CAVs) to achieve efficient and safe merging operations. A tactical layer controller employs a second-order car-following model with a cooperative merging mode to represent a cooperative merging process and generates an optimal vehicle merging sequence and time instants when on-ramp CAVs start to adapt their speeds and positions to prepare merging into the target gaps respectively. An operational layer controller is designed based on Model Predictive Control (MPC). It uses a third-order vehicle dynamics model and optimizes desired accelerations for CAVs and the time instants when the on-ramp CAVs initiate the lane-changing executions respectively. Both the tactical layer controller and operational layer controller derive their control commands by minimizing an objective function for different time horizons. The objective function penalizes deviations of CAVs' inter-vehicle gaps to their desired values, relative speeds to their direct predecessors, and actual or desired accelerations, subject to constraints on velocities, actual or desired accelerations, and inter-vehicle gaps. The performance of the proposed hierarchical control framework and a benchmark on-ramp merging method using a first-in-first-out rule to determine the merging sequence is demonstrated under 135 scenarios with different initial conditions, desired time gap settings, and numbers of on-ramp vehicles

[2] S. Prajapati and E. Fernandez, "Rooftop solar PV system for commercial office buildings for EV charging load," in Proc. IEEE Int. Conf. Smart Instrum., Meas. Appl. (ICSIMA), Kuala Lumpur, Malaysia, Aug. 2019, pp. 1–5.

This paper explores the design, implementation, and optimization of solar PV systems tailored for EV charging loads, emphasizing energy efficiency, cost-effectiveness, and environmental benefits. By utilizing renewable energy to power EV charging stations, businesses can reduce grid dependency, lower operational costs, and contribute to carbon neutrality goals. Key challenges, such as energy storage, load balancing, and system scalability, are addressed to ensure reliability and resilience. This approach demonstrates a practical pathway for promoting sustainable energy practices in urban commercial settings.

[3] D. Lyu, T. B. Soeiro, and P. Bauer, "Design and implementation of a re-configurable phase-shift full-bridge converter for wide voltage range EV charging application," IEEE Trans. Transp. Electrific., early access, May 20, 2022, doi: 10.1109/TTE.2022.3176826.

This paper analyzes, designs, and tests a reconfigurable phase shift full-bridge (r-PSFB) isolated dc/dc converter well suited for a wide voltage operating range. By controlling the auxiliary switches, a series or parallel connection can be realized on the secondary side of the converter. As a result, the r-PSFB converter can operate in an extremely wide voltage range without compromising the system efficiency. In this article, the characteristics of the r-PSFB converter and its design considerations are discussed in detail. An 11-kW r-PSFB converter prototype with 640–840-V input voltage and 250–1000-V output voltage ranges is developed and tested to validate the analysis and efficiency of the designed converter.

III.PHOTOVOLTAIC TECHNOLOGY

Photovoltaic's is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation.

The photovoltaic effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel prize in physics. The first photovoltaic module was built by Bell Laboratories in 1954. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through the space programs, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.

The solar cell is the elementary building block of the photovoltaic technology. Solar cells are made of semiconductor materials, such as silicon. One of the properties of semiconductors that makes them most useful is that their conductivity may easily be modified by introducing impurities into their crystal lattice. For instance, in the fabrication of a photovoltaic solar cell, silicon, which has four valence electrons, is treated to increase its conductivity. On one side of the cell, the impurities, which are phosphorus atoms with five valence electrons (n-donor), donate weakly bound valence electrons to the silicon material, creating excess negative charge carriers.

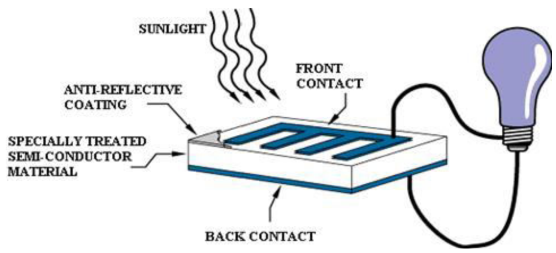


Fig 1: Solar cell.

IV.ELECTRIC VEHICLE

Electric Vehicle (EV) is an emerging technology in the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles. Multilevel inverter controls electric drive of EV of high power and enhances its performance which is the reflection of the fact that it can generate sinusoidal voltages with only fundamental switching frequency and have almost no electromagnetic interference. This paper describes precisely various topology of EVs and presents transformer less multilevel converter for high voltage and high current EV. The cascaded inverter is IGBT based and it is fired in a sequence. It is natural fit for EV as it uses separate level of dc sources which are in form of batteries or fuel cells. Compared to conventional vehicles, Electric Vehicles (EVs) are more fuel efficient due to the optimization of the engine operation and recovery of kinetic energy during braking. With the plug-in option (PEV), the vehicle can be operated on electric-onlymodes for a driving range of up to 30–60 km. The PEVs are charged overnight from the electric power grid where energy can be generated from renewable sources such as wind and solar energy and from nuclear energy. Fuel cell vehicles (FCV) use hydrogen as fuel to produce electricity, therefore they are basically emission free. When connected to electric power grid (V2G), the FCV can provide electricity for emergency power backup during a power outage. Due to hydrogen production, storage, and the technical limitations of fuel cells at the present time, FCVs are not available to the general public yet. EVs are likely to dominate the advanced propulsion in coming years. Hybrid technologies can be used for almost all kinds of fuels and engines. Therefore, it is not a transition technology. In EVs and FCVs, there are more electrical components used, such as electric machines, power electronic converters, batteries, ultra capacitors, sensors, and microcontrollers. In addition to these electrification components or subsystems, conventional internal combustion engines (ICE), and mechanical and hydraulic systems may still be present. The challenge presented by these advanced propulsion systems include advanced powertrain components design, such as power electronic converters, electric machines and energy storage; power management; modeling and simulation of the powertrain system; hybrid control theory and optimization of vehicle control

V. ELECTRIC STORAGE TECHNOLOGIES

A number of electric storage technologies have been developed which serve various electric applications, including:

- Pumped Hydropower
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Super capacitors
- Hydrogen Storage

5.1 Pumped Hydropower: Pumped hydro has been around as an electric storage technology since 1929, making it the oldest used technology.

Operation: Conventional pumped hydro facilities consist of two reservoirs, each of which is built at two different levels. A body of water at the higher elevation represents potential or “stored” energy. Electrical energy is produced when water is released from this reservoir to the lower reservoir while causing the water to flow through hydraulic turbines which generate electric power as high as 1000 MW. Within last ten years the advanced pumped storage (APS) technology has been introduced to increase efficiency, speed and reliability.

Example: A seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). There is over 90 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity.

VI.MODELLING OF CASE STUDY

6.1 SYSTEM CONFIGURATION

The EV charging station with BES is developed, as depicted in Fig. 2. The bidirectional exchange of power between the PV array, BES, EV, and grid is performed by the VSC. It transforms the dc power to ac and vice versa to be exchanged with the grid. The EV and the BES are connected via separate bidirectional dc–dc converters at the common dc link. The charging/discharging of the BES and EV is controlled using this converter. Interfacing inductors are used for the connection of the VSC at the PCC for harmonics current reduction. A static transfer switch (STS) connects and synchronizes the system to the grid.

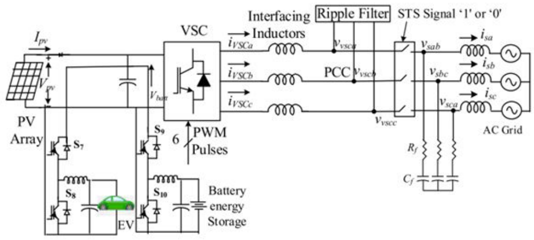


Fig. 2. System topology

6.2 CONTROL APPROACH

The main purpose of the system is the EV charging. In case the grid is not available, the remaining power is used for the charging of the BES. If required, either EV or BES or both are discharged to the grid. The control is classified as: 1) MPPT control; 2) grid connected (GC) mode control; 3) synchronization and standalone mode (SM) control; 4) BES control; and 5) EV control.

A. GC Mode Control

The VSC switching pulses are generated in the GC mode using the control, as shown in Fig. 6.2

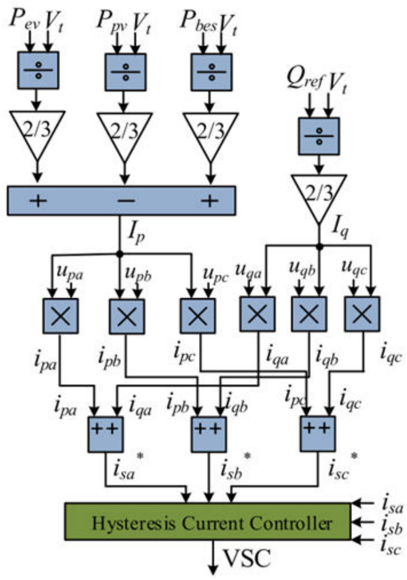


Fig:3. GC control

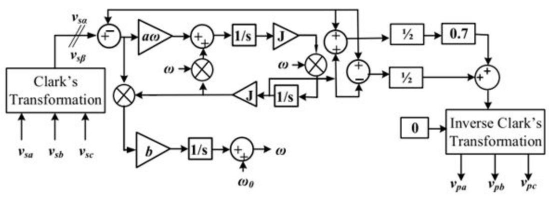


Fig. 4. PSCs estimation.

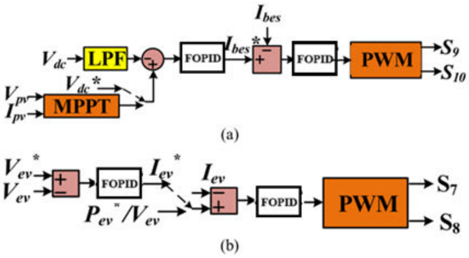


Fig. 5. Control approach. (a) BES control. (b) EV battery charging/discharging control algorithm

EV Control Algorithm

The EV is controlled by giving desired switching pulses to dc–dc converter. For charging of the EV battery, the current reference is estimated by comparing reference EV voltage with actual EV voltage and providing this error to the FOPID controller. However, if grid requires active power from EV, then EV battery current reference is estimated by dividing reference EV power with EV voltage, as shown in Fig. 6.4(b).

D. Synchronization and Standalone Control

When grid is unavailable, signal S = 0 for the STS, the VSC operates in the SM, as shown in Fig. 6.5(a). The grid (θg) and PCC voltage angle (θs) are compared, and the error is estimated as

$$\theta_e(k) = \theta_g(k) - \theta_s(k)$$

It is then given to the FOPID controller and reference PCC voltages are computed. These reference PCC voltages are then compared with actual PCC voltage to obtain the voltage error. This error is passed to the FOPID controller, and hence, PCC reference currents are obtained. The reference grid currents obtained are subtracted from actual grid currents. The error obtained is given to hysteresis current controller and VSC gate pulses are obtained. When PV array power and BES power are unavailable or not that much enough for the charging of EV battery, the islanded control shifts to the GC control after meeting the specified boundary conditions via synchronizing. The boundary conditions necessary for the GC operation of the system are the amplitude, frequency, and angle, as shown in Fig. 6.

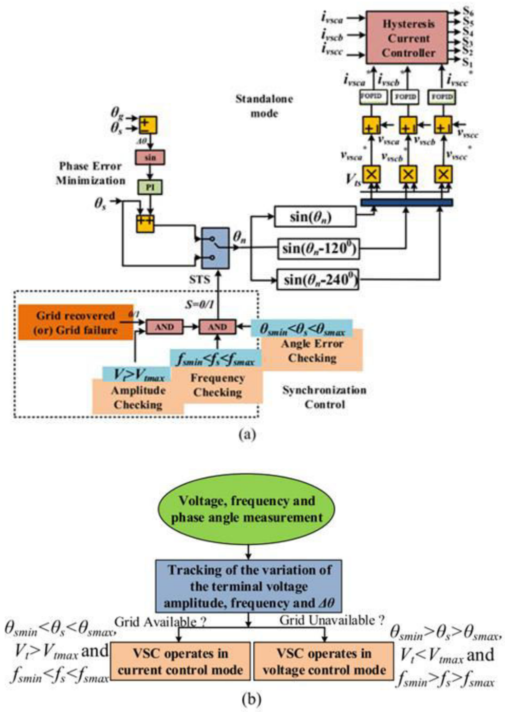


Fig. 6. (a) Synchronization and standalone control. (b) System-level coordination control for transition between the GC mode and SM

VII.SIMULATION RESULTS

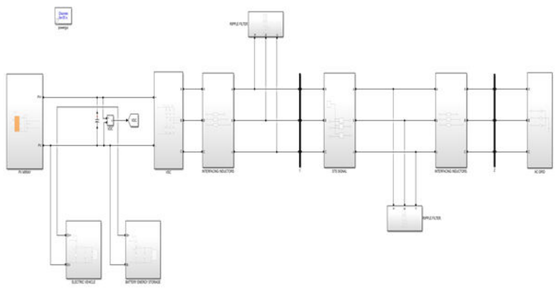


Fig7 : MATLAB/SIMULINK circuit of the Grid Connected PV Array and Battery Energy Storage Interfaced EV Charging Station

EXTENSION RESULTS (FOPID CONTROLLER)

A. Performance Under Variation of Solar Insolation

During rise in PV array irradiation from 600 to 1000 W/m2 , PV array generation increases, since EV and battery are in floating mode, as shown in Fig. 7

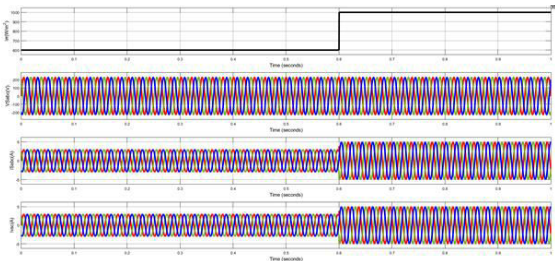
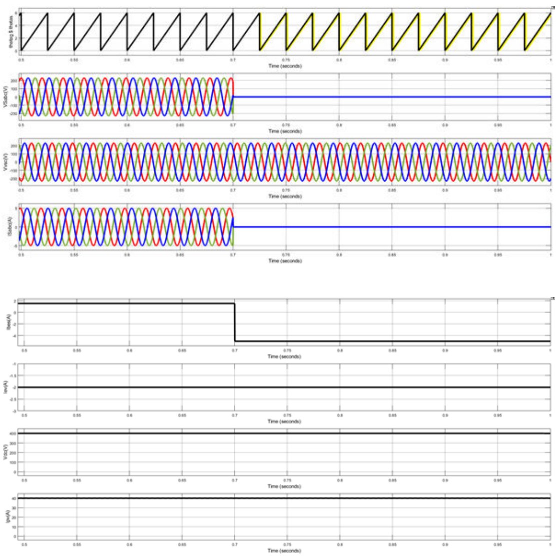


Fig 8 Simulated response of EV charging station under variation of PV insolation

B. Performance of System at Outage of Grid

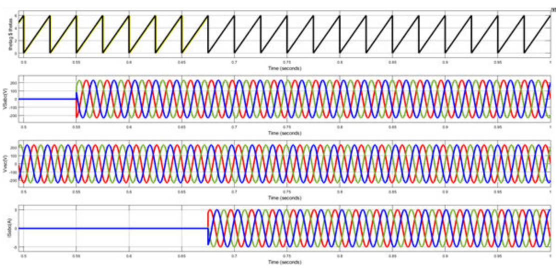
Simulated performance at grid outage is shown in Fig. 8. When grid outage is observed, charging station operates in SM. Therefore, grid currents and voltages immediately become zero. The BES compensates for surplus power and starts charging. EV charging remains unchanged.

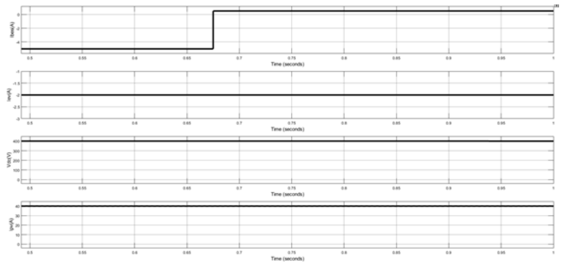


(a)

C. Performance of System at Grid Reconnection

The simulated response of system at grid recovery is presented in Fig. 9 During grid restoration, the VSC synchronizes to the grid, and the grid voltages and the currents are appeared. The BES starts discharging without affecting the EV charging.





(b)

Fig. 9 Simulated performance at (a) grid disconnection and (b) grid reconnection

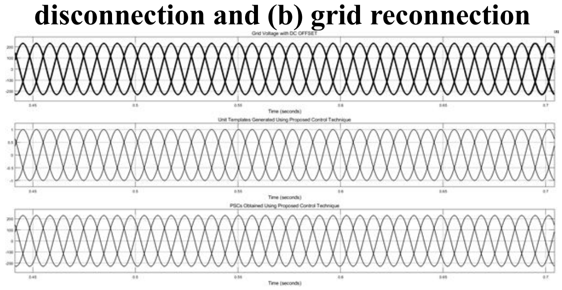
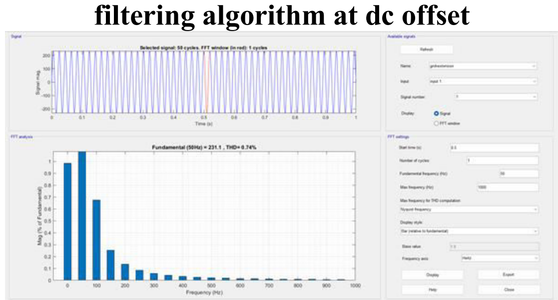
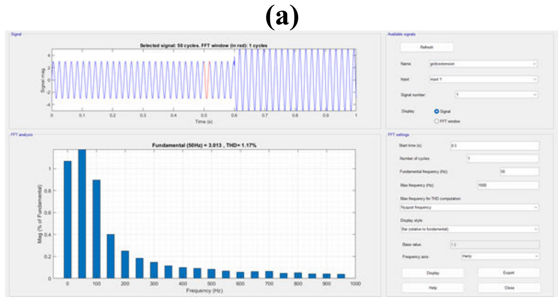


Fig. 10 Comparative of the proposed control with fractional order correntropy adaptive filtering algorithm at dc offset



(a)



(b)

Fig 11 THD of grid voltage and grid current

VIII.CONCLUSION

The PV array-based charging station with BES is presented here. Simulation results have validated the improved power quality operation of EV charging station under various dynamic conditions, such as intermittent PV insolation with a BES in floating mode, compensating mode, and constant power grid mode. The system response at changing/discharging of BES system has also studied in detail.

FUTURE SCOPE

The future of grid-connected PV arrays and battery energy storage integrated EV charging stations is ripe with potential. As technological advancements in energy storage, AI, grid integration, and EV technologies continue to progress, these systems will play a pivotal role in creating a cleaner, more sustainable, and resilient energy future. With expanding applications and continuous innovations, the synergy between renewable energy, electric vehicles, and smart grids will transform the global transportation and energy landscape.

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