

Synergizing Solar PV and Regenerative Braking in Electric Vehicles using a Zeta Converter

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Abstract: The integration of solar photovoltaic (PV) systems and regenerative braking in electric vehicles (EVs) represents a promising approach to enhancing energy efficiency and extending driving range. This paper proposes a novel energy management system that synergizes solar PV power generation and regenerative braking energy recovery using a Zeta converter. The Zeta converter, known for its ability to step-up or step-down voltage levels with high efficiency, is employed to ensure seamless energy transfer between the PV system, the battery, and the load. By leveraging maximum power point tracking (MPPT) algorithms, the solar PV system operates at optimal efficiency under varying environmental conditions. Simultaneously, the regenerative braking system recaptures kinetic energy during deceleration, directing it back into the battery. The proposed system design is analyzed through simulation and experimental validation to assess its performance in terms of energy recovery, battery health, and system efficiency. The results demonstrate significant improvements in energy utilization and vehicle autonomy, underscoring the potential of this approach in advancing sustainable transportation solutions.

Keywords: Solar Photovoltaics (PV), Regenerative Braking, Electric Vehicles (EVs), Zeta Converter, Energy Efficiency, Maximum Power Point Tracking (MPPT), Energy Management System, Sustainable Transportation.

1. Introduction

The global electrical power system plays a vital role in the development of human civilization and, now it emerges as one of the basic needs in human life. Electricity is the most valuable form of energy and is essential for the development of civilization. There is a strong relationship between sophistication of life and the use of electricity. The major amount of electricity is being generated by means of fossil, hydro and nuclear energy. The population growth and the fact that only a part of the world's population is benefiting from electricity will increase energy consumption considerably [1]. The growing demand will dramatically increase the need for power generation and transmission, primarily to those areas that have not yet been supplied with electricity.

In this context, Electrical transmission and distribution play a significant role in transporting energy from the generator site to the load centers. While the capacity of such a power system network is huge and complex constant disturbances remain in the system which may be dangerous both for the customers and the power electronics equipment in the network [2].

Due to the need of electricity in modern life, the investment is moving towards the non-renewable energy sources (solar, wind, hydro, biogas). Achieving solutions to environmental problems that altogether facing today requires long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be one of the most efficient and effective solutions. Hence there is an intimate connection between renewable energy and sustainable development and also, potential solutions to current environmental problems are identified along with renewable energy technologies [3]. In fact, the deployment of non-renewable sources would require more energy storage systems to compensate for the fluctuation in power generation and increase the stability of the system. A smart energy system is required to increase the system's stability and reliability and provide coordination between different parts of the system. In this research, the bidirectional converters are used for the energy management system on battery in electric vehicle application [4].

DC-DC Converter

A DC-DC converter can be defined as a system formed by power devices, such as diodes, Metal-Oxide Field-Effect Transistors (MOSFETs) and Insulated-Gate Bipolar Transistors (IGBTs) and passive elements, such as capacitors and inductors. In a DC-DC converter, a DC voltage or current level is applied in the input terminals and, with a command strategy for the turning-on/off of the power devices, these levels can be adjusted to desired values as required at the load terminals [5]. The function of a DC-DC converter is to transfer energy from a DC energy source to a DC load, where high conversion efficiency is a key factor. The traditional DC-DC converters are characterized by transistor (operating as a switch), diode with one or more capacitors and inductors [6].

voltage step-up function (Boost). The traditional DC-DC Converter (a) Buck (b) boost is shown in Figure 1.

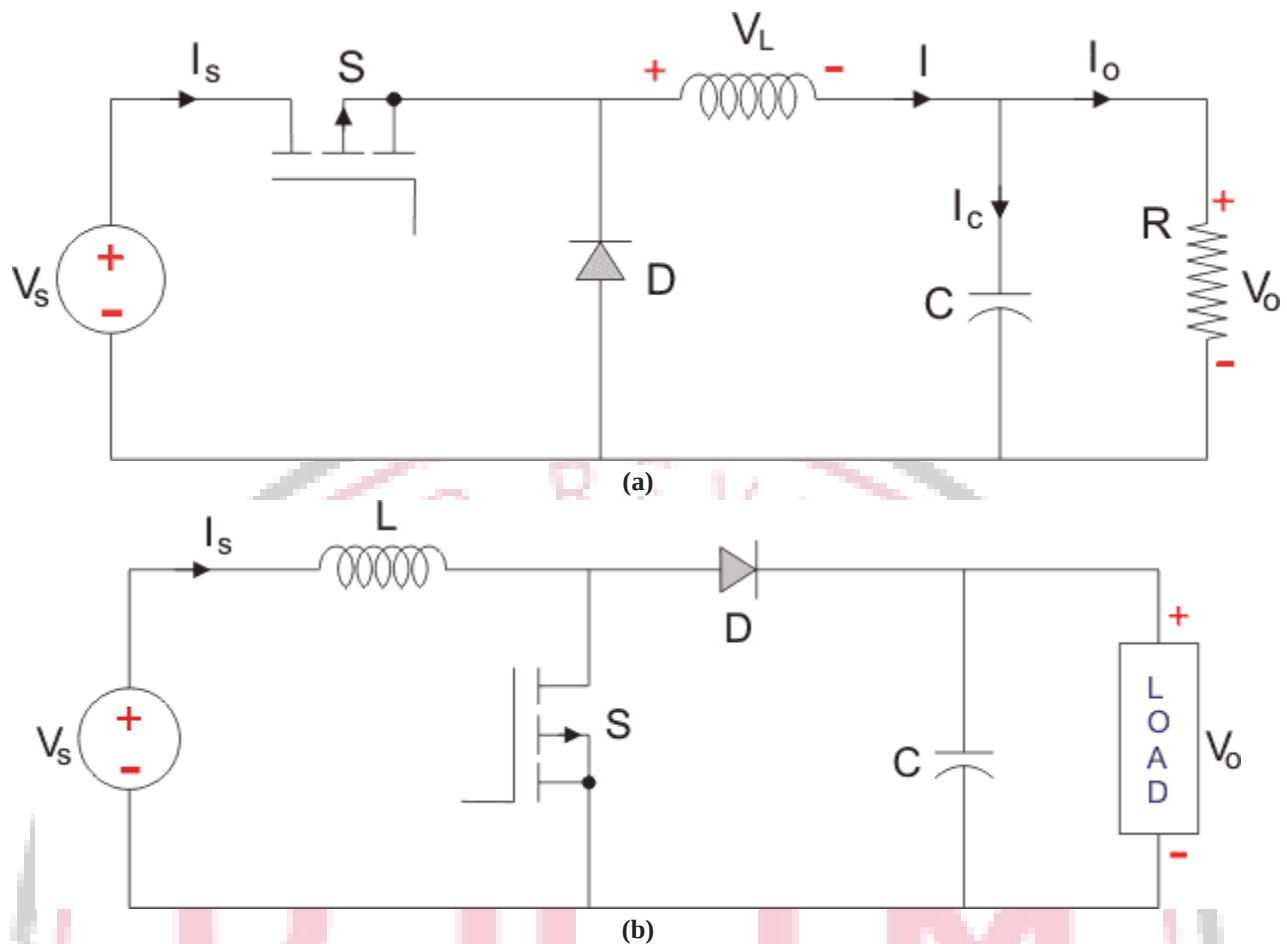


Figure 1 Traditional DC-DC converters: (a) Buck (b) Boost

The operating principle of the topologies is based on the fact that transistor and the diode will not conduct at the same time when the transistor is conducting, the diode will be blocked, and when the transistor blocks then the diode will start to conduct [7]. DC-DC converters will also contains three different operation modes, which are characterized by the behavior of inductor current the Continuous Conduction Mode (CCM), where the inductor current never reaches zero; the Discontinuous Conduction Mode (DCM), where the inductor current reaches zero in more than one instant of time and the Critical Conduction Mode (CrCM), where the current will reach zero in a single instant of time. DC-DC converters can be isolated or non-isolated [8].

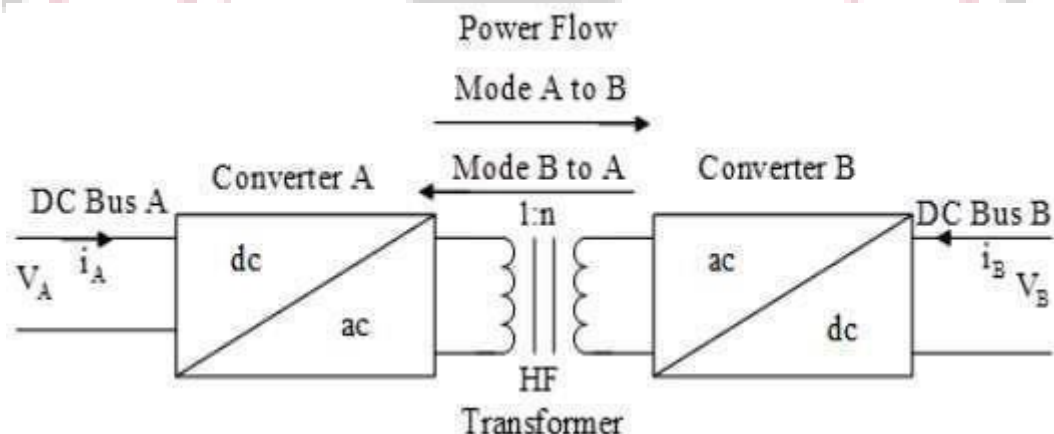


Figure 2 Basic Structure of an Isolated Bidirectional DC Converter

Machine learning (ML), a subset of artificial intelligence, has emerged as a transformative technology in various domains, including power system engineering. Its ability to analyze large volumes of data, identify complex patterns, and make data-driven decisions in real time has made it particularly suitable for addressing the challenges of

adaptive protection in microgrids [8]. By leveraging ML techniques, protection systems can enhance fault detection, classification, and location capabilities, ensuring rapid and accurate responses to system disturbances. This integration of ML into adaptive protection frameworks represents a significant advancement in the quest for smarter and more resilient energy systems. Designing an effective protection system is a significant challenge in the widespread deployment of microgrids [9]. The protection system must respond to faults in both the utility grid and the microgrid itself. In the event of a fault on the utility grid, the microgrid should act swiftly to protect critical loads. The speed of isolation depends on customer dependence on the microgrid [10]. Charged loads do not depend on specific customer loads but rely on the speed of isolation and are determined by load characteristics and conditions. Ensuring the economic advantages of microgrids necessitates a reliable protective scheme to accurately and quickly detect faults[6]. The diverse operational characteristics of each energy source, along with weather- dependent behaviors, increase the complexity of fault detection and classification in microgrids compared to conventional macro grids [11]. Classical protection technologies based on threshold settings are not directly applicable to microgrids, especially during islanded operation, due to weather interference and significantly reduced fault current capacity[12].

To address these challenges, the protection system incorporates a module for detecting the mode of operation, allowing separate settings for grid-connected and isolated modes[13]. The process involves removing noise components and redundant information while extracting useful functional features (attributes) to reflect the distribution line's state accurately and differentiate between a healthy and faulty state. A low- pass second-order Butterworth filter processes instantaneous voltage and current signal values recorded in each phase. The signals are sampled at 1.2 kHz following filtering, adhering to Nyquist sampling criteria[14].

II. Literature Review

Regenerative braking in electric vehicles is studied in the paper. Conditions for regeneration, energy flow during the process and the ways of implementation are discussed. The efficiency of the system comprising of electric motor, power converter and storage elements is estimated[15]. The Plug in Hybrid Electric Vehicles are driven by the energy stored in the battery. Through conductive AC charging method, Electric vehicle supply equipment (EVSE) is connected to Electric vehicle(EV) for charging the battery. Apart from charging it can also help in creating trustworthy equipment ground track and exchange control data among EV and EVSE[16]. This paper discusses electrical and physical interface between EV and EVSE to facilitate conductive charging and design of an on-board charger for fast charging of the hybrid electric vehicle. The aim of this project is to design interfacing system between EV and EVSE as per automotive industry standard and to design prototype of 3.45 kw on-board charger using Matlab software[17]. By modeling the charger, charging of Li-ion battery can be done which is used for providing propulsion torque and through various stages of charger voltage and current level is controlled and make them desired for charging. For electric vehicles (EVs) on the move, the only viable solution of electromagnetic energy charging consists of static and dynamic charging, where Inductive Power Transfer (IPT) offers possibilities that no other technology can match[18]. The main objective of this paper is the analysis of the energy charging technologies for vehicles, using magnetically coupled coils. The main idea of such a system consists of an electrified driveway which offers the vehicles the possibility of moving and charging at the same time. The article presents the wireless power transfer principles followed by a presentation of inductive wireless power systems and an example of a parallel-series topology. In this paper, we combined the berth allocation problem with the scheduling of electric vehicle charging stations and formed a new problem namely the position allocation problem (PAP)[19]. To solve this problem, we used a meta-heuristic algorithm namely the Simulated Annealing (SA) and presented the results as a scheduling chart. Our findings are focused on the reduction of the charging time. Also, we considered the length of the cars and the length limit of the charging stations in order to allocate a suitable number of cars. For this reason, we choose several electric vehicle models and by considering their characteristics like the length and time of charging, formed an optimized schedule for the charging. The result showed a considerable reduction in charging time for the 3, 5 and 10 electric vehicle charging scenarios[20]. This paper represent mathematical model for representing vehicle mechanics using Newton's Second law of motion. Automobile industries are investing much time and money to find out the practical alternative to vehicle powered by the internal combustion engine.

III. Research Methodology

In general, photovoltaic (PV) arrays convert sunlight into electricity. DC power generated depends on illumination of solar and environmental temperature which are variable. It is also varied according to the amount of load. Under uniform irradiance and temperature, a PV array exhibits a current-voltage characteristic with a unique point, called maximum power point, where the PV array produces maximum output power. In order to provide the maximum power for load, the maximum-power-point-tracking (MPPT) algorithm is necessary for PV array. Briefly, an MPPT algorithm controls converters to continuously detect the instantaneous maximum power of the PV array .

Photovoltaic Modelling

The equivalent circuit of the ideal PV cell is shown in figure 3. The basic equation from the theory of semiconductors that mathematically describes the I-V characteristic of the ideal PV cell is as follows:

$$I = I_{PV,l} - I_{0,cell} \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] \quad (1)$$

$$I_d = I_{0,cell} \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] \quad (2)$$

where $I_{PV,cell}$ is the current generated by the incident light (it is directly proportional to the sun irradiation), I_d is the Shockley diode equation, $I_{0,cell}$ is the reverse saturation or leakage current of the diode, q is the electron charge ($1.60217646 \times 10^{-19}$ C), k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), T (in Kelvin) is the temperature of the p-n junction, and “ a ” is the diode ideality constant .

where I_{PV} and I_0 are the PV current and saturation currents, respectively, of the array and $V_t = N_s kT/q$ is the thermal voltage of the array with N_s cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the array is composed of N_p parallel connections of cells, the PV and saturation currents may be expressed as $I_{PV} = N_p I_{PV,cell}$, $I_0 = N_p I_{0,cell}$.

All PV array datasheets bring basically the following information: the nominal open- circuit voltage ($V_{oc,n}$), the nominal short-circuit current ($I_{sc,n}$), the voltage at the MPP (V_{mpp}), the current at the MPP (I_{mpp}), the open-circuit voltage/temperature coefficient (K_V), the short- circuit current/temperature coefficient (K_I), and the maximum experimental peak output power (P_{max}). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature and solar irradiation. Some manufacturers provide I - V curves for several irradiation and temperature conditions. These curves make easier the adjustment and the validation of the desired mathematical I - V equation. Basically, this is all the information one can get from datasheet of PV arrays.

Electric generators are generally classified as current or voltage sources. The practical PV device presents hybrid behavior, which may be of current or voltage source depending on the operating point. The practical PV device has a series resistance R_s whose influence is stronger when the device operates in the voltage source region and a parallel resistance R_p with stronger influence in the current source region of operation. The R_s resistance is the sum of several structural resistances of the device. R_s basically depends on the contact resistance of the metal base with the p semiconductor layer, the resistances of the p and n bodies, the contact resistance of the n layer with the top metal grid, and the resistance of the grid. The R_p resistance exists mainly due to the leakage current of the p-n junction and depends on the fabrication method of the PV cell. The value of R_p is generally high and some

TABLE .1 : PV PARAMETERS

Parameters	Specifications
Maximum power (W)	334.905 W
Parallel strings	1
Series-connected modules per string	1
Cells per module (Ncell)	80
Open circuit voltage Voc (V)	49.9
Short-circuit current Isc (A)	9
Voltage at maximum power point Vmp (V)	41.5
Current at maximum power point Imp (A)	8.07

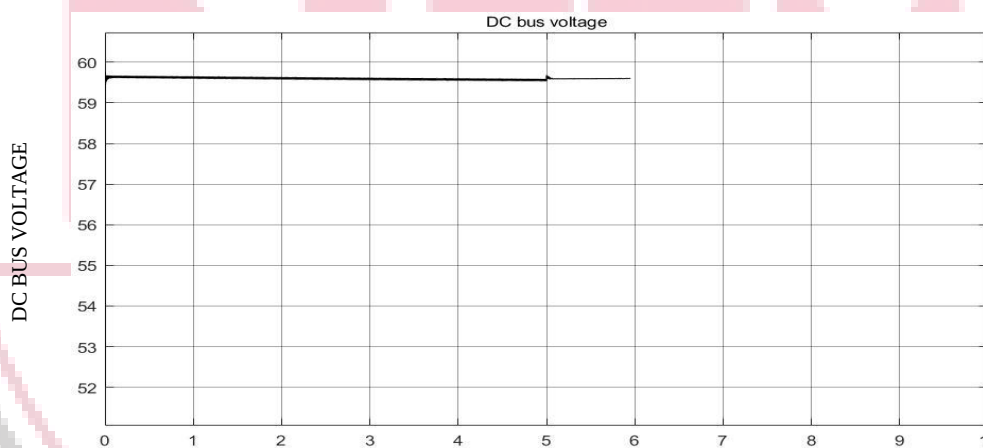


Figure 5. DC Bus Voltage Vs Time

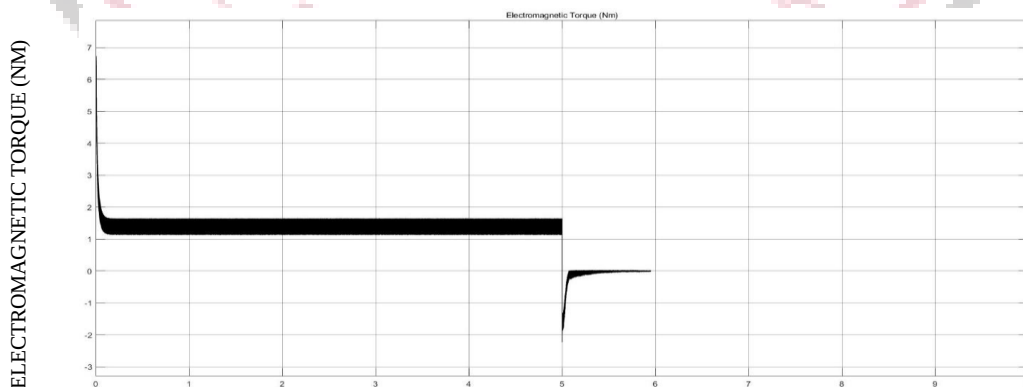


Figure 6. Electromagnetic Torque (NM) Vs Time

V. Conclusion

The integration of solar PV systems and regenerative braking in electric vehicles using a Zeta converter offers a transformative solution for enhancing energy efficiency and sustainability. By enabling bidirectional energy flow and optimizing voltage levels, the Zeta converter effectively combines energy from solar PV and regenerative braking to support the vehicle's battery and load requirements. Simulation and experimental results highlight the system's capability to improve energy recovery, extend battery life, and reduce dependency on external charging. This approach not only contributes to the advancement of energy-efficient electric vehicles but also promotes the adoption of renewable energy in transportation, paving the way for more sustainable and eco-friendly mobility solutions.

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