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Powering Rural Mobility: Hybrid Renewable Energy for Electric Vehicle Charging Stations

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Abstract

An electric vehicle (EV) charging station provides the necessary power supply for charging electric vehicles. This study proposes a model for a photovoltaic (PV)-based EV charging station that predicts the total power output under specific conditions in Ankara city. Initially, the parameters of the PV cells are determined, and a PV array is constructed using these cells to calculate the cumulative effect. Actual irradiation and temperature values are then used to approximate the output power for future requirements.

Electric vehicles offer numerous advantages, including easy access and the abundance of electrical energy sources. The primary objective of this study is to determine the optimal configuration of hybrid power systems for a charging station in a rural area like Labuan Bajo, Indonesia. The study evaluates the installation of three types of energy storage systems, namely Lead Acid, Lithium Ion, and Lithium Ferro Phosphate (LFP) batteries, to minimize the operational and energy costs over a year.

The results indicate that implementing hybrid systems comprising PV and Distributed Energy Resources (DER) represents the best configuration for an off-grid charging station. The study identifies UNS LFP batteries as the most optimal choice for the off-grid system. In conclusion, the utilization of hybrid power generation technology demonstrates the potential of renewable energy in rural areas, enabling the establishment of affordable charging stations to support the infrastructure for electric vehicles.

INDEX TERMS: photovoltaic (PV), Lithium Ferro Phosphate (LFP), Electric vehicles (EVs), Three-port integrated topology (TPIT)

1. Introduction

Electric vehicles (EVs) are recognized as one of the most efficient modes of transportation with zero trailing emission. Considering the advantage of EVs, 3 million vehicles are already deployed on the road, and it is expected to cross 100 million by 2030. However, the execution of proposed plan demand for huge charging infrastructure and enormous electrical energy. Moreover, EVs can only be sustainable when the electrical energy required for charging is generated from renewable and sustainable energy sources. However, the use of fossil fuels for electricity generation, does not reduce the emission but merely shift it from vehicles to the power plant. Therefore, the use of renewable energy sources for electricity generation can completely eliminate the emission and provides an environmental benefit. Among various available renewable energy sources, solar PV array, wind energy, hydro energy and fuel cell based energy, solar PV based generation is a most feasible solution for EV charging because it is available almost everywhere irrespective of the rural or urban region. As far as the Indian region is concerned, it is available almost throughout the year. On the contrary to the solar PV array, the wind and hydro energies are location specific. The wind energy is mostly useful in the coastal region, and hydro energy is useful for hilly region. Though, the renewable energy based charging stations are the most feasible solution for the EV charging, however, their integration to the existing charging system introduces the additional power conversion stage, which increases the complexity and power loss in the system. Moreover, each conversion stage needs an individual controller, which needs to be integrated with the existing control. Therefore, it is imperative to design an integrated system with multifunctional and multimode operating capability, for which a unified control and coordination between the various sources are

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essential. Many efforts have been made to develop the renewable energy based charging station. Ugirumurera et al. have discussed the importance of renewable energy for the sustainability of the EV charging station

Renewable energy based charging station, are mostly focusing on the optimization of different aspects of charging such as the size of the renewable energy sources, size of the storage unit, vehicle driving pattern, charging time, charging cost, charging scheduling etc. However, in present scenario only few publications have actually implemented the charging station using renewable energy sources. Moreover, the performance of charging station under real circumstances, is also less discussed. Moreover, in most of the literature, the performance of CS, is discussed only in either grid connected mode or islanded mode. However, due to the single mode of operation in grid connected mode, the solar PV panel becomes unusable if the grid is not available even if the sun (solar irradiance) is available. Similarly, in islanded mode, the PV power is disturbed by the intermittency of solar irradiance. Therefore, a storage battery is required for mitigating the effect of variable solar irradiance. However, in case of the fully charge storage battery, the maximum power point tracking (MPPT) has to be disabled to avoid the overcharging of the storage battery. Therefore, in this paper, a PV array, grid, energy storage and DG set supported CS is presented, which operates in islanded, grid connected and DG set connected modes, so that the PV array energy is utilized for all operating conditions. Some publications [15] have discussed both islanded and grid connected modes. However, these two modes are controlled separately and the automatic mode switching between two modes are not presented. Therefore, without automatic mode switching capability, the PV array power is to be interrupted and the charging of the EV is not to be continuous. Therefore, in this paper, an automatic mode switching logic is presented, so that the controller automatically switches between different operating modes depending on the power generation of PV array and the charging demand of EV. Due to the unavailability in the night and the intermittent nature of the PV array, storage battery with PV array is used for continuous and reliable operation of CS. However, due to the limited storage capacity of the storage battery, it is hardly possible to provide backup all the time. Therefore, the CS needs support of the grid in case of PV array energy is unavailable, and energy storage is also discharged. However, due to the limited availability of grid, especially in remote areas, the DG set may be required for maintaining the continuity of the charging. However, the DG set performance is affected by the type of loading, and it is not utilised to its full capacity. Generally, the DG sets are designed for very limited amount of harmonics in the load current [21]. Therefore, the DG set performance is severely affected by the EV charging, due to presence of harmonics in the EV current because the charger of the EV generally uses rectifier followed by a power factor correction circuit and a DC-DC converter for step down. However, in this paper, the DG set is always loaded to at least 80% of the rated value because the harmonics and reactive current requirement of the EV charger are provided by the voltage source converter (VSC). A rural area may provide many natural potentials energy resources that gives a lot of benefits. The availability of renewable energy in rural areas is the main key in realizing the distribution of electric vehicle technology and also increasing the electrification ratio. With renewable energy, a reliable power plant can be built by combining natural components as the main potential of electrical energy sources. By utilizing solar, wind and small-scale DER, construction of charging stations infra structure for EV can be realized especially to support implementation of electric vehicle technology and reducing consumption of fossil energy for transportation. The major contributions in this paper, are as follows.

- Design and experimental validation of PV array, energy storage and DG set supported grid integrated CS, which uninterruptedly supports both DC and AC charging of EVs.
- Design of a unified controller, which enables the charging station to operate in islanded, grid connected and DG set connected modes without changing the hardware and using only a single VSC.
- Design of a mode switching logic using which, the charging station changes the mode seamlessly to provide the continuous charging.

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- Design of control strategy for vehicle-to-vehicle (V2V) power transfer for charging the EV and vehicle-to-grid (V2G) power transfer for supporting the grid.
- Active power filter operation of the charging station for mitigating the grid current harmonics, so that the power exchange takes place at unity power factor. This is required for the compliance of the charging station with the IEEE-519 standard.
- Strategy for regulating the frequency and voltage of DG set without mechanical automatic voltage regulator.
- Strategy to feed the surplus PV array generated power into the grid for avoiding the overcharging of the storage battery.

The remainder of the paper is organized as follows: Photovoltaic System described in section II, followed by the EV charging station in section III, In Section IV describes the simulation results and section V ends with some concluding remarks.

II. PHOTOVOLTAIC SYSTEM

The modeling of the Photovoltaic system is done with MATLAB SIMULINK. The system consists of a photovoltaic panel, boost converter, a resistive load and Butterfly optimizer and a single-phase inverter.

OPERATING PRINCIPLE

Solar cells are the basic components of photovoltaic panels. Most are made from silicon even though other materials are also used.

Solar cells take advantage of the photoelectric effect: the ability of some semiconductors to convert electromagnetic radiation directly into electrical current. The charged particles generated by the incident radiation are separated conveniently to create an electrical current by an appropriate design of the structure of the solar cell, as will be explained in brief below. For further details, the reader can consult references [4] and [10].

A. Solar cell

A solar cell is basically a p-n junction which is made from two different layers of silicon doped with a small quantity of impurity atoms: in the case of the n-layer, atoms with one more valence electron, called donors, and in the case of the p-layer, with one less valence electron, known as acceptors. When the two layers are joined together, near the interface the free electrons of the n-layer are diffused in the p-side, leaving behind an area positively charged by the donors. Similarly, the free holes in the p-layer are diffused in the n-side, leaving behind a region negatively charged by the acceptors. This creates an electrical field between the two sides that is a potential barrier to further flow. This electric field pulls the electrons and holes in opposite directions so the current can flow in one way only: electrons can move from the p-side to the n-side and the holes in the opposite direction. A diagram of the p-n junction showing the effect of the mentioned electric field is illustrated in below figure.

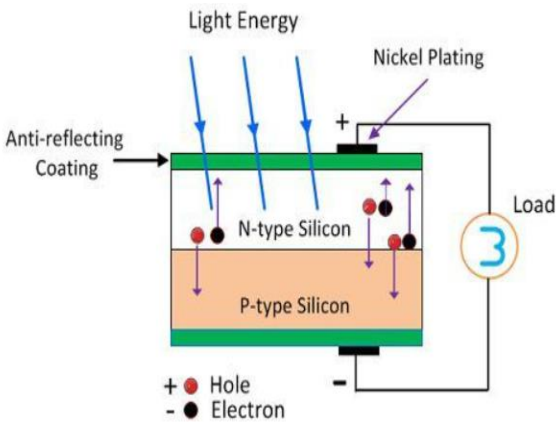

Fig.1: Solar cell

Metallic contacts are added at both sides to collect the electrons and holes so the current can flow. In the case of the n-layer, which is facing the solar irradiance, the contacts are several metallic strips, as they must allow the light to pass to the solar cell, called fingers.

MPPT Controller

- Maximum power point tracking (MPPT) is a technique used to maximize energy extraction.
- Maximum power point tracking (MPPT) is an algorithm implemented in photovoltaic (PV) inverters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions.
- Output of boost converter is compared with previous power of the module. Duty cycle is adjusted to

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track the Max Power Point. It continuous until the power of the PV reaches the max.

- The condition at which Max power is transferred to the load is
  $R_L = R_{\text{solar cell}}$

B. Wind Turbine

The supply is not reliable and sustainable. So this type of problem can be overcome by using a hybrid system, which is a system that combines aspects of renewable energy, such as solar and wind turbine simultaneously. Hybrid power systems can be defined as a combination of different energy sources. Complementary energy generation systems can be provided by renewable or mixed energy (with reserves from DER). The hybrid system provides better features of each energy resource compared to conventional sources and also provides electricity. The main advantage of hybrid systems is when a resource is lack for supporting energy, other resource can be supported as a main energy source. Solar panels are less effective on cloudy and windy days so they will produce lower energy levels while wind generators can produce a lot of energy. Similarly, for wind power plants the main problem is the location of the plant which has a certain amount of wind regularly. The main use of non-conventional energy makes this system almost independent and reduces energy prices in the long run, and a combination of diesel generators is used as a backup in emergencies such as high loads or low availability of renewable power [2]. A rural area may provide many natural potentials energy resources that gives a lot of benefits. The availability of renewable energy in rural areas is the main key in realizing the distribution of electric vehicle technology and increasing the electrification ratio. With renewable energy, a reliable power plant can be built by combining natural components as the main potential of electrical energy sources. By utilizing solar, wind and small-scale DER, construction of charging stations infra structure for EV can be realized especially to support implementation of electric vehicle technology and reducing consumption of fossil energy for transportation.

From the historical point of view the idea of electric drive for propulsion propeller isn't new. In the end of the 19th century in some countries such as Russia and Germany took place experiments which were directed for designing vessels with electric propulsion (EP) drives (electric power transmission).

➢ Contemporary propulsion systems

By the moment in the world the most widespread propulsion systems are:

- Diesel-mechanical (Diesels engines through a gear connected to a shaft and consequently to a propeller), Fig.2

- Conventional diesel-electric arrangement (Diesel engines (sometimes as prime mover may be used a steam turbine in a nuclear-powered ships) – electric generators – distribution and energy delivering system – electric motor-gear-shaft-propeller), Fig. 3
- Pod propulsion- so called azimuth thrusters (Prime movers – electric generators – distribution, delivering and energy conversion system – podded motors with on shaft propellers), Fig. 4

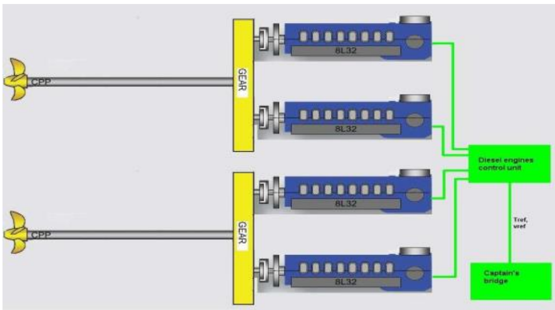

Fig.2: Typical diesel mechanical propulsion configuration

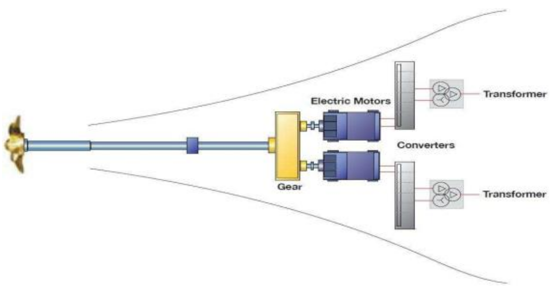

Fig.3: Conventional diesel-electric arrangement [2]

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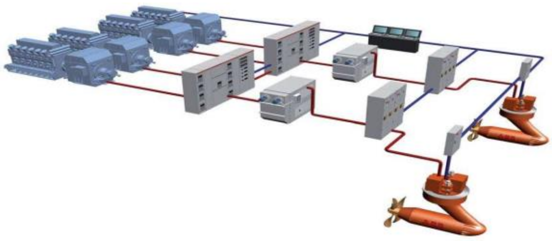

Fig.4: Podded propulsion- so called Azimuth thrusters or Azipod, made by ABB [2]

Nowadays, the electric propulsion is used in more and more application areas and replaces the classical mechanical configuration. In most cases azimuth thrusters or combined assemblies are used. Electrical propulsion is applied in a wide range of vessels such as: icebreakers, drilling vessels, cruise vessels, shuttle tankers, cable and pipe layers, war ships. Such a wide spread got a reality because of advantages inherent EP:

1 Reduced consumption of the fuel, especially, in maneuvering operation modes
2 Reduced maintenance cost due to flexible and smooth operating, avoiding jerky torque and speed change, decreasing tear modes
3 Optimized load of prime
4 mover (prime mover operates at rated parameters and life cycle is prolonged)
5 Decreased vibrations (absence long shaft) and noise (important on cruise vessels)
6 Higher level reliability directed for preventing blackouts
7 Opportunity to locate power equipment properly based on load in different vessel's parts
8 Mounting places of thrusters are not restricted because of delivering energy via cables

Typical efficiency of each component of the power system in the power level of ship components:

1. generator: 95 – 97 %
2. switchboard: 99.99 %
3. transformer 99.1 – 99.7 %
4. frequency converter 95 – 99 %
5. electric motor 93 – 97 %

III. EV CHARGING STATION

A charging station, also called an EV charger or electric vehicle supply equipment (EVSE), is a piece of equipment that supplies electrical power for charging plug-in electric vehicles (including hybrids, neighborhood electric vehicles, trucks, buses, and others). Although batteries can only be charged with DC power, most electric vehicles have an onboard AC-to-DC converter that allows them to be plugged into a standard household AC electrical receptacle. Inexpensive low-power public charging stations will also provide AC power, known as "AC charging stations". To facilitate higher power charging, which requires much larger AC-to-DC converters, the converter is built into the charging station instead of the vehicle and the station supplies already-converted DC power directly to the vehicle, bypassing the vehicle's onboard converter. These are known as "DC charging stations". Most fully electric car models can accept both AC and DC power.

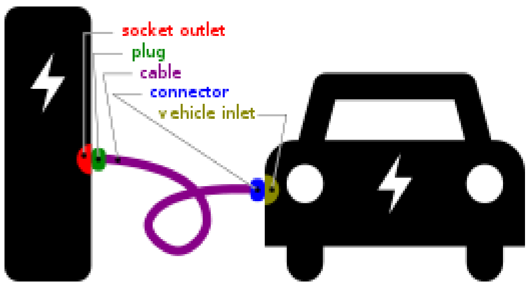

Fig.5: Charging station and vehicle terminology.

The terms "electric vehicle connector" and "electric vehicle inlet" were previously defined in the same way under Article 625 of the National Electric Code (NEC) of 1999. NEC-1999 also defined the term "electric vehicle supply equipment" as the entire unit "installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle", including "conductors ... electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatuses".
Voltage and Power

TABLE.1: Early standards

NEC(1999) levels[4]:9 hide	
Method	Maximum supply

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	Current (A)	Voltage (V)	Power (kW)
Level 1 (1Φ AC)	12	120	1.44
	16	120	1.92
	24	120	2.88
Level 2 (1Φ AC)	32	208/240	7.68
Level 3 (3Φ AC)	400	480	332.6

The Society of Automotive Engineers (SAE International) defines the general physical, electrical, communication and performance requirements for EV charging systems used in North America, as part of standard SAE J1772. SAE J1772 defines four levels of charging, two levels each for AC and DC supplies; the differences between levels are based upon the power distribution type, standards and maximum power.

TABLE.2: SAE

SAE J1772(2017) levels hide

Method	Maximum supply		
	Current (A)	Voltage (V)	Power (kW)
AC Level 1	12	120	1.44
	16	120	1.92
AC Level 2	80	208–240	19.2
DC Level 1	80	50–1000	80
DC Level 2	400	50–1000	400

Alternating Current (AC)

AC charging stations connect the vehicle's onboard charging circuitry directly to the AC Supply.

- AC Level 1: Connects directly to a standard 120 V North American residential outlet; capable of supplying 6–16 A (0.7–1.92 kW) depending on the capacity of a dedicated circuit.
- AC Level 2: Utilizes 240 V residential or 208 V commercial power to supply between 6 and 80 A (1.4–19.2 kW). It provides a significant charging speed increase over Level 1 AC charging.

Direct Current (DC)

Commonly, though incorrectly called "Level 3" charging based on the older NEC-1999 definition, DC charging is categorized separately in the SAE standard. In DC fast-charging, grid power is passed through an AC-to-DC rectifier before reaching the vehicle's battery, bypassing any onboard rectifier.

- DC Level 1: Supplies a maximum of 80 kW at 50–1000 V.
- DC Level 2: Supplies a maximum of 400 kW at 50–1000 V.

IV. SIMULATION RESULTS

Simulink

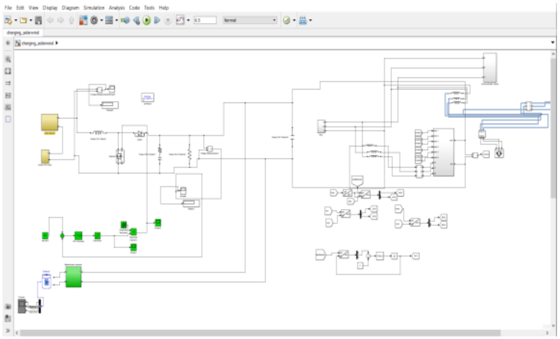

Fig.6: Solar panel design

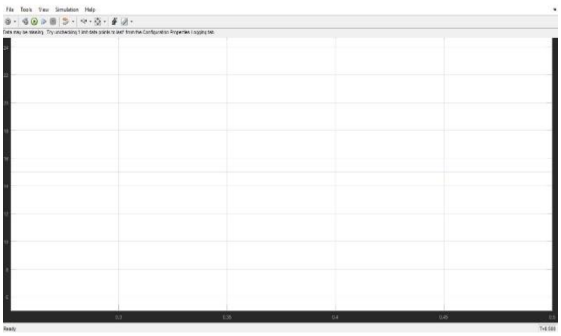

Fig.7: Solar voltage

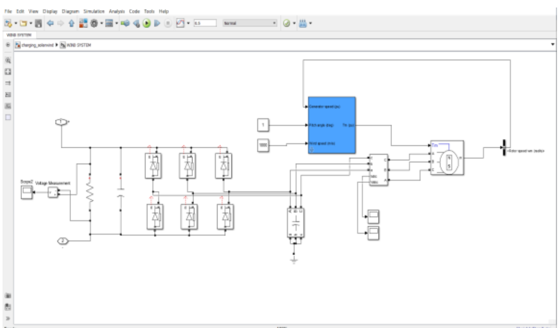

Fig.8: Wind design

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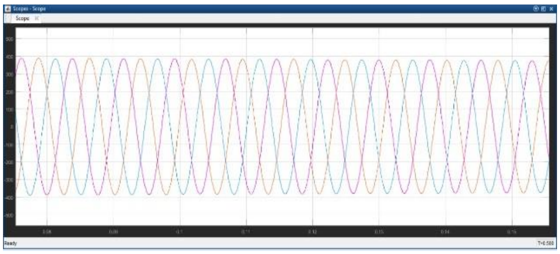

Fig.9: WIND OUTPUT VOLTAGE

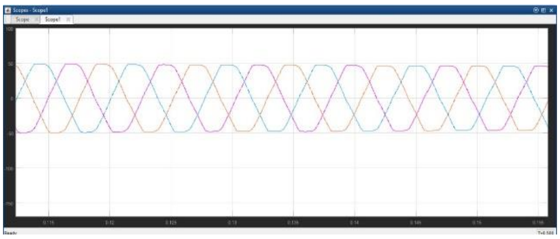

Fig.10: Output current

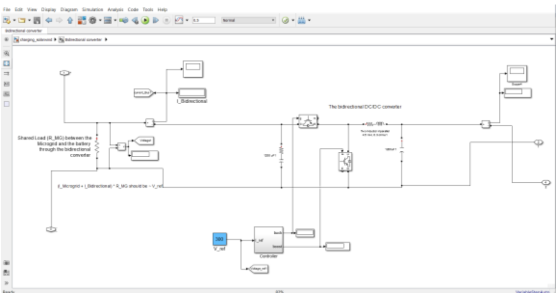

Fig.11: Bidirectional converter

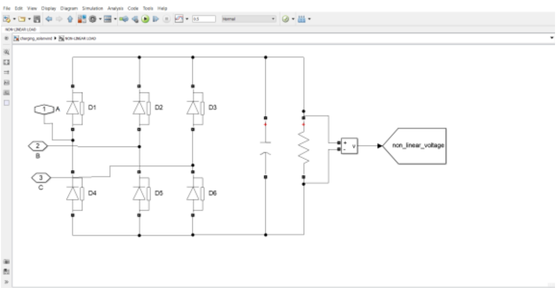

Fig.12: Nonlinear load

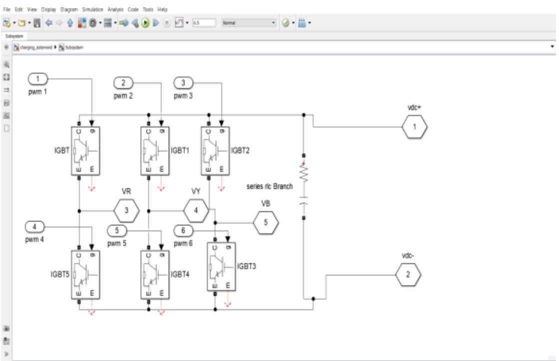

Fig.13: Inverter design

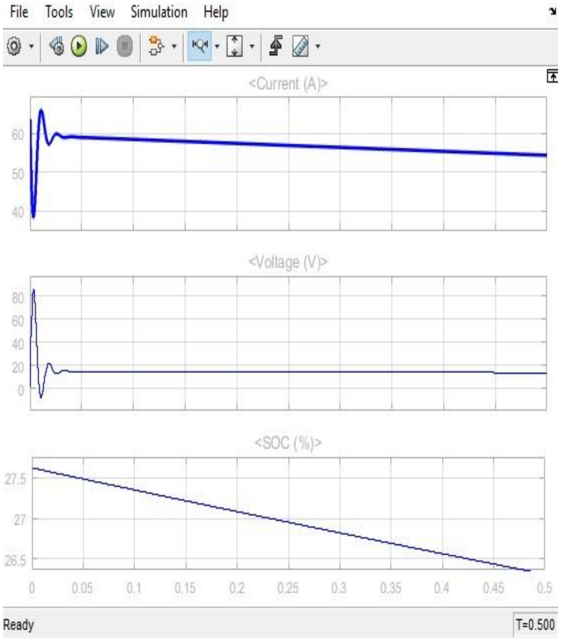

Fig.14: Battery status

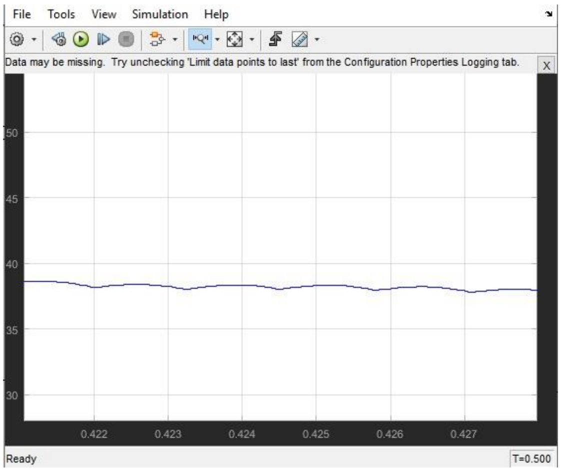

Fig.15: Hybrid voltage

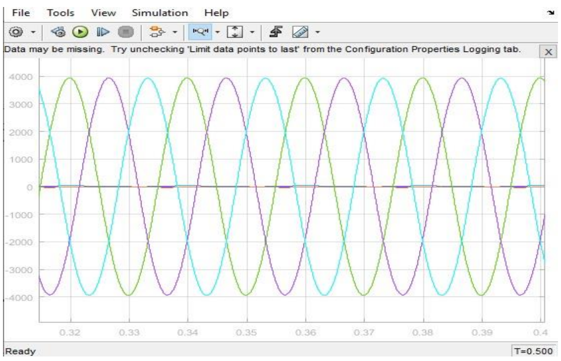

Fig.16: Load voltage

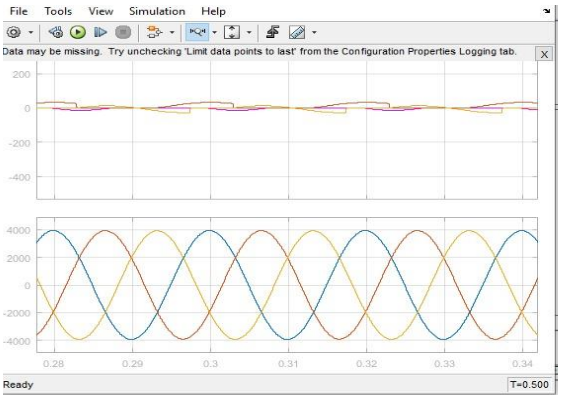

Fig.17: Electric vehicle current

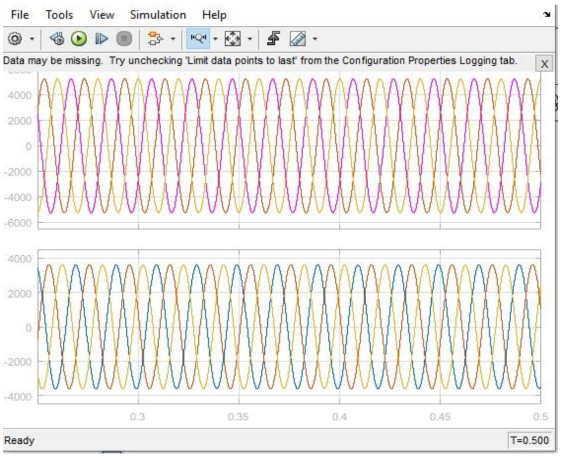

Fig.18: Gate signals

V. Conclusion

A charging station for electric vehicles (EVs) has been implemented using a photovoltaic (PV) array, storage battery, grid connection, and a diesel generator (DG) set. The results demonstrate the station's ability to operate in multiple modes, including islanded operation, grid-connected mode, and DG set-connected mode, using only one Voltage Source Converter (VSC). Changes in EV charging current and loading were observed, showcasing the station's versatility.

The station was tested for standalone operation, demonstrating good voltage quality. In grid-connected or DG set-connected modes, an Active Neutral Current (ANC) based control algorithm was used to maintain power exchange with the grid at Unity Power Factor (UPF) or to optimize the loading of the DG set.

The ability to switch between islanded operation, grid-connected mode, and DG set-connected mode, along with automatic mode switching, increased the probability of Maximum Power Point (MPP) operation of the PV array and optimized DG set loading, enhancing charging reliability. The station also complies with IEEE standards for voltage and current Total Harmonic Distortion (THD), with values always below 5%, highlighting the effectiveness of the control strategy.

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