Optimizing Stand-Alone Solar Systems with AI-Controlled Battery Management: Comparative Performance Analysis under Transient Conditions

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Abstract: *Electricity demand is escalating globally, driven by population growth, industrialization, and technological advancement. This rising demand necessitates a transition towards sustainable energy sources to mitigate environmental impacts and address concerns over dwindling fossil fuel reserves. Solar power, particularly through Photovoltaic (PV) systems, represents a promising solution due to its abundance and renewability. However, PV systems face challenges such as variability in energy output due to weather conditions and efficiency issues inherent in energy conversion processes. Maximum Power Point Tracking (MPPT) techniques play a crucial role in optimizing the performance of PV systems by ensuring they operate at their maximum power point (MPP), where the module generates the most power given the prevailing conditions. This optimization significantly enhances energy conversion efficiency and mitigates power losses. The principles of MPPT involve dynamically adjusting the electrical operating point of the PV system to track changes in solar irradiance and temperature, thereby maximizing energy extraction from the solar panels. This paper provides a comprehensive review of MPPT principles, focusing on its role in improving overall PV system efficiency through advanced control strategies. Emphasis is placed on the integration of artificial intelligence (AI) techniques within MPPT controllers, which enables intelligent decision-making based on real-time data inputs. AI-based controllers adapt to changing environmental conditions more effectively than traditional methods, thereby optimizing energy harvesting efficiency. Two case studies are presented to illustrate the practical application of AI-based MPPT controllers in standalone solar systems with battery backup. These case studies include a comparative analysis under transient loading conditions, evaluating parameters such as active power, reactive power, power factor, and total harmonic distortion (THD). The results demonstrate that AI-based MPPT controllers effectively optimize PV system performance, achieving higher energy yields and improved stability under varying operational conditions. In conclusion, the integration of AI in MPPT controllers represents a significant advancement towards enhancing the efficiency and reliability of PV systems.*

Keywords: *Photovoltaic systems, Maximum Power Point Tracking (MPPT), artificial intelligence (AI), solar energy, renewable energy, transient loading conditions, battery backup, power factor, total harmonic distortion (THD).*

I. INTRODUCTION

Electricity consumption is increasing at a faster rate than any other form of energy worldwide, creating a perpetual challenge due to socioeconomic growth. The use of fossil fuels is declining, yet the rate of consumption to support the industrial revolution is still high. Traditional sources are insufficient to meet the ever-growing energy demands, causing concerns about energy security and rising fossil fuel prices. The urgent need to find compatible options has led to increased research and development in renewable energy sources such as solar and wind power, which are widely accessible [1,2]. Solar energy is particularly promising due to its abundance and potential to meet global energy needs. Photovoltaic cells (Solar PV) are a leading option for energy technology due to their direct conversion of solar radiation into electrical energy. However, there are still significant challenges to overcome, such as fluctuating energy, low energy conversion efficiency, and high energy costs. To address these challenges, researchers are working to enhance the power output of photovoltaic modules through Maximum Power Point Tracking (MPPT), which matches the characteristics of the module to deliver maximum power output and prevent power loss. [3]

The foremost objective of the MPPT technique is to reduce oscillations due to changing weather conditions and to achieve fast and accurate tracking performance by controlling the operating point of the converter to operate the system constantly at Maximum Power Point (MPP) for regularisation of the output of the PV device [4]. The principal goal of the MPPT is to extract the highest power from the PV device. By locating the MPP and adjusting the duty ratio of the converter, the MPPT technique reduces the power loss and improves the conversion efficiency [5].

A. Photovoltaic Systems

A photovoltaic system, also known as a PV system or solar power system, is an electric power system that utilizes photovoltaic cells to generate usable solar power. The system comprises several key components, including solar panels that absorb and convert sunlight into electricity, a solar inverter that converts the generated electricity from direct current

(DC) to alternating current (AC), and various mounting, cabling, and electrical accessories to complete the setup shown in figure 1.

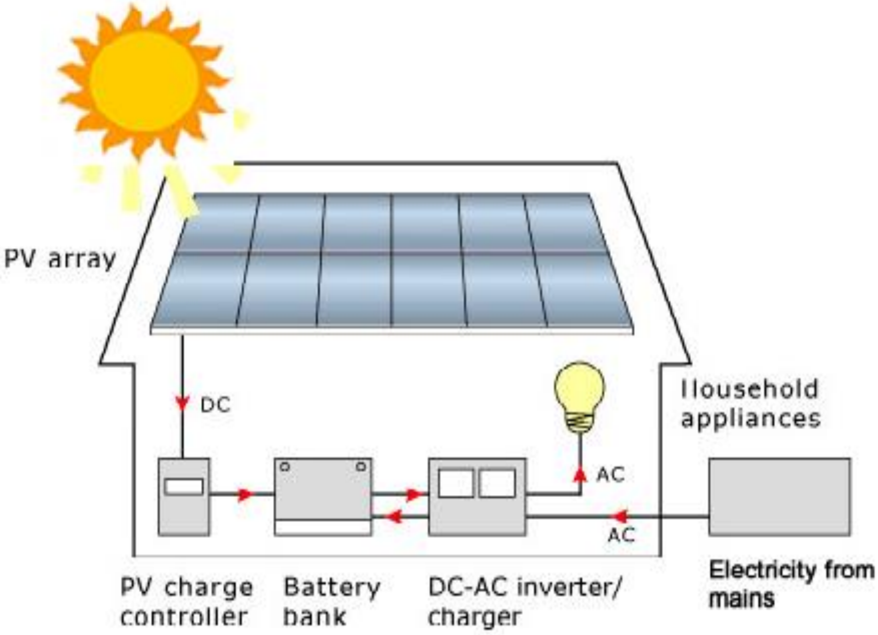

Figure 1 Typical Rooftop PV System

PV systems vary in size, ranging from small rooftop-mounted systems or building-integrated setups with capacities of a few to several tens of kilowatts, to large utility-scale power plants with capacities exceeding hundreds of megawatts. The majority of PV systems are now grid-connected, although off-grid or stand-alone systems constitute a smaller portion of the market.

B. Operation Principle of Solar Photovoltaic Systems

When light strikes the semiconductor, it transfers its energy to negatively charged particles called electrons. This energy boost enables the electrons to flow through the material, creating an electrical current. Metal contacts on the cell's surface extract this current, which can then be used to power homes and the electric grid.

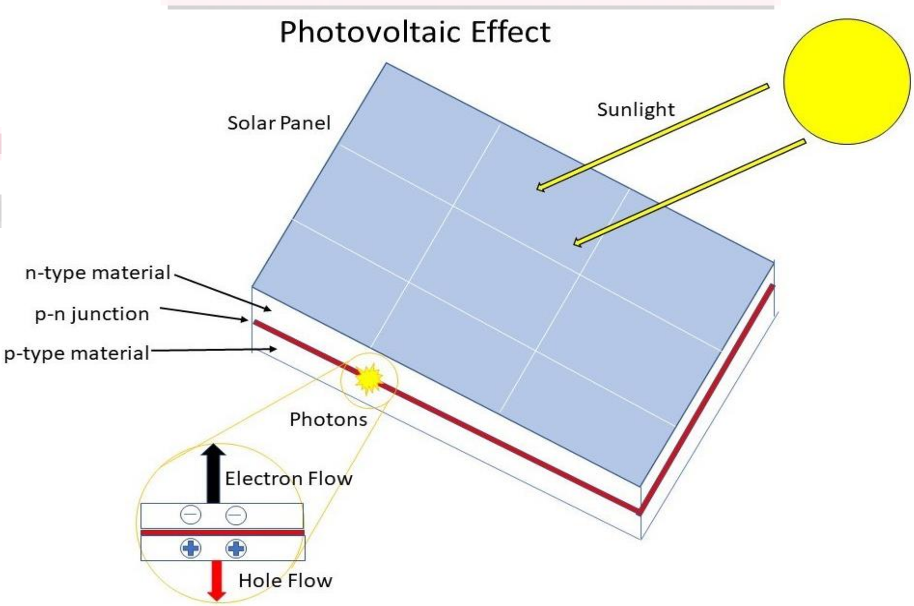

Figure 2. Working Principle of Solar Photovoltaic Systems

Figure 2 shows PV cell efficiency is a measure of the electrical power output compared to the energy input from the light, indicating how well the cell converts energy from one form to another. The electricity production from PV cells relies on light characteristics (such as intensity and wavelengths) and various cell performance attributes. A key characteristic of PV semiconductors is the band gap, which determines the wavelengths of light the material can absorb and convert into electrical energy. When a semiconductor's band gap matches the light wavelengths hitting the PV cell, the cell can efficiently utilize all available energy[6]

II. LITERATURE REVIEW

Al-Buraiki et al. (2023): This study investigates the optimization of standalone PV renewable energy systems by coordinating load with solar energy availability in Dammam City, Saudi Arabia. Using MATLAB, the research demonstrates that aligning load with peak solar radiation reduces energy costs by 24% and storage system size by 39%. Partial coordination for residential and industrial systems also shows cost savings of 11-16% and storage size reductions of 17-26%.

Hosseini Dolatabadi et al. (2024): Addressing inaccuracies in current methods, this research introduces the MMALH ELCC metric for accurately estimating the capacity value of photovoltaic (PV) plants. Case studies in Belgium, Texas, and California validate the metric's effectiveness in reflecting real-world capacity value patterns, reducing reliance on hourly data. The study underscores the metric's significance for enhancing PV system design, maintenance, and integration efficiency.

Govindasamy and Kumar (2023): This investigation explores the use of phase change materials (PCMs), specifically vermiculite & paraffin jelly composite (VP-PCM) and expanded perlite & paraffin jelly composite (PEP-PCM), to manage and reduce temperatures in monocrystalline solar panels. Experimental results reveal that PCM integration effectively lowers panel temperatures, enhances power output, and increases overall electrical efficiency.

Amole et al. (2023): Focusing on rural Nigeria, this study evaluates energy scenarios including grid-only, PV-only, and PV-grid configurations using the HOMER tool. Economic and technical analyses highlight that the PV-grid system offers optimal performance with higher grid purchase, excess electrical production, and economic indicators such as net present cost and levelized cost of energy, supporting sustainable energy solutions in rural settings.

Ibrahim et al. (2023): Describing a grid-tied PV system integrated with a Dynamic Voltage Restorer (DVR), this research develops a rotating dq reference frame (dqRF) controller optimized with artificial rabbits optimization (ARO). Comparative analysis with other optimization techniques demonstrates superior performance in mitigating power quality issues. The study validates system stability through Lyapunov analysis and confirms improved voltage waveform quality under fault conditions using MATLAB/SIMULINK simulations.

III. OBJECTIVE

There are following objective are to be expected from the present work

- To design a solar photovoltaic system in MATLAB/SIMULINK environment in standalone mode and study the quality factors at the load end.
- To improve the power output from the solar system by designing an efficient controller for the battery system that is capable of handling the output parameters available at the loading points.
- Making the battery controller efficient for handling the transient loading conditions as well to make it more reliable in driving multiple loads.
- Enhance the system efficiency when in operation in standalone mode along with its load handling capacity to reduce dependency on the grid.

IV. METHODOLOGY

PV cells have single operating point where the values of the current (I) and voltage (V) of the cell result in a maximum power output. These values correspond to a particular resistance, which is equal to V/I. A simple equivalent circuit of PV cell is shown in Figure 3.

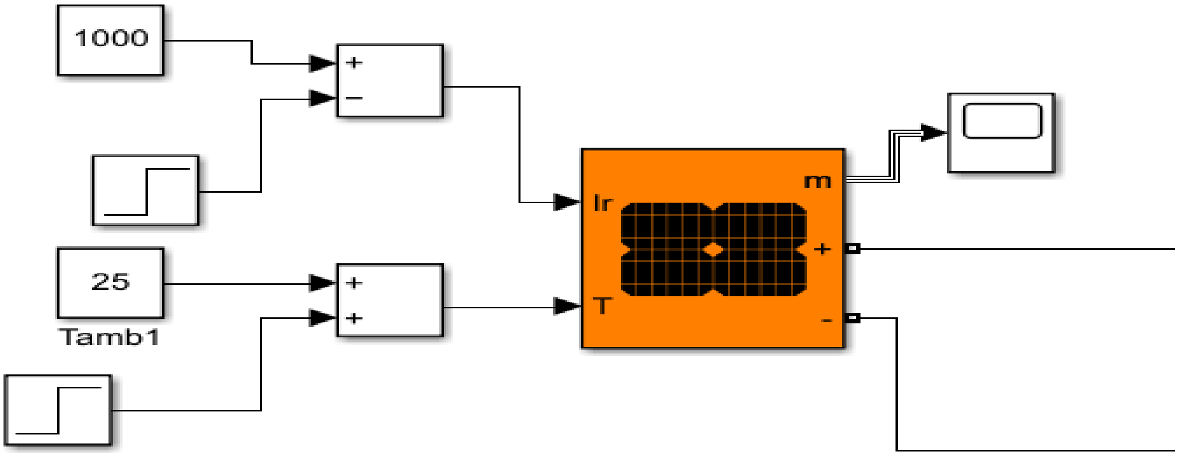

Figure 3 Modeled solar systems

A cell series resistance (Rs) is connected in series with parallel combination of cell photocurrent (Iph),exponential diode (D), and shunt resistance (Rsh) , I pv and Vpv are the cells current and voltage respectively. It can be expressed as

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh}$$

Where:

I ph - Solar-induced current

Is - Diode saturation current

q - Electron charge (l.6e-l9C)

K - Boltzmann constant (l.38e-23J/K)

n - Ideality factor (l~2)

T - Temperature 0K

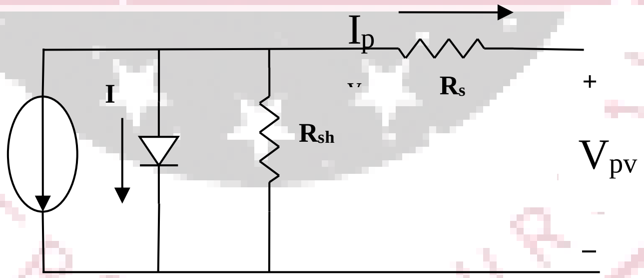

Figure 4. Equivalent circuit of solar pv cell

The solar induced current of the solar PV cell depends on the solar irradiation level and the working temperature can be expressed as:

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000}$$

Where:

Isc Short-circuit current of cell at STC

ki Cell short-circuit current/temperature coefficient (A/K)

Ir Irradiance in w/m

Tc, Tr Cell working and reference temperature at STC

A PV cell has an exponential relationship between current and voltage and the maximum power point (MPP) occur at the knee of the curve as shown in the Figure 5.

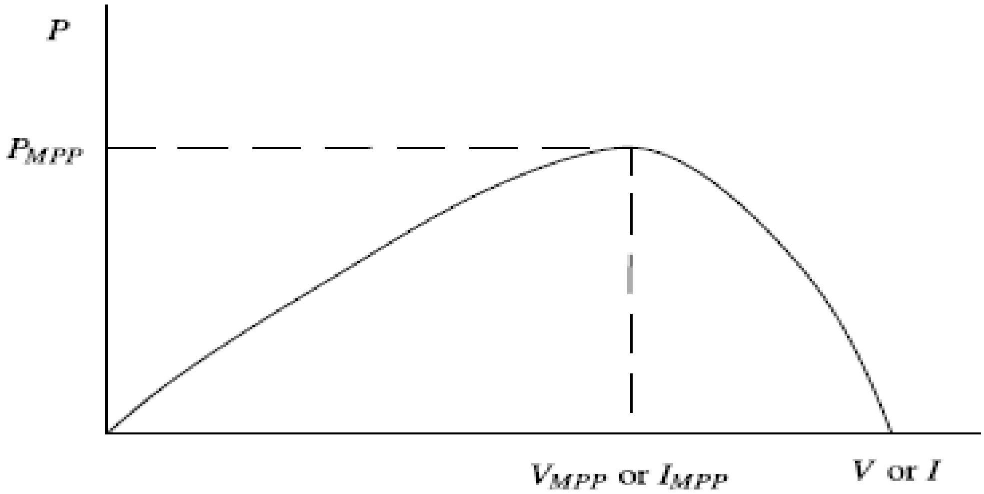

Figure 5 Characteristic PV array power curve

The P&O algorithm will track the maximum power to supply the DCMGs system. The assumptions for model derivation are that the ideal current source can be presented as the PVs behavior. In addition, all power converters are operated under the continuous conduction mode (CCM) and the harmonics are also ignored.

Table 1: PV module Parameters

Maximum Power	213.5 Watts
Number of parallel strings	40
Number series modules	10
Open circuit voltage	36.3 Volts
Shot circuit current	7.84 Ampere

The provided table 1. Outlines key parameters of a photovoltaic (PV) system with a maximum power output of 213.5 Watts per module. It consists of 40 parallel strings, each containing 10 modules in series, enabling the system to generate a substantial total power of 85.4 kW under optimal conditions. The system's open circuit voltage is 36.3 Volts, and its short circuit current is 7.84 Amperes, crucial for designing compatible system components and ensuring safety through appropriate wiring and protective devices. These specifications make the PV system suitable for commercial or small utility applications, emphasizing its capability to deliver significant renewable energy efficiently and reliably.

Standalone systems represent a dynamic and evolving field that holds the key to unlocking a range of sustainable, resilient, and cost-effective energy solutions. The research into these systems not only fosters technological innovation but also supports broader goals of environmental stewardship and social equity.

V. SIMULATION AND RESULT ANALYSIS

A. Modelling of Solar System

The solar panel has been modelled with PV arrays having 10 cells connected in each series with 40 parallel branches that together give out the DC output from the system. The variable illumination of 1000 lux is provided along with varying temperature of 250 C .This output is then merged with the DC output from the wind energy system and further sent to the inverter for its AC conversion.

Case 1: Solar system model using battery controller driven by standard voltage control

Case 2: Solar system model using artificial bee colony optimization method for battery control and parameters regulation

a) Case 1: Modelling of Solar power system in standalone mode

The system has been modeled with solar energy system using battery system with controller before the converter and disconnected from the grid directly feeding the loads. This system has used solar based energy generation in it driven by an inverter for DC to AC conversion of the electrical output generated from the solar system. Solar power system modeling with battery controller driven by standard voltage control Shows in figure 6.

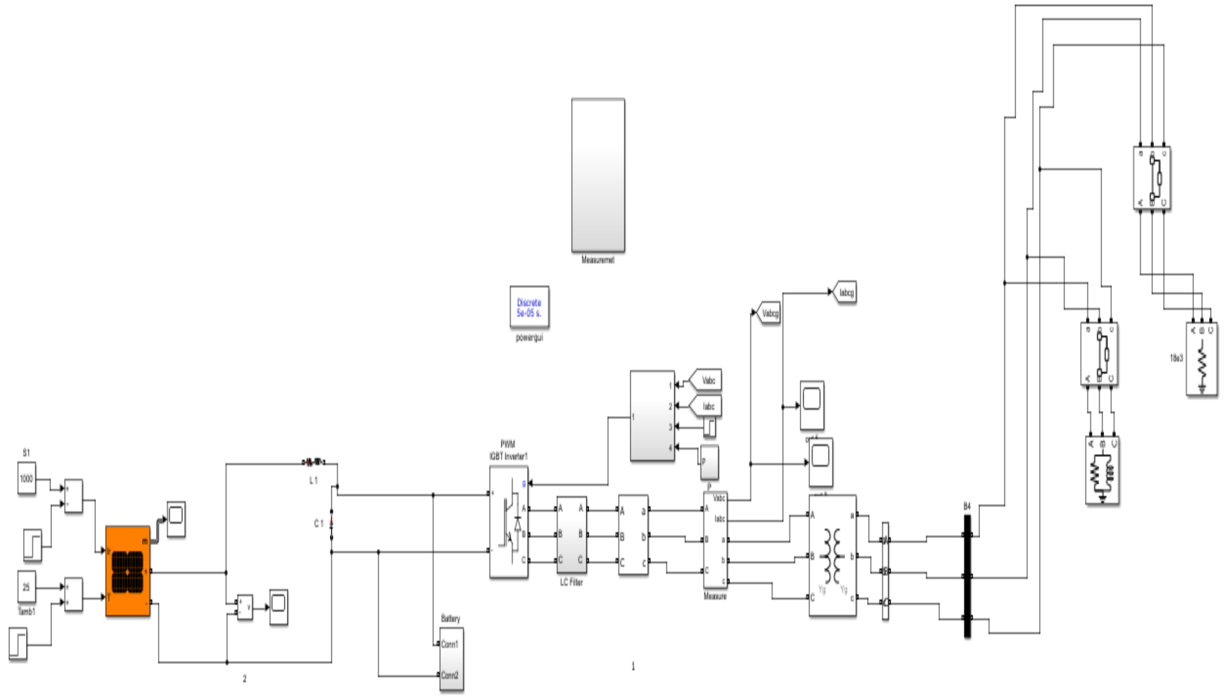

Figure 6 Solar power system modeling with battery controller driven by standard voltage control

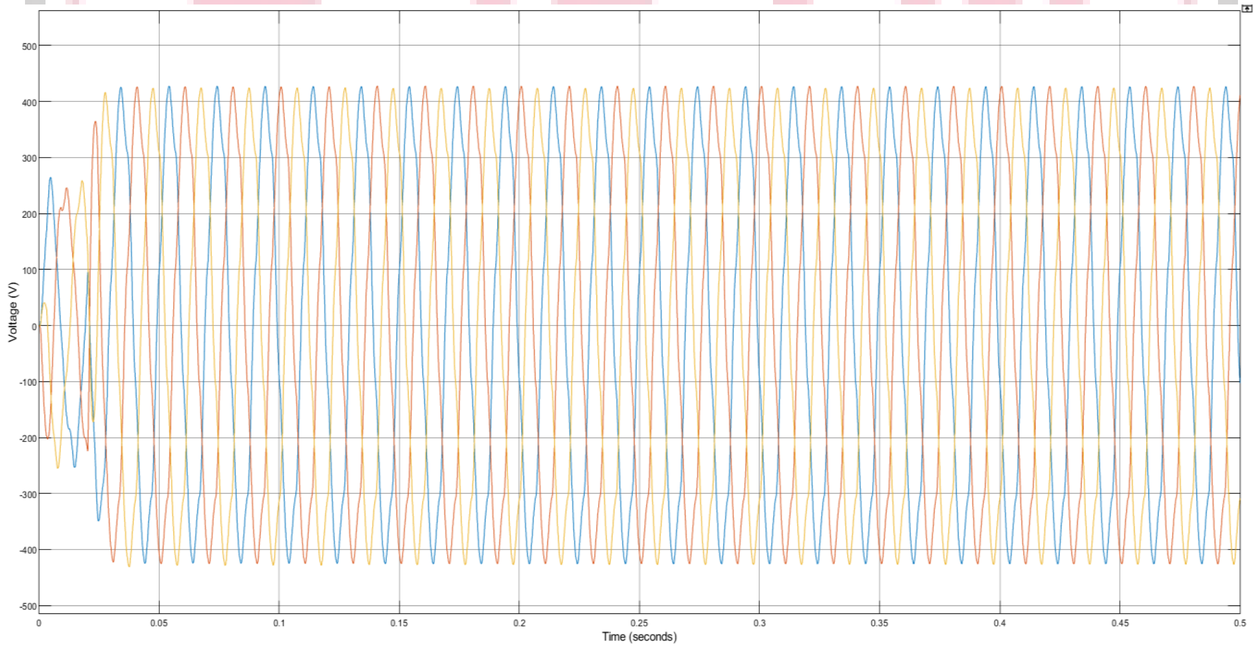

Figure 7 Voltage output available at the load bus in case 1

The figure 7 depicts the three phase AC voltage presented by three colors for each phase. This voltage output is 410 V in system with battery controller driven by voltage regulation control.

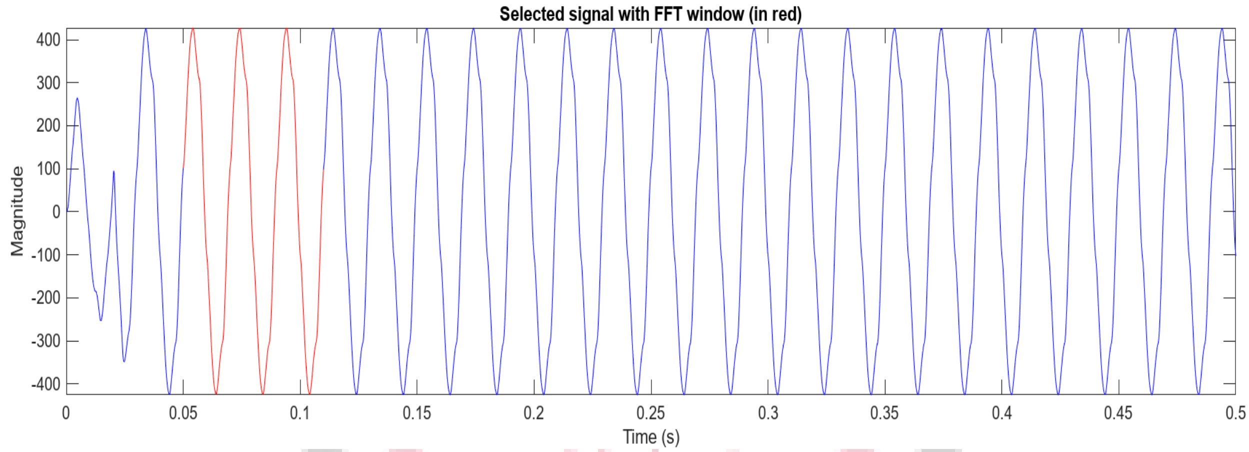

Figure 8 FFT analysis of load voltage in case 1 with battery controller driven by voltage regulation control

The figure 8 depicts the FFT analysis of the three phase AC voltage for each cycle in the system which is analyzed with battery system controller driven by voltage regulation control and is further used for calculating the total harmonic distortion level.

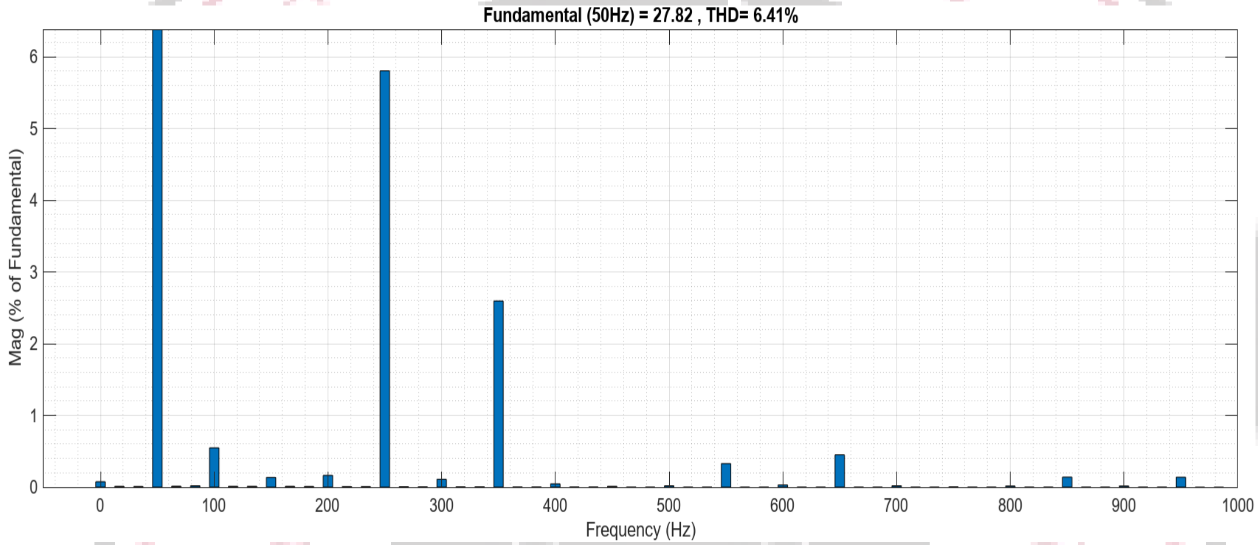

Figure 9. THD% of load current in case 1 with battery controller driven by voltage regulation control

The THD% is calculated in the software which comes to be 6.41% in current waveform in system in case 1 and lower order harmonics are found in them which is represented in figure 9.

The graph above further describes the voltage output coming from the Transformer that is feeding the load because the system in this case is not integrated with the grid. The phase to phase voltage output from the Transformer is approximately 420 volts and when we see the Phase to ground voltage output from the Transformer it is coming to be 230 volts approximately

b) Case 2 : Modelling of Solar power system in standalone mode

The system in this case is modeled with solar energy using battery controller whose regulation parameters are continuously studied and optimized artificial bee colony optimisation method that yields better outcomes at the loading bus and model figured out below in figure 10 . The proposed controller is designed to effective manage the flow of power to the load during constant as well as switching conditions. The AC power quality is recorded and corrected by the optimisation process adopted in the battery controller. Further the voltage current, active power and reactive power waveforms have been analyzed.

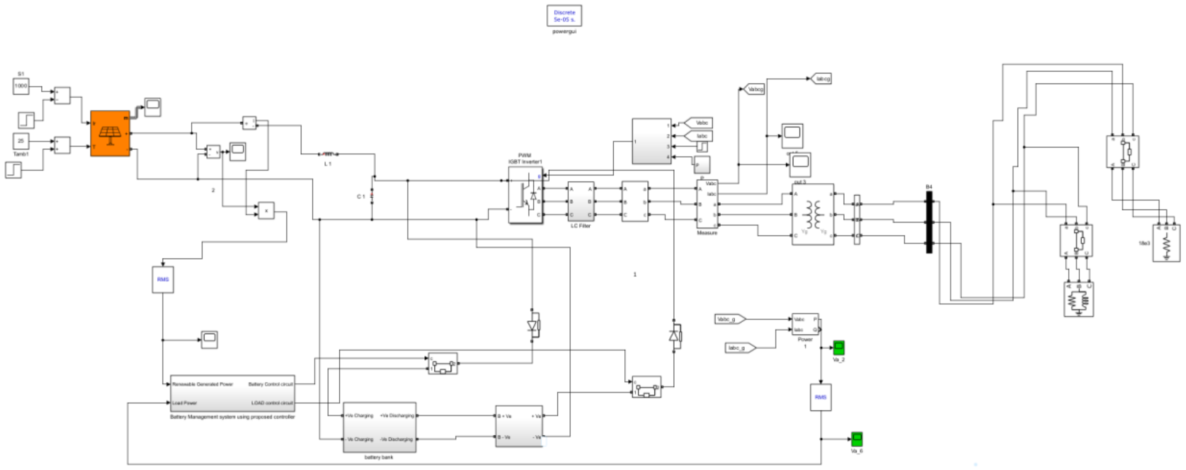

Figure 10. Solar system model using Artifical bee colony optimisation method for battery control and paramters regulation

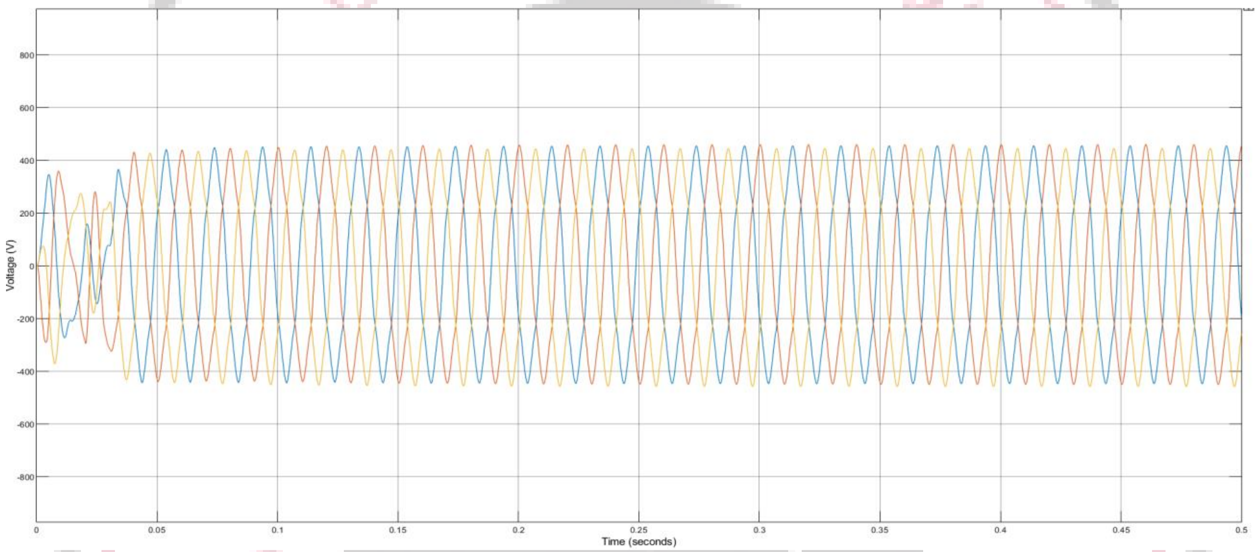

Figure 11. Voltage Output available at the load bus in case 2

The figure 11. represents the three phase AC voltage which is represented by three colors for each phase and magnitude approximately 410 V for work. This voltage output is analyzed with controller driven by proposed ABC based battery optimization control in PV system.

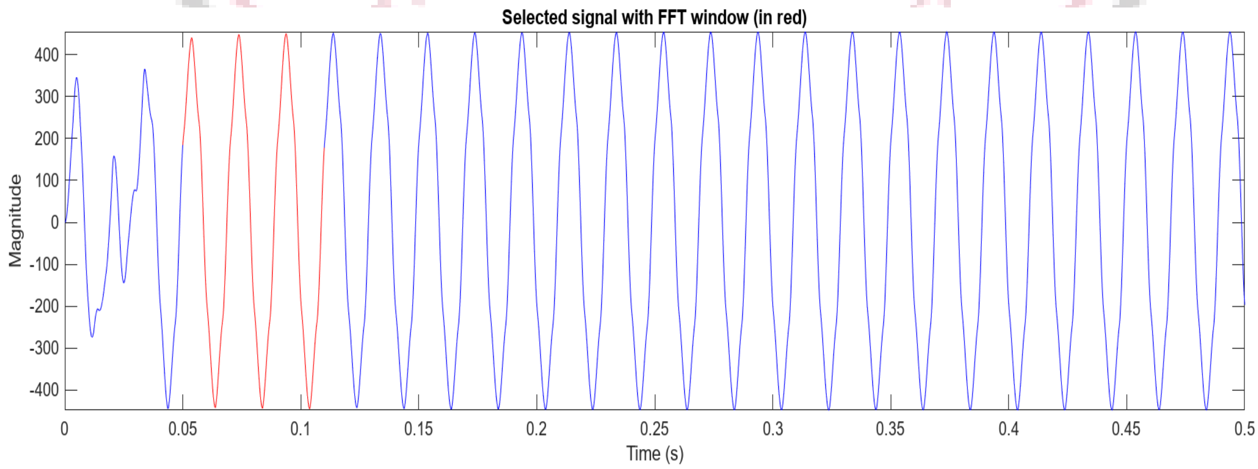

Figure 12. FFT analysis of load voltage in case 2 with battery controller driven by ABC algorithm

The figure 12. depicts the FFT analysis of the three phase AC voltage for each cycle in the system which is analyzed with controller driven by proposed ABC algorithm and is further used for calculating the total harmonic distortion level in this system

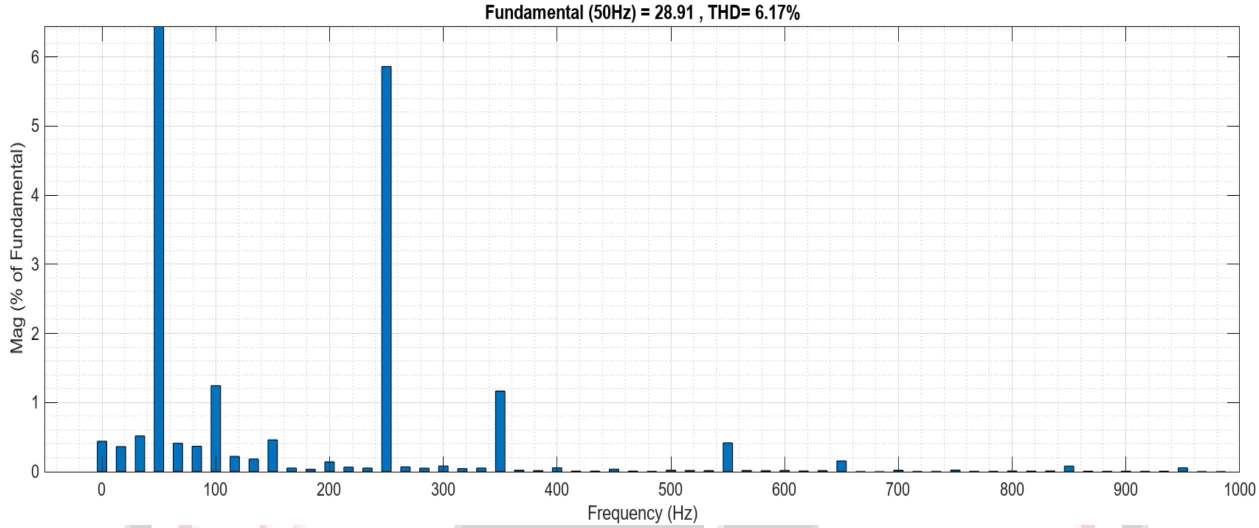

Figure 13.THD% in load current in case 2 with battery controller driven by ABC algorithm

The THD% is calculated in the software which comes to be 6.17% in current waveform in system having battery system with ABC algorithm for load management and higher order harmonics are reduced in them discussed in figure 13.

The table 2 presents a comparative analysis of two cases based on several key parameters related to power and transient loading. Case 2 shows higher active power at 19.89 kW compared to Case 1 at 17.95 kW, indicating potentially improved energy output or efficiency. However, Case 1 exhibits higher reactive power at 8.18 kVar versus 4.04 kVar in Case 2, which could impact overall power quality. Case 2 demonstrates a higher power factor of 0.98 compared to Case 1's 0.91, suggesting more efficient power utilization. In terms of harmonic distortion, Case 2 generally shows lower percentages in both voltage (6.24% vs. 6.49% in Case 1) and current (6.17% vs. 6.41% in Case 1), indicating better electrical quality. Moreover, Case 2 maintains lower THD% in current at both loading (5.82% vs. 8.86% in Case 1) and off-loading points (5.75% vs. 9.12% in Case 1), suggesting more stable operation under varying loads.

Table 2 Comparative analysis of proposed controller

Parameters	Case 1	Case 2
Active power	17.95 KW	19.89 KW
Reactive power	8.18 KVar	4.04 KVar
Power Factor	0.91	0.98
THD% in voltage	6.49 %	6.24 %
THD% in current	6.41 %	6.17 %
Transient loading comparison		
THD% in current (loading point)	8.86 %	5.82%
THD% in current (off-loading point)	9.12%	5.75%

% increase in efficiency = $\left(\frac{New\ output\ power - Old\ output\ power}{old\ output\ power}\right)\ x\ 100$

= [(19890-17950)/ 17950] x 100

= 10.8%

V. CONCLUSION

The analysis underscores the critical role of MPPT techniques enhanced by AI in optimizing solar PV system performance under dynamic conditions. The comparative analysis reveals that AI-based control strategies significantly enhance active power output and power factor while reducing reactive power and THD levels compared to traditional voltage regulation methods. Case 2, employing AI-based bee colony optimization, demonstrates superior efficiency in managing transient loading conditions, making it a promising approach for enhancing the reliability and robustness of standalone PV systems with battery backup. These findings highlight the potential of AI-driven solutions to advance the adoption of sustainable energy technologies, paving the way for more resilient and efficient solar PV systems in diverse operational environments.

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