Advanced MPPT Strategy and Interleaved SEPIC Converter for Efficient Hybrid Micro-grid with IoT Monitoring

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***Abstract*—The increase in global energy demand continues to cause the supply demand imbalance, thus necessitating the adoption of advanced approaches for efficient energy generation and management. This work addresses this situation by proposing an Internet of Things (IoT)-enabled micro grid that combines an Advanced Maximum Power Point Tracking (MPPT) method and an Interleaved SEPIC Converter to maximise solar energy collection of Photovoltaic (PV) systems. The Interleaved SEPIC Converter assists with improving output voltage level and minimising input current ripple. The MPPT method, is developed using a Tabu Search-driven Artificial Neural Network (ANN), which process real time voltage and track the Maximum Power Point (MPP) of solar PV systems with high precision. This DC output is converted AC using three phase Voltage Source Inverter (VSI) suitable for grid integration. Additionally, the IoT connected PV system provides real-time monitoring, fault diagnostics, and data logging to assist in overall management, and operational flexibility. Simulation using MATLAB validates that the proposed work demonstrates an improvement in converter efficiency by 94% and optimized MPPT tracking efficiency by 98.5%.**

Keywords—Internet of Things, Maximum Power Point Tracking, Interleaved SEPIC Converter, Artificial Neural Network, Tabu Search, and Photovoltaic.

I. INTRODUCTION

The advancement of Renewable Energy (RE) in the future is essential since it provides an alternative to fossil fuel materials while acting as an initial step towards achieving a green environment [1]. The use of RES is assumed by many countries as part of their contribution to addressing the challenge of global warming [2]. RES like solar PV assist to availability of electricity which is usable, profitable, and non-environmentally harmful. Also, it is ethically conscious, economically feasible, and environmentally safe [3]. However, the fluctuation of climatic changes affect the energy need of the grid [4]. Thus, converters and controllers are fundamental for solar power systems to change and boost the voltage level of the energy before it used by the grid [5].

A. Literature Review

Alireza Asadi *et al* (2023) explored a non-isolated Single-Inductor Multi-Input Single-Output (SI-MISO) boost converter and Proportionate-Integral Derivative (PID) cascade controller for regulating input power and output voltage, but the converter efficiency is relatively low [6]. Kanagaraj N *et al* (2024) proposed a Multi-Port Z-Network Converter (MPZNC) topology which is intended to increase input-output voltage transformation ratio and expanded voltage control range. Nonetheless, the converter active switches suffer high voltage stress and make poor conversion efficiency [7]. Omarabdel-Rahim *et al* (2023) utilized a modified SEPIC converter along with Model Predictive Control (MPC)-based MPPT algorithm to track MPP in PV systems. The SEPIC converter is characterized by high voltage gain and low voltage stress, and MPC controller ensures consistent power extraction. However, the MPP fail to track accurately under certain conditions [8]. Salah Beni Hamed *et al* (2023) developed a MPPT controller using PV systems based on boost converter with a sliding mode control (SMC) technique to effectively track MPP under disturbed environmental conditions. Nevertheless, design, tuning and implementation of SMC is challenging [9]. Younes Sahri *et al* (2023) proposed an MPPT algorithm initiated on a Fuzzy Controller (FC) for the PV subsystem, utilizing an Energy Management Algorithm (EMA) for energy balance solutions. However, the MPTT algorithm cause implementation complexity due to advanced control [10].

When irregular sources are connected to the grid, it creates larger concerns on the stability of the grid. Therefore, monitoring the electricity generated is essential, hence Smart Grid (SG) based IoT system are used for this purpose [11].

B. IoT Monitoring

A SG stands a large network of wireless devices that collect and send large volumes of heterogeneous ecological information in real time. The IoT has brought significant importance to an individual's life by allowing numerous devices to link to the internet [12]. The IoT links devices to permit for new forms of interaction between devices and

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individuals for data transfer to monitor and control devices from any location in the world while connected to the Internet [13]. The principle of IoT is linked to the sensors and devices of a specific system using wired or wireless nodes to a common network. IoT based harness wireless technologies are typically adopted to minimize the risks involved in wired systems. Accordingly, RE adopts an SG based on IoT to ensure efficient real power monitoring [14].

Hence, this work implemented an IoT-based SG system for monitoring power from PV energy sources using an interleaved boost converter and Tabu search optimized ANN MPPT controller to increase the output voltage, with the IoT device continuously monitoring the output voltage

C. Contributions & Paper Organization

The contribution of the work are,

- Interleaved SEPIC converter is designed for significant boosting PV voltage, contributing to increased energy efficiency.
- Tabu search optimized ANN MPPT controller is applied to extract MPP from PV source.
- IoT module is integrated to monitor system performance in real time through smart devices.

This work begins with Section II, which discusses the description of proposed system. In Section III, models are developed for each individual component of the proposed system. Next, in Section IV, the results and discussions are presented. Finally, a conclusion of proposed research are discussed in Section V.

Research Gaps:

This research proposes a smart and efficient hybrid micro-grid system that integrates advanced MPPT algorithms such as neural networks or fuzzy logic for accurate and fast power tracking under varying conditions. An interleaved SEPIC converter ensures efficient, ripple-free DC-DC conversion with step-up/down capability. Coupled with real-time IoT-based monitoring for data acquisition, fault detection, and control, the system offers a reliable, scalable, and intelligent solution to enhance energy conversion and management in modern hybrid micro-grids.

II. Proposed System Description

The global population's rising energy requirements lead to RES like solar energy. However, the energy produced by PV system is essential to monitor due to the gap between energy supply and consumer demand. Hence, the use of the IoT facilitates the efficient monitoring of the energy produced by this PV system shown in Fig. 1. The PV system captures solar energy, but due to fluctuations in solar irradiation, the output voltage from the PV array varies.

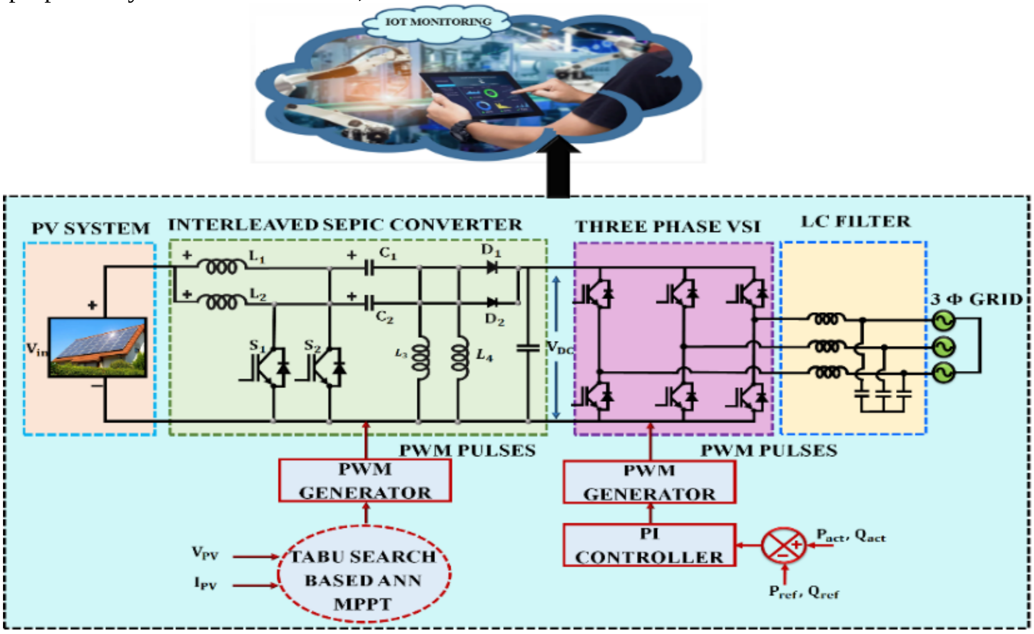

Fig. 1. Proposed block diagram of IoT monitoring

To address this, an interleaved SEPIC converter for boosting voltage from the PV source while capturing the produced pulses with the switches to control the converter operation. A Tabu search optimized ANN-based MPPT extracts maximum power from PV module, sending maximum current and voltage to the PWM generator, which produces a pulse. The DC link voltage is created from the separate input and output DC currents from the interleaved SEPIC converter, which is then converted to AC voltage by a three phase VSI. The output AC voltage and current is filtered by LC filter and processed to grid. Furthermore, an IoT-based SG device is designed to efficiently monitor hybrid micro-grid.

III. Proposed System Modelling

A. PV Modelling

A solar cell is made up of a current source connected in parallel to a diode, with additional series and shunt resistances to simulate non-ideal behaviour. Series connected resistance is to resist the flow of electrons. The circuit of solar cell is given in Fig. 2. Current equation as follow,

$$I = I_{pv} - I_O\left[e^{\frac{(v+R_S.I)}{\propto V_k}} - 1\right] - \frac{(v+R_S.I)}{R_p} \qquad (1)$$

Here, thermal voltage & photocurrent is represented by V_k and I_{pv}, electron charge & temperature denoted by q and T, ideality factor stands ∝, series resistance by R_s, and I_O indicates cell saturation current, R_p shunt resistance respectively.

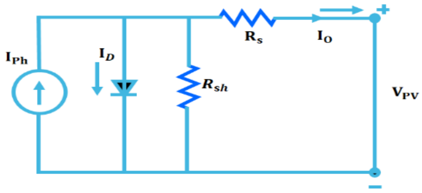

Fig. 2. Circuit diagram of solar cell

Temperature, radiation, and number of arrays in PV panel have each an impact on the PV current. Thus, Eq. (2) become

$$I = I_{pv} - I_O\left[exp\frac{(v+R_S.I)q}{\propto kT.N_S} - 1\right] - \frac{(v+R_S.I)}{R_p} \quad (2)$$

Here, Ns represents series of connected cells. Therefore, an interleaved SEPIC converter is used to step up low voltage drawn from the PV system, which is explained as follows.

B. Minterleaved Sepic Converter

In PV system, widely used converters have encountered critical problems on high input current ripples. The problem is resolved by initiating interleaved SEPIC converter. This converter contains a multi-phase shifting control signal that operates at the same switching frequency. Fig. 3 shows the schematic depiction of this DC–DC converter, which produces excess power, lowers harmonic distortion, and eliminates electromagnetic waves. There are four modes of operations shown in Fig. 4.

Mode 1:

The S_2 switch is ON state and S_1 switch is OFF state in mode 1. Capacitors C_1, C_2 in charge using the PV output potential, and inductors L_2, L_3 discharge to the load. Diode D_1 reversed biased the load, and D_2 is forward-biased and delivers power into load's device.

Mode 2:

In this mode, the switches S_1 and S_2 are ON position. During this time, the inductors $L_1, L_2, L_3, and\ L_4$, are charged by the input PV. Due to reverse bias state, diodes $D_1\ and\ D_2$stop the current from flowing through the load.

Mode 3:

Switch S_1 closes and switch S_2 remains open in this mode. The inductors L_2, L_3, receive a charge supplied by the PV source, and the inductors L_1, L_4 release their energy over the load. For this state, the diode D_2 blocks the backward current of the PV system.

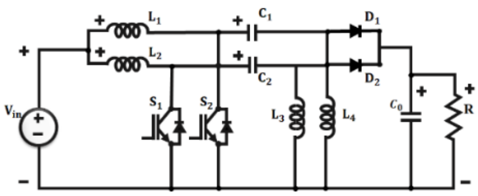

Fig. 3. Proposed interleaved SEPIC converter

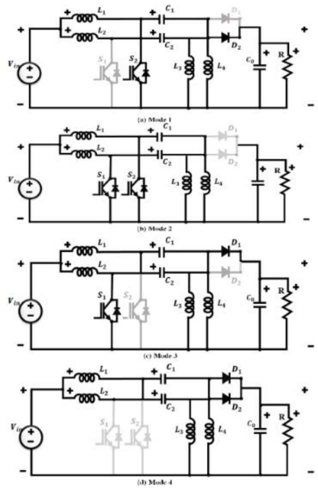

Fig. 4. Four modes of operation.

Mode 4:

In Mode 4, the S_1 and S_2 switches are turned OFF. When the load is applied in this mode, the inductors discharged L_1, L_2, L_3 and L_4. Forward bias is present in diodes D_1 and D_2.

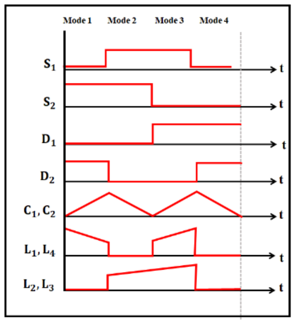

Fig. 5. Timing diagram of proposed converter

The formulas for proposed converter's output voltage V_{out}, inductances, and capacitances are represented in constant state as follows:

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}} = \frac{d}{d-1} \quad (3)$$

$$L_1 = L_2 = \frac{(1-d)V_{out}}{\Delta i_{L1}.f_{sw}} = \frac{(1-d)V_{out}}{\Delta i_{L2}.f_{sw}} \quad (4)$$

$$L_3 = L_4 = \frac{L_1}{2} = \frac{L_2}{2} \quad (5)$$

$$C_1 = C_2 = \frac{dI_{out}}{\Delta v_{out}f_{sw}} \quad (6)$$

$$C_{out} = \frac{dP_{out}}{\Delta v_{ripple}V_{out}f_{sw}} \quad (7)$$

Thus, proposed converter conducts effective raising of input DC voltage with development of minimized electromagnetic radiation and ripples. Waveform of proposed converter is shown in Fig. 5. For the maximum power from PV, a MPPT controller used and which is discussed below.

C. Tabu Search Optimized ANN MPPT Controller

a) ANN MPPT

ANNs are probabilistic models for learning which forecast or indicate functions based on an extensive amount of unpredictable inputs. ANN are shown as Fig. 6 networks of connected "neurons" that communicate via adjustable to numerical weights. In solar power systems, ANN are applied to model and predict the output power, improving MPPT speed and accuracy. It has been demonstrated to respond faster and oscillate less around MPP.

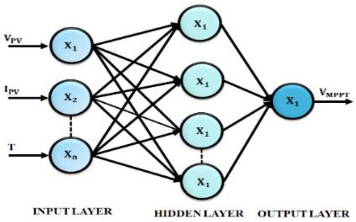

Fig. 6. ANN MPPT architecture diagram

The model of a typical neuron is provided by the relationship in Eq. (8), where Z stands for the increase of activation function:

$$Z = \sum_{m=1}^{M} w_m x_m + \alpha \quad (8)$$

The weights of the associated connections are shown by $w1, w2, \ldots, wm$, while the M incoming impulses are represented by $x1, x2, \ldots, xm$. The following represents the activation function of the sigmoid, threshold, and linear transfer operations:

$$y = \frac{1}{1+e^{-z}} \quad (9)$$

It has been demonstrated that ANN-based MPPT can track MPP with the least amount of transition time and minimal ripple in actual operating conditions. ANN then processes the measured voltages and currents to determine the optimal voltage for achieving the MPP efficiently. For the parameter tuning for controller, an optimized technique used and discussed below.

b) Tabu Search Optimization (Tso)

To solve the problem of optimizing parameters for controller, the meta-heuristic TSO approach is used. Optimization begins by choosing an initial value, after which a larger search is executed. The Tabu List (TL) remembers previous solutions in order to drive the search procedure, avoiding regions that have previously been searched as well as circumventing local optimization. Irrelevant data are restrained, and perfect solutions are delineated by aspiration criteria (AC). This allows the algorithm to concentrate on the best solutions by applying the outcome space and local heuristic analysis.

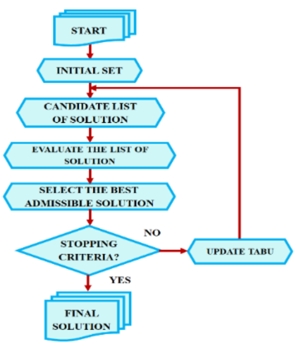

Fig. 7. Flowchart of TSO

TSO is illustrates Fig. 7 specially designed for finite-solution set optimization problems as it offers adjustable memory usage in Tabu moves to ensure the repeated solutions are not encountered. Three strategies of TSO exist: forbidding strategy, freeing strategy, and short-term strategy (STS). The STS keeps a connection between the current solution and the final set of solutions, whereas the final set of solutions (FSS) manages the remaining solutions after optimization, and the solution set (FS) decides which data enters the operational zone. The following is the updated collection of T(S) solutions:

$$S^I \epsilon N) = \{N(S) - T(S)\} + A(S) \quad (10)$$

TSO unites goal programming and assesses solutions by weighing the most vital parameters, e.g., control error, response time, and stability, on a hierarchical level.

D. IoT Monitoring

A monitoring system built on the IoT created to track and evaluate the power produced by the PV-based micro grid. Voltage and current sensors are installed at output of the PV system and interleaved SEPIC converter to determine voltage, current, and power in real-time. This monitored data is wirelessly uploaded to the cloud using Wi-Fi communication and analysed/visualized through the platform. The recorded data is uploaded in real-time and visualized graphically on a smartphone or PC to allow users to monitor the performance of the system and energy trends remotely. The Application Programming Interface (API) of the open-source IoT platform is used to on-board, analyse, and display sensor data. The incorporation of IoT as a real-time monitoring system enhances the visibility and transparency of the system, and allows for fault detection of the micro grid energy system, as well as further enhances the capability to promote effective energy management and decision-making. Finally, an IoT-based SG system is specified to monitor the hybrid micro grid effectively using any application or devise which is discussed below.

IV. Result And Discussion

This paper describes an integrating interleaved SEPIC converters with optimized Tabu search ANN-MPPT controller to monitor micro-grid stability using IoT. The developed work implemented using MATLAB simulation, and the results are shown in below. Table I shows the parameter specification for the proposed system.

TABLE I. Parameter Specification

Parameters	Specifications
PV System	
Open Circuit Voltage	37.25 V
Short Circuit Voltage	8.95 A
Series connected solar PV cell	12
Parallel connected solar PV cell	4
Cell linked in series	36
Rated Power	10kW
Interleaved Sepic Converter	
Switching Frequency	10KHz
L_1, L_2, L_3, L_4	4.7mH
C_1, C_2	22μF
C_0	2200 μF

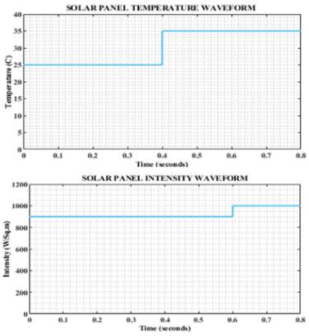

Fig 8. Solar panel temperature & intensity waveform

Fig. 8 shows characteristic waveforms of a solar panel temperature and intensity. Initially, the temperature increases & stabilizes at 35°C after 0.4 s. Also, the solar intensity is stable, then it increases after 0.4 s and stabilizes at 1000 W/m².

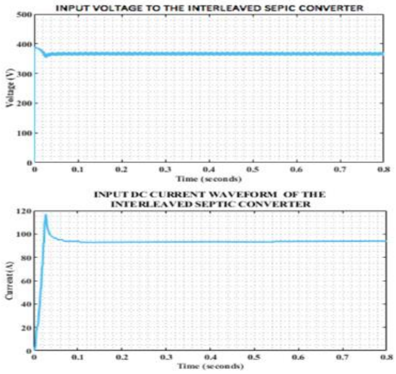

Fig. 9. Converter input voltage & current waveform

Fig. 9 shows converters input voltage & current waveforms. The input voltage is kept steady at 350V while the input current is constant at 90A, indicating a controlled power input condition where the converter likely operates in a continuous conduction mode to maintain stable energy transfer.

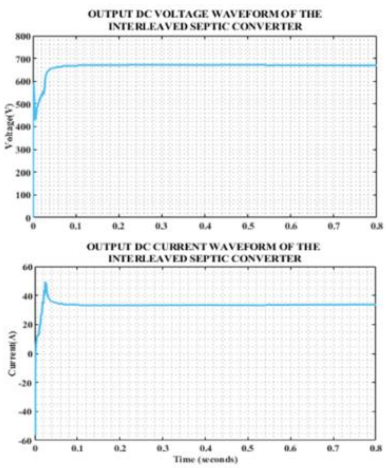

Fig. 10. Converter output voltage & current waveform

Fig. 10 shows converters output voltage & current waveforms. The output voltage steadily increases and stabilizes at 690V, while the output current is fluctuating until reaching 38A. This shows that the converter effectively regulates both current and voltage, for reliable and steady power conversions.

Fig. 11 shows the conditions of the three-phase grid, including the waveforms of grid voltage and current. The grid voltage is stable at 320V, creating a steady voltage supply and a constant grid current of 30A, which reflects steady currents continuing through the circuits. Also, both grid an important role in maintaining a steady and balanced power supply from the grid.

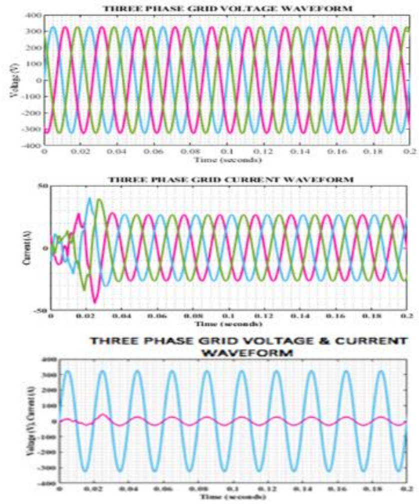

Fig. 11. Three phase grid voltage & current waveform

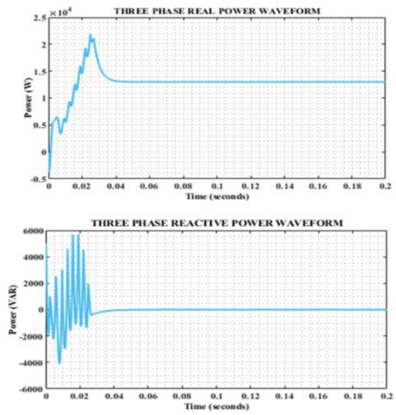

Fig. 12. Real & reactive waveform

Fig. 12 shows waveforms of reactive and real power in alternating current systems which shows some fluctuation while ensuring a steady power supply, thus demonstrating stability and efficiency in the energy transfer.

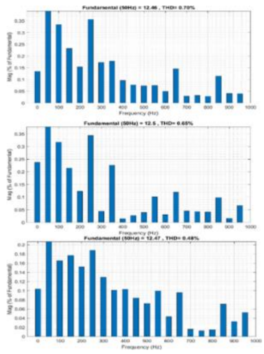

Fig. 13. THD value for three phases

Total harmonic distortion (THD) values for three phases are depicted in the Fig. 13 as follows: B phase has a THD of 0.70%, R phase has a THD of 0.65%, and Y phase has a THD of 0.48%.

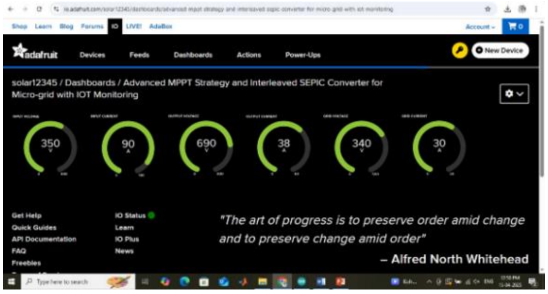

Fig. 14. IoT based real time monitoring

Fig. 14 Dashboard based on IoT for monitoring the hybrid microgrid system with real-time visualization platform for monitoring the important variables. The dashboard is capturing important data around PV, load, and grid of voltage and current using NodeMCU, where the data is wirelessly collected and enables continuous performance monitoring .

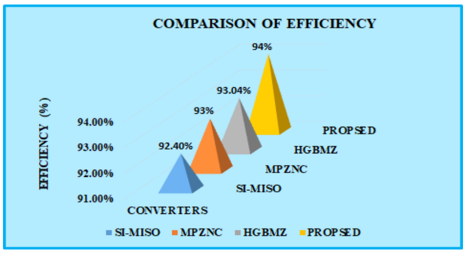

Fig. 15. Comparison of converter efficiency

Fig. 15 depicts an efficiency comparison of numerous converters, with the proposed converter outperforming the efficiency of 94 % comparatively higher than existing methods such as SI-MISO [6] 92.4%, MPZNC [7] 93% and HGBMZ [15] 93.4%.

TABLE II. COMPARISON OF TRACKING EFFICIENCY

MPPT Controller	Tracking Efficiency
SSOA-FUZZY [15]	95.11%
PSO-P&O [3]	96%
P&O-FL [5]	97%
PROPOSED	98.5%

Table II compares tracking efficiency of numerous MPPT controllers, with the proposed controller outperforming the tracking efficiency of 98.5 % comparatively higher than listed existing methods.

V. CONCLUSION

In this study, an advanced power monitoring approach for grid-connected micro-grids, integrating an advanced Tabu Search-driven ANN-based MPPT strategy with an interleaved SEPIC converter and IoT monitoring. The interleaved SEPIC converter effectively enhancing the DC voltage and reducing input current ripple, ensuring stable and efficient power conversion. Also, Tabu Search-driven ANN-based MPPT technique, which optimizes power tracking in real-time with high precision. Furthermore, the IoT module facilitates continuous monitoring of the PV system's performance, providing real-time data logging, and operational flexibility. Simulation results demonstrate a substantial improvement in converter efficiency of 94% and MPPT tracking accuracy of 98.5%, validating the effectiveness of the proposed system.

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