Journal of Mechanical, Elecrical & Industrial Technology **Vol. 1 No. 2**
e-ISSN 3047-7778 **September 2024**

Renewable Energy System Optimization: MPPT Inverter Integration, Energy Storage Systems, and Its Impact on Sustainability and Efficiency Use of Energy

Ary Pratama Paluga[1], Anggara Trisna Nugraha[1], Rama Arya Sobhita[1], Mukhammad Jamaludin[2]

[1]Department of Ship Electrical Engineering, Surabaya State Shipping Polytechnic, Indonesia
(arrypaluga@gmail.com)
[1]Department of Ship Electrical Engineering, Surabaya State Shipping Polytechnic, Indonesia
(anggaranugraha@ppns.ac.id)
[1]Department of Ship Electrical Engineering, Surabaya State Shipping Polytechnic, Indonesia
(ramasobhita@student.ppns.ac.id)
[2]Bio-Industrial Mechatronics Engineering, National Chung Hsing University, Taiwan
(g112040520@mail.nchu.edu.tw)

Abstract

This study aims to enhance the utilization of solar panel energy by integrating Maximum Power Point Tracking (MPPT) inverters and energy storage systems. Solar panels are vital for harnessing renewable energy; however, their energy output is often unstable due to variations in sunlight. MPPT inverters optimize the power output by adjusting the operating point of the solar panels, ensuring maximum energy harvest. The research will be conducted at the Renewable Energy Laboratory of the Institute of Technology Sampling over one academic year. Utilizing an experimental design with a single control group, the study will measure energy efficiency and supply stability before and after the integration of MPPT inverters and energy storage systems. Primary data will be collected through direct measurements of solar panels equipped with these technologies, focusing on energy production, supply fluctuations, and system stability. Data collection methods will include state-of-the-art energy measurement equipment and interviews with renewable energy experts and technicians. To ensure the validity of the findings, variables such as weather conditions and energy consumption will be controlled, and external validity will be enhanced by comparing results with existing literature. Statistical analyses using advanced software will be employed to identify significant differences pre- and post-integration. Furthermore, qualitative observations will assess system stability and the impact of optimization on the sustainability and efficiency of renewable energy utilization.

Keyword: Solar panel, MPPT inverter, Energy storage system, Renewable energy.

1. Introduction

Renewable energy, particularly solar power, is widely recognized for its potential to serve as a clean and sustainable energy source, offering significant environmental benefits by reducing greenhouse gas emissions and dependence on fossil fuels (Jusoh et al., 2015; Brambilla et al., 1999; Subrata et al., 2019). Solar panels, as a key technology in harnessing this energy, are increasingly being integrated into energy systems worldwide. However, despite their promise, solar panels face inherent challenges, particularly in maintaining a stable energy supply. Fluctuations in energy production due to variations in sunlight—caused by factors such as time of day, weather conditions, and seasonal changes—can disrupt energy supply stability, posing a significant challenge for their widespread adoption, particularly in regions with inconsistent sunlight (Jusoh et al., 2017; Khamis et al., 2018; Loukriz et al., 2016). Without addressing these fluctuations, solar energy cannot be fully reliable for continuous power supply.

To overcome this issue, optimizing solar power utilization through Maximum Power Point Tracking (MPPT) inverters and the integration of energy storage systems has become essential. MPPT inverters are designed to dynamically adjust the operating point of solar panels in response to varying environmental conditions, ensuring that they continuously operate at their maximum efficiency and thereby enhancing overall power conversion efficiency (Mäki & Valkealahti, 2014; Pandey et al., 2008; Putra et al., 2024a). While MPPT technology significantly improves the performance of solar panels, it does not entirely resolve the issue of intermittent energy generation. This is where energy storage systems, such as lithium-ion batteries, come into play. These systems store excess energy produced during peak sunlight hours for later use during periods of low sunlight or nighttime, thereby ensuring a more stable and reliable energy supply.

Despite the advantages, both MPPT inverters and energy storage systems have certain limitations. MPPT inverters, though effective, can be complex and costly, with efficiency levels dependent on environmental factors. Meanwhile, energy storage systems face issues such as high upfront costs, limited lifespan, and energy losses during charging and discharging. These limitations highlight the need for continued innovation and improvement in solar energy technologies to ensure that solar power can be a viable and consistent energy source on a large scale.

In this research, we propose the integration of MPPT inverter technology with advanced energy storage systems to address these challenges and create a more efficient, responsive, and reliable solar energy system. By combining the benefits of optimized power tracking and energy storage, we aim to improve not only the efficiency of solar energy conversion but also the stability of energy supply, particularly in areas with fluctuating solar resources. The objective of this study is to assess the impact of this integration on energy production, supply consistency, and overall system efficiency. Through this research, we hope to contribute to the development of more reliable and sustainable renewable energy solutions, addressing key barriers to the broader implementation of solar technology (Nugraha et al., 2023a; Nugraha et al., 2023b; Nugraha et al., 2023c)..

2. Material and methods

Various methods have been proposed in the literature for performing MPPT under uniform environmental conditions (Nugraha et al., 2023d; Putra et al., 2024b; Utomo et al., 2023). The methods considered in this section include the beta method, parabolic curve prediction, ripple correlation control (RCC), extremum seeking control (ESC), bisection search theorem, sliding mode control, and MPPT through optimization of output parameters.

2.1. Optimization of Output Parameters

In some implementations of Maximum Power Point Tracking (MPPT), the focus is on optimizing the output of the DC/DC converter connected to the photovoltaic (PV) module rather than directly identifying the Maximum Power Point (MPP) on the panel itself. This approach typically utilizes a single sensor to optimize output parameters, such as load current or voltage (Nugraha & Arifuddin, 2020; Sugianto & Nugraha, 2022). However, due to losses in the DC/DC converter, the optimized output may not perfectly align with the MPP of the PV panel. The underlying assumption in these single-sensor methods is that the converter operates without losses; thus, maximizing load power is viewed as achieving MPPT. Various load types—voltage sources, current sources, resistive loads, or combinations thereof—have specific parameters that can be optimized (Ivannuri & Nugraha, 2022). For instance, current source loads necessitate maximizing load voltage to achieve maximum power, although this often requires expensive current sensors. By leveraging single-sensor methods and optimizing multiple output parameters based on load type, researchers can reduce overall PV system costs. These methods include measuring reference inductor current to connect it to the PV output current for MPPT, applying perturb and observe (P&O) techniques with a single current sensor, and utilizing gradient ascent algorithms with a single voltage sensor. Additionally, multichannel systems—consisting of multiple independently controlled PV modules—can also be implemented as single-sensor approaches. Adaptive neuro-fuzzy inference systems (ANFIS) can further enhance MPPT response time when using single-voltage sensors.

This study aims to collect data through direct measurements of solar panel performance equipped with MPPT inverters, utilizing single-sensor setups to monitor crucial parameters like load current and voltage in conjunction with energy storage systems. The necessary equipment includes single current or voltage sensors, DC/DC converters, multichannel control systems, and adaptive models such as ANFIS. Observations will focus on optimizing performance metrics by measuring reference inductor current and analyzing output parameters to assess efficiency in real-time.

3. Results and discussion

This chapter has explored the main MPPT methods designed to work with both uniform and non-uniform environmental conditions. These methods determine how effective they are in achieving accurate and fast MPPT with minimal cost and complexity. The discussion presented in this chapter highlights that none of the existing MPPT methods can meet all the specified criteria for effective MPPT methods. Instead, some methods perform very well for certain criteria and not so well for others. This suggests that the selection of MPPT methods is quite dependent on application constraints. Future work in the field of MPPT for PV systems may include combining the benefits of individual methods to develop more combined methods, developing effective reset initialization conditions to enable broader use of time-invariant optimization methods, and further development through understanding of non-uniform environmental conditions.

Table 1. Energy Storage Technology

Technology	**density**		**Efficiency (%)**	**Year life cycle**	**Self-discharge**
	Energy (Wh/Kg)	Power (Wh/Kg)			
Pumped Hidro	0.3	–	70 – 85	>20	Ignore
CAES	10–30	–	70–89	>20	–
Supercapacitor	<50	4000	95	>50.000	High
Pb-Acid	20–35	25	70–90	200–2000	Low
Ni-Cd	40–60	140–180	70–90	500–2000	Low
NaS	120	120	70	2000	–

Table 1 compares several energy storage technologies based on key performance, such as energy density, power density, efficiency, cycle life and self-discharge. Pumped hydro has a low energy density (0.3 Wh/kg) with moderate efficiency (70-85%) and a cycle life of more than 20 years, as well as negligible self-discharge, suitable for long-term large-scale energy storage. CAES is slightly better with an energy density of 10-30 Wh/kg and an efficiency of 70-89%, also durable with a lifespan of more than 20 years. Supercapacitors offer high power density (4000 Wh/kg), 95% efficiency, and exceptional cycle life (>50,000 cycles), but with high self-discharge, making them suitable for applications that require fast power delivery. Lead-Acid batteries, with energy density of 20-35 Wh/kg and power of 25 Wh/kg, efficiency of 70-90%, and cycle life of 200-2000 cycles, have low self-discharge, making them effective for short-term storage at low cost. Ni-Cd batteries offer energy density of 40-60 Wh/kg and power of 140-180 Wh/kg with efficiency and cycle life similar to Lead-Acid, but also with low self-discharge, making them reliable enough for medium energy storage. Sodium-Sulfur (NaS) batteries excel in high energy density (120 Wh/kg) and reasonably good cycle life (2000 cycles), although their efficiency is lower (70%).

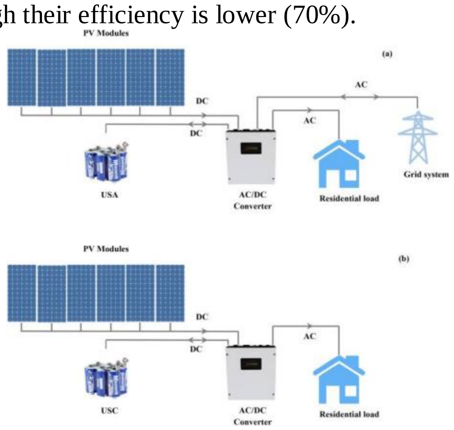

Figure 1. (a) On grid (b)Off grid

The main difference between on-grid and off-grid systems lies in how connected to the electrical grid.

a. On-grid (Grid-tied) System: In an on-grid system, the solar PV system is connected to the utility grid. When the solar panels generate electricity, it is first used to power the electrical loads in the building. If the electricity demand exceeds what the solar panels can provide, additional power is drawn from the utility grid. Conversely, if the solar panels generate more electricity than is needed, the excess power is fed back into the grid, often through a process called net metering. On-grid systems do not typically have battery storage because they rely on the grid as a backup power source.

b. Off-grid System: In contrast, an off-grid system operates independently of the utility grid. It consists of solar panels, a charge controller, batteries for energy storage, and sometimes a backup generator. The solar panels generate electricity, which is stored in the batteries for use when the sun is not shining, such as during nighttime or cloudy days. The energy stored in the batteries is then used to power the electrical loads in the building. Off-grid systems are commonly used in remote areas where access to the utility grid is not available or is too expensive to install. They offer energy independence but require careful sizing and management of the battery bank to ensure reliable power supply.

4. Conclusion

this article highlights the advancements in Maximum Power Point Tracking (MPPT) methods for photovoltaic (PV) systems, emphasizing their capability to overcome the limitations of traditional approaches. While conventional methods offer ease of development, they often face challenges such as oscillations around the maximum power point and slower tracking speeds. The advanced MPPT techniques discussed employ intelligent algorithms and optimization strategies, significantly enhancing tracking performance and overall power output efficiency. However, effective implementation of these methods requires a solid understanding of the underlying theories, robust programming skills, and reliable processors to manage increased complexity.

The comparison of various energy storage technologies reveals important distinctions in their performance characteristics. Pumped hydro is ideal for long-term large-scale storage, while compressed air energy storage shows slight improvements in metrics. Supercapacitors are distinguished by their high power density and efficiency, though they have high self-discharge rates. Lead-acid and Ni-Cd batteries serve as cost-effective solutions for short-term and medium energy storage, respectively. Sodium-sulfur batteries provide high energy density despite lower efficiency. Ultimately, the selection of energy storage technology is determined by specific application requirements

Credit authorship contribution statement

Ary Pratama Paluga: Conceptualization, Writing – review & editing. **Rama Arya Sobhita**: Supervision, Writing – review & editing. **Anggara Trisna Nugraha**: Conceptualization, Supervision, Writing – review & editing. **Mukhammad Jamaludin**: Conceptualization, Supervision, Writing – review & editing.

References

A. Jusoh, O. J. E. I. Mohammed, and T. Sutikno, “Variable step size Perturb and observe MPPT for PV solar applications,” Telkomnika, vol. 13, no. 1, p. 1, 2015.

A. Brambilla, M. Gambarara, A. Garutti, and F. Ronchi, “New approach to photovoltaic arrays maximum power point tracking,” in 30th Annual IEEE Power Electronics Specialists Conference. Record.(Cat. No. 99CH36321), 1999, vol. 2, pp. 632–637.

A. C. Subrata, T. Sutikno, S. Padmanaban, and H. S. Purnama, “Maximum power point tracking in pv arrays with high gain Dc-Dc boost converter,” in International Conference on Electrical Engineering, Computer Science and Informatics (EECSI), 2019.

A. Jusoh, R. Alik, T.K. Guan, T. Sutikno, “MPPT for PV system based on variable step size P & O algorithm,” Telkomnika (Telecommunication Computing Electronics and Control), 15 (1), pp. 79-92, 2017.

A. Khamis, M.R.A. Ghani, G.C. Kim, M.S.M. Aras, M.A.B. Zabide, T. Sutikno,”Control strategy for distributed integration of photovoltaic and battery energy storage system in micro-grids,” Telkomnika (Telecommunication Computing Electronics and Control), 16 (5), pp. 2415-2427, 2018.

A. Loukriz, M. Haddadi, and S. Messalti, “Simulation and experimental design of anew advanced variable step size Incremental Conductance MPPT algorithm for PV systems,” ISA Trans., vol. 62, pp. 30–38, 2016.

A. Mäki and S. Valkealahti, “Differentiation of multiple maximum power points ofpartially shaded photovoltaic power generators,” Renew. energy, vol. 71, pp. 89–99, 2014.

A. Pandey, N. Dasgupta, and A. K. Mukerjee, “High-performance algorithms for drift avoidance and fast tracking in solar MPPT system,” IEEE Trans. Energy Convers., vol. 23, no. 2, pp. 681–689, 2008.

A. S. Kislovski and R. Redl, “Maximum-power-tracking using positive feedback,” in Proceedings of 1994

Anggara Trisna Nugraha, H. Agus, Rini Indartini, N. Ade, and D. Ilham, "RANCANG BANGUN ALAT PENYEIMBANG ARUS BEBAN PADA KAPAL BERBASIS MICROCONTROLLER DENGAN METODE DECISION TREE," Jurnal 7 Samudra, vol. 8, no. 2, Nov. 2023, doi: https://doi.org/10.54992/7samudra.v8i2.131.

Anggara Trisna Nugraha, N. Edy, Purwidi Asri, Briyen Rangga Prayoga W, and D. Ilham, "PROTOTIPE SISTEM PENGENDALIAN DAN PEMANTAUAN CARGO HOLD BILGE KAPAL DENGAN METODE DECISION TREE BERBASIS MIKROKONTROLER," Jurnal 7 Samudra, vol. 8, no. 2, Nov. 2023, doi: https://doi.org/10.54992/7samudra.v8i2.130.

Anggara Trisna Nugraha,Purwidi Asri, Perwi Darmajanti, D. Ilham, and N. Muhammad, "RANCANG BANGUN MONITORING KUALITAS AIR TAMBAK UDANG VANAME DENGAN KONTROL PADDLE WHEEL BERBASIS MIKROKONTROLLER," Jurnal 7 Samudra, vol. 8, no. 2, Nov. 2023, doi: https://doi.org/10.54992/7samudra.v8i2.132.

A. Faza, N. Muhammad, Purwidi Asri, Anggara Trisna Nugraha, and Perwi Darmajanti, "PROTOTYPE SISTEM OILY WATER SEPARATOR OTOMATIS PADA KAPAL MENGGUNAKAN METODE DECISION TREE BERBASIS MIKROKONTROLER," Jurnal 7 Samudra, vol. 8, no. 2, pp. 1–6, Nov. 2023, doi: https://doi.org/10.54992/7samudra.v9i1.128.

Agung Prasetyo Utomo et al., "Pelatihan Pembuatan Miniatur Kapal Berdasar Standar Desain Berbahan Fiberglass Reinforced Plastic (FRP) untuk Kelompok Pengrajin di Wilayah Pantai Situbondo," vol. 7, no. 2, pp. 391–391, Dec. 2023, doi: https://doi.org/10.36841/integritas.v7i2.3808.

Anggara Trisna Nugraha, Aminatus Sa'diyah, Endang Pudji Purwanti, Syafiuddin, Muhammad Bilhaq Ashlah, and Fortunaviaza Habib Ainudin, "Application of the Coulomb Counting Method for Maintenance of VRLA Type Batteries in PLTS Systems," E3S web of conferences, vol. 473, pp. 02003–02003, Jan. 2024, doi: https://doi.org/10.1051/e3sconf/202447302003.

A. Putra, Anggara Trisna Nugraha, Yuning Widiarti, Wafiq Safaroz, and Rama Arya Sobhita, "Design of Unipolar Pure Sine Wave Inverter with Spwm Method Based On Esp32 Microcontroller As a Support of The Ebt System On Ship," E3S web of conferences, vol. 473, pp. 01008–01008, Jan. 2024, doi: https://doi.org/10.1051/e3sconf/202447301008.

Anggara Trisna Nugraha et al., "Design Build an Off Grid Based Solar Power Plant System Using The Bidirectional Buck And Boost Topology In The Conservation Of Sea Pearl Turtles," vol. 473, pp. 01006–01006, Jan. 2024, doi: https://doi.org/10.1051/e3sconf/202447301006.

M. Santoso, A. Putra, Anggara Trisna Nugraha, Faiqotin Najudah, and Rahmania Firdiansyah, "Enhancing Measurement Quality of Voltage Divider Circuit and ACS712 DC Current Sensor in PPNS Baruna 01 Crewboat Solar Power Plant," E3S web of conferences, vol. 473, pp. 01009–01009, Jan. 2024, doi: https://doi.org/10.1051/e3sconf/202447301009.

A. T. Nugraha and R. Arifuddin, "O2 Gas Generating Prototype In Public Transportation," JEEMECS (Journal of Electrical Engineering, Mechatronic and Computer Science), vol. 3, no. 2, Aug. 2020, doi: https://doi.org/10.26905/jeemecs.v3i2.4584.

Agung Prasetyo Utomo, M. Apriani, Ruddianto Ruddianto, Luqman Cahyono, Anggara Trisna Nugraha, and Mochammad Ilham Nugroho, "PELATIHAN PEMBUATAN TERUMBU BUATAN BERBASIS ECO-FRIENDLY SEBAGAI SARANA REHABILITASI TERUMBU KARANG DI DAERAH PANTAI WISATA PASIR PUTIH, SITUBONDO," Integritas, vol. 5, no. 2, pp. 298–298, Nov. 2021, doi: https://doi.org/10.36841/integritas.v5i2.1340.

Moh. G. P. A. Sugianto and A. T. Nugraha, "Implementasi sensor cahaya sebagai level bahan bakar pada tangki harian kapal," Journal of Computer Electronic and Telecommunication, vol. 2, no. 1, Jul. 2022, doi: https://doi.org/10.52435/complete.v2i1.191.

Chusnia Febrianti and Anggara Trisna Nugraha, "Implementasi Sensor Flowmeter pada Auxiliary Engine Kapal Berbasis Outseal PLC," Journal of Computer, Electronic, and Telecommunication, vol. 3, no. 2, Dec. 2022, doi: https://doi.org/10.52435/complete.v3i2.188.

Fahmi Ivannuri and Anggara Trisna Nugraha, “Implementation Of Fuzzy Logic On Turbine Ventilators As Renewable Energy,” Journal of Electronics, Electromedical Engineering, and Medical Informatics, vol. 4, no. 3, pp. 178–182, Jul. 2022, doi: https://doi.org/10.35882/jeeemi.v4i3.236.