Journal of Electronics and Electrical Engineering
http://www.sciencepg.com/journal/jeee

UNIVERSAL WISER PUBLISHER

Research Article

Impact of Inductance and Capacitance on MPPT Charge Controller Performance across Various Locations

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Received: 2 August 2025; **Revised:** 31 August 2025; **Accepted:** 16 September 2025

Abstract: The transition toward sustainable energy systems has intensified the demand for more efficient solar power technologies, with Maximum Power Point Tracking (MPPT) charge controllers serving as a critical component for improving photovoltaic performance. However, the role of passive elements such as inductance and capacitance in shaping MPPT efficiency under diverse environmental conditions remains underexplored. In this study, MATLAB Simulink models were developed to investigate the impact of inductive and capacitive configurations on MPPT controller performance across two geographically distinct regions: St. John's, Newfoundland, and Kaptai, Chittagong. Multiple design scenarios were simulated to evaluate system adaptability and output stability under varying solar irradiance and temperature profiles. The results demonstrate that optimized component sizing significantly enhances energy extraction, while inappropriate tuning leads to sharp declines in system efficiency. To assess long-term dependability, a reliability analysis was also conducted, supported by probability density and cumulative distribution function evaluations. The findings indicate that the proposed configurations exhibit high operational stability and strong reliability metrics, ensuring consistent performance over extended lifespans. This study highlights the necessity of location-specific tuning of inductance and capacitance in MPPT design. By providing a quantified understanding of their influence on controller dynamics, the study offers practical insights for developing robust, efficient, and reliable solar energy systems tailored to diverse climatic contexts.

***Keywords*:** environmental adaptability, efficiency optimization, inductance and capacitance effects, maximum power point tracking (MPPT), reliability analysis

1. Introduction

In the rapidly evolving field of renewable energy, solar power generation stands out as a pivotal technology in the global quest for sustainable energy solutions. With the International Energy Agency reporting that solar energy capacity has grown by over 20% annually in recent years, optimizing the efficiency and output of solar panels has become increasingly critical, especially as countries strive to meet ambitious renewable energy targets [1].

As nations pivot from fossil fuels, efficient energy conversion technologies are paramount. For instance, according to a recent U.S. Department of Energy report, solar power is projected to contribute significantly to the nation's energy mix, potentially supplying 40% of U.S. electricity by 2035. This growing reliance on solar energy underscores the importance of innovations in solar technology, particularly in harnessing and optimizing solar panels' power output [1, 2]. To ensure sustainable power generation, it is important to minimize environmental impacts while meeting energy demands. Bhutia et

DOI: https://doi.org/10.37256/jeee.4220258111

al. [3] demonstrated, through a comparative analysis of fossil fuel and renewable energy systems in Alberta, that fossil fuel–based generation produces substantially higher greenhouse gas emissions, reinforcing the urgency of transitioning toward renewables. Similarly, Mahtab et al. [4] analyzed hybrid energy systems for the remote Lakshadweep Islands and showed that integrating solar and wind with conventional diesel generators can significantly reduce CO_2 emissions and improve energy security. Together, these studies highlight the necessity and feasibility of adopting renewable and hybrid systems for achieving sustainable energy development.

Maximum power point tracking (MPPT) plays a crucial role in optimizing the efficiency of solar energy systems by ensuring that the photovoltaic (PV) panels operate at their maximum power point, which is the point where the panel generates the highest possible power output under specific environmental conditions. The role of MPPT in solar energy systems is crucial because the power output of solar panels varies depending on factors such as sunlight intensity, temperature, and panel age. MPPT algorithms continuously track the maximum power point to adjust the operating voltage and current of the solar panels, thereby maximizing energy harvest.

MPPT charge controllers face several challenges in providing optimal output due to the dynamic nature of solar energy production and environmental conditions. One of the primary challenges is the fluctuation in solar irradiance caused by changing weather patterns, cloud cover, and time of day, which can cause significant variations in the power output of PV systems. As Singh et al. [5] point out; the performance of MPPT controllers can be hindered by the continuous fluctuations in irradiance and temperature, making it challenging to maintain accurate tracking of the Maximum Power Point (MPP). Additionally, traditional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) can experience oscillations near the MPP, reducing their efficiency, particularly under rapidly changing conditions, according to Manna et al. [6]. Furthermore, advanced algorithms such as Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC) improve efficiency but require precise training datasets and computational resources, which may not be feasible for all applications, as reflected in the research by Li et al. [7]. The complexity of integrating various algorithms to enhance controller reliability also presents a challenge in terms of cost and implementation in large-scale solar power systems. Despite these challenges, ongoing research continues to focus on improving the adaptability, efficiency, and robustness of MPPT controllers, with methods like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) showing promise in overcoming these limitations, which is found in the research by Mirza et al. [8] and Renaudineau et al. [9].

2. Literature review

Recent research has explored various MPPT algorithms to optimize the performance of solar charge controllers in PV systems. Ghazi et al. [10] introduced the Circle Search Algorithm-based Super Twisting Sliding Mode Control (CSA-STSMC) method for enhancing the efficiency of grid-connected PV systems. By integrating MPPT with sliding mode control, the CSA-STSMC method achieved superior performance in tracking the maximum power point, outperforming conventional techniques in both efficiency and speed.

Mazumder et al. [11] proposed a sliding mode MPPT controller for PV systems, focusing on electric vehicle charging stations under fluctuating atmospheric conditions. Utilizing a genetic algorithm to optimize the sliding mode controller improves tracking performance, minimizes oscillation, and ensures a stable power supply to electric vehicles under rapidly changing environmental conditions. Acharya and Aithal [12] implemented the P&O algorithm, demonstrating its ability to effectively track the maximum power point under stable or slowly changing irradiance and temperature conditions. The study highlighted the operational point where the battery achieves the highest power output, further validating the P&O method's reliability.

Majwa et al. [13] analyzed the integration of MPPT and Pulse Width Modulation (PWM) in solar charge controllers for solar-powered systems with batteries. Their study emphasized the importance of managing power flow from the solar panel to the batteries, with modern charge controllers increasingly incorporating both MPPT and PWM technologies. Güven [14] further examined the benefits of integrating MPPT controllers into PV systems, highlighting improved energy harvesting efficiency, particularly in challenging weather conditions. The study demonstrated that dynamically adjusting the operating point of the solar array enhances system reliability and cost-effectiveness.

Mazumder et al. [15] also explored the integration of MPPT controllers with Artificial Intelligence (AI), comprehensively evaluating solar PV research and predicting future trends. This study synthesized various MPPT algorithms used in PV systems under different conditions and compared AI-based and traditional control strategies. Samuel et al. [16] addressed the efficiency challenges of MPPT charge controllers by integrating a Proportional and Integral (PI) controller with the P&O method. Their simulations showed that adding the PI controller significantly improved efficiency, achieving 99.96% efficiency at the maximum power point.

Chao and Zhang [17] introduced an enhanced Firefly Algorithm (FA) for MPPT implementation in Photovoltaic Module Arrays (PVMAs) with partially shaded modules. The study developed a high-voltage step-up converter and incorporated a coupled inductor design to enhance voltage gain and reduce output voltage ripple. The improved FA-based tracker mitigated shading effects on partial modules, optimizing the overall output power of the PVMA. Jeannot et al. [18] applied fuzzy logic to MPPT control in a DC/DC boost converter, modeling a PV panel to account for various physical factors, such as temperature, irradiation, and resistance. The study demonstrated the system's ability to stabilize at maximum power after a brightness fluctuation within 1.4 seconds.

Manna et al. [19] introduced an adaptive control design for MPPT in PV systems, using Model Reference Adaptive Control (MRAC) techniques to optimize power delivery under changing solar radiation and temperature conditions. The MRAC-MPPT scheme achieved an average tracking efficiency of 99.77%, significantly outperforming traditional methods like INC and P&O regarding speed and accuracy. Serrano et al. [20] compared the performance of PWM and MPPT charge controllers in off-grid PV systems, concluding that the MPPT controller demonstrated superior efficiency even in challenging environmental conditions.

Lastly, Shahbazi et al. [21] presented a novel active thermal-controlled MPPT algorithm designed to enhance the reliability of power converters by minimizing junction temperature increase. The algorithm employed neural networks and real mission profile data to balance energy generation with device longevity, thereby substantially reducing study cycle durations and lifetime consumption. The results demonstrated a 4.4% reduction in lifetime consumption with only a 1.4% decline in energy generation. This body of study underscores the importance of optimizing MPPT algorithms to improve the efficiency, reliability, and longevity of PV systems. These studies contribute to the growing understanding of how advanced algorithms and control strategies can enhance the performance of solar charge controllers across various environmental conditions and applications.

Table 1 presents a range of studies focused on improving the performance of MPPT in solar energy systems. It highlights different methodologies employed for MPPT optimization, including boost converters, PID controllers, INC, and P&O algorithms. Key findings indicate that specific methods, such as the boost converter, offer high efficiency and low current stress, making them ideal for PV applications. Advanced techniques such as ANN, GA, and FLC show improved tracking efficiency and stability, especially under fluctuating environmental conditions. Moreover, several studies have demonstrated the advantages of hybrid approaches combining soft computing and AI, such as NN and PSO, which outperform traditional methods in tracking accuracy and speed. Some controllers, like STSMC, provide the highest efficiency, while others, like the Adaptive Neuro-Fuzzy Inference System (ANFIS) and modified MRAC excel in faster response times. Overall, these studies emphasize the potential of advanced algorithms and hybrid methods in optimizing MPPT performance, ensuring higher efficiency, and providing robust solutions for solar power systems operating in diverse environmental conditions.

Table 1. Review of related studies on MPPT

Theme/Approach	Reference	Methodology	Key Findings
Conventional MPPT Methods	[5] Singh et al. (2022) [22] Podder et al. (2019) [24] Jagadeshwar et al. (2022)	• Focus on MPPT topologies (buck-boost, boost, buck converters) • Low switching losses, ideal for PV applications • Traditional INC method to track MPP	• Boost converter is ideal for PV applications due to low switching losses and low current stress • Efficiency and low current stress make the boost converter ideal for solar applications • Simple but inefficient with varying weather
Classical Control Approaches	[23] Kler et al. (2018)	• Proportional–Integral–Derivative (PID) control	• PID showed low performance and tracking inefficiency for MPPT
Soft Computing & AI Approaches	[7] Li et al. (2022) [8] Mirza et al. (2020) [9] Renaudineau et al. (2015)	• Use of AI and soft computing for MPPT optimization • Genetic algorithms (GA) • Particle Swarm Optimization (PSO)	• AI-based MPPT improves accuracy and tracking efficiency • GA achieves higher efficiency but computationally expensive • PSO shows better efficiency than traditional methods
Fuzzy Logic–Based Methods	[25] Parvaneh et al. (2020) [26] Fathi & Parian (2021)	• Offline short-circuit current + fuzzy logic • Fuzzy Logic Controller (FLC) for MPPT	• Hybrid fuzzy logic methods outperform traditional methods under variable conditions • FLC superior to ANN–PSO in accuracy, speed, and stability
Advanced Hybrid & Robust Control	[27] Kayisli (2023) [28] Dadkhah Tehrani & Shabaninia (2018) [29] Bani Salim et al. (2019) [30] Tariba et al. (2016) [31] Haji & Naci (2020)	• Super-Twisting Sliding Mode Control (STSMC) + fuzzy logic • Global Perturbation-Based Extremum Seeking Control (GPESC) + MRAC • Robust Direct Adaptive Control (RDAC) using boost converter • Modified MRAC with INC • Adaptive Neuro-Fuzzy Inference System (ANFIS)	• STSMC–Fuzzy logic: highest efficiency (99.59%) compared to traditional methods • GPESC+MRAC: improved stability and accuracy • RDAC: reliable across operating conditions • Modified MRAC–INC: robust under temperature/radiation variations • ANFIS: faster MPP tracking in variable weather than P&O and FLC
Advanced Hill-Climbing and Perturbation-Based MPPT Methods	[32] Jately et al. (2021a) [33] Jately et al. (2021b) [34] Jately and Arora (2017) [35] Jately and Arora (2018)	• Dual perturbation MPPT with step-size reduction and deviation detection • Adaptive hill-climbing MPPT optimized for low irradiance • Dual-tracking MPPT simulated under dynamic conditions • Modified hill-climbing MPPT compared with conventional methods	• High-speed tracking with low oscillations, robust under sudden irradiance/load changes • Outperforms conventional HC methods under low irradiance; ADC resolution critical • Faster convergence and higher energy yield than conventional MPPT • Improved dynamic response and lower steady-state losses compared to conventional HC

However this study presents;

- First quantitative study analyzing the combined effects of inductance and capacitance on MPPT charge controller performance under varying environmental conditions.
- Geographic dual-location analysis (St. John's, Newfoundland, and Kaptai, Chittagong), offering insights into how climatic and irradiance variations influence MPPT efficiency.
- Integration of reliability analysis (MTTF, failure rate, reliability index) into MPPT performance evaluation, which is rarely addressed in prior literature.
- Application of PDF and CDF statistical modeling to assess system stability and operational variability, providing deeper insights beyond average performance metrics.
- Practical design guidance for engineers by identifying optimal ranges of inductance and capacitance that improve adaptability and long-term reliability of solar systems.

3. Methodology

This study consists of design and simulation of an MPPT charge controller in MATLAB Simulink. Through rigorous analysis of the controller's behavior under varying configurations, the research shows how design parameters influence performance. Subsequently, a comparative study will be conducted in St. John's, Newfoundland, Canada, and Kaptai, Chittagong, Bangladesh, to evaluate the controller's efficiency in diverse environments. Building on these findings, a modified MPPT controller design will be proposed to enhance efficiency and address identified challenges. Lastly a thorough reliability analysis will ensure the long-term performance and durability of the controller, utilizing various metrics to optimize its design for sustainable operation.

3.1 *MPPT controller design in simulink*

The initial step of the project involves designing and simulating the MPPT charge controller using MATLAB Simulink. This phase aims to analyze the behavior of the MPPT controller under various inductance and capacitance configurations. Through simulation, the team will gain insights into how different design parameters impact the performance and efficiency of the MPPT controller.

3.2 *Comparison studies in St. John's, Newfoundland, Canada and Kaptai Chittagong, Bangladesh*

Next, the project will compare the performance of the MPPT charge controller in St. John's and Bangladesh. By evaluating the controller's effectiveness in diverse environmental conditions, the study seeks to determine the geographical location where the MPPT controller yields the highest output. This comparative analysis will provide valuable data on how environmental factors influence the controller's efficiency and overall performance

3.3 *Reliability analysis*

In the final phase of this study, a comprehensive reliability analysis of the MPPT charger will be conducted using methods such as PDF and CDF, with evaluation of MTTF and failure rate. By determining these reliability metrics, this study aims to ensure the long-term performance and durability of the MPPT charge controller. This thorough analysis will provide valuable insights into the controller's operational reliability and assist in optimizing its design for sustainable performance over time

3.4 *Mathematical modelling*

3.4.1 *Mean time to failure*

The MTTF for an MPPT charge controller indicates the typical duration anticipated before the controller encounters a breakdown or malfunction. This metric is a reliability measure that approximates the average period the controller operates effectively before experiencing issues. MTTF assessments play a vital role in gauging the dependability and longevity of the MPPT charge controller over an extended timeframe, aiding in evaluating its sustained performance and maintenance needs. The MTTF value obtained for this study is 21666.67 hours [36].

$$\mathrm{MTTF}_{\mathrm{system}} = \frac{1}{\lambda_1 + \lambda_1 + \ldots + \lambda_n} \tag{1}$$

Where $\mathrm{MTTF}_{\mathrm{system}}$ is the MTTF of the entire system, and λ_1, λ_2, ..., λ_n are the failure rates of individual components in the system.

3.4.2 *Reliability of MPPT charge controller*

The dependability of an MPPT charge controller pertains to its capacity to consistently enhance the power generation of a solar panel by precisely following the maximum power point amidst changing environmental circumstances. An effective MPPT controller is expected to function effectively, endure environmental adversities, exhibit minimal failure occurrences, and uphold the enduring efficiency of the solar power setup. Reliability evaluation can be conducted through various methods such as MTTF assessments, analysis of field performance data, and reliability trials, facilitating the enhancement and resilience of the controller in the long run. Reliability $R(t)$ at time t is 0.999954, obtained through the following [36]:

$$R(t) = e^{\left[-\frac{t}{MTTF}\right]} \tag{2}$$

3.4.3 *Failure rate of MPPT charge controller*

The failure rate of an MPPT charge controller, represented by the symbol (λ), signifies the frequency of malfunctions or breakdowns experienced by the controller within a specific timeframe. This metric offers valuable information regarding the reliability of the controller and its anticipated operational longevity. A diminished failure rate indicates enhanced reliability and an extended expected lifespan for the MPPT charge controller. In this work, the Failure rate obtained is 0.000046 per hour. The failure rate of a system can be calculated using the following equation [36]:

$$\lambda = \frac{1}{\text{MTTF}} \tag{3}$$

4. Circuit design

The circuit design in Figure 1 is an MPPT charge controller model consisting of an MPPT charge controller alongside a buck converter circuit to effectively manage the battery charging process using solar panels. Solar PV Array functions to convert sunlight into electrical energy. The output voltage of the array varies based on sunlight levels and temperature. The MPPT controller is tasked with identifying the optimal power point of the solar panels by adjusting voltage and current parameters continuously. The best operational point is determined through algorithms that analyze voltage and current data from the PV array. The buck converter, a DC/DC converter, reduces the voltage from the PV array to align with the battery charging voltage requirement. It efficiently transforms the higher solar panel voltage into a lower appropriate level for charging. Inductor (L) and capacitor (C) are in the buck converter circuit, and the inductor and capacitor store and release energy during the conversion process. The inductor regulates current flow, while the capacitor minimizes voltage fluctuations. Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) employs a switching element to manage the current flow from the PV array to the battery. The MOSFET acts as a rapid switch, enabling efficient voltage regulation by toggling on and off. A diode integrated into the buck converter circuit prevents reverse current flow from the battery to the solar panels when the converter is inactive. A battery storage system stores the energy generated by the solar panels is stored in the battery bank for future use. The buck converter ensures efficient and safe battery charging by controlling the voltage and current. An MPPT charge controller is designed to optimize solar power system efficiency by continuously adjusting voltage and current parameters to extract maximum power from solar panels. It uses advanced algorithms to determine the best operational point by analyzing data from the PV array. The MPPT charge controller uses a buck converter to lower the solar panel voltage for battery charging, utilizing an inductor, capacitor, MOSFET, and diode to regulate current and prevent reverse flow.

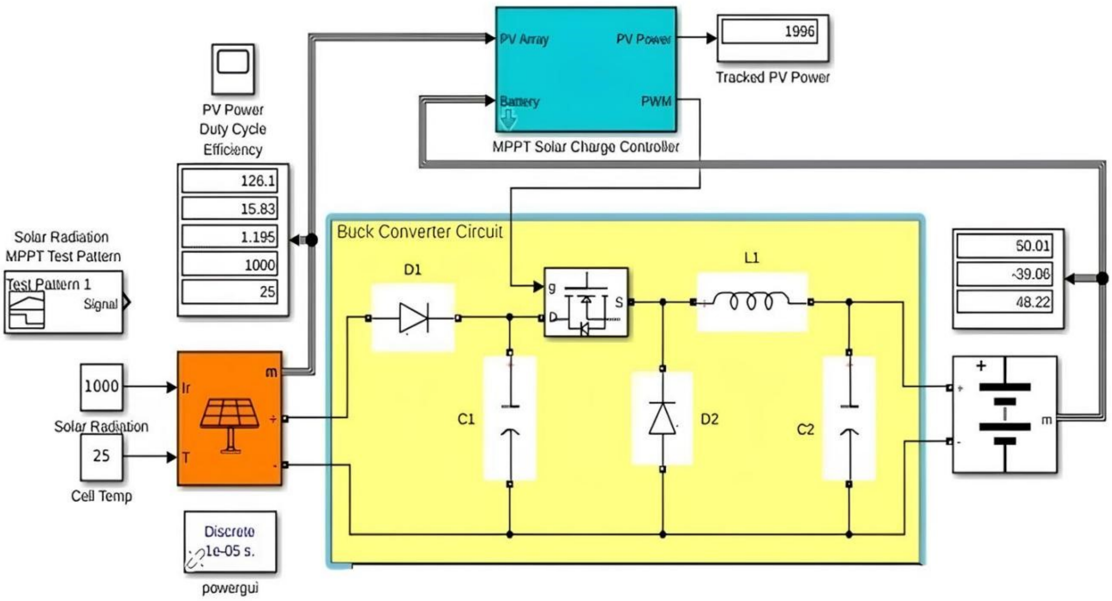

Figure 1. MPPT controller circuit

5. Results and discussion

5.1 *Results obtained for St. John's, Newfoundland, Canada*

Figure 2 illustrates the effect of varying inductance on power output while keeping capacitance constant, under irradiation levels of 2,720 W/m^2 (summer) and 7,320 W/m^2 (winter). The results show that in summer conditions, the power output increases with inductance, peaks at approximately 1,000 mH with a maximum output of 5,500 W, and then gradually declines. In contrast, under winter conditions, the power output rises more linearly with inductance and exceeds 12,000 W, without showing a distinct peak within the measured range. This suggests that the system performs more efficiently at higher inductance values in winter.

The differences in performance between seasons can be attributed to temperature-dependent changes in material properties and system impedance. Higher ambient temperatures in summer improve energy conversion efficiency by reducing internal resistive and magnetic losses. This enhances the effectiveness of impedance matching between the MPPT controller and the photovoltaic system, allowing the system to maintain optimal power output near 1,000 mH. On the other hand, colder winter temperatures lead to increased losses and possibly saturation in magnetic components at higher inductance levels, which limits efficiency. The increase in power beyond 12,000 W in winter is not problematic; rather, it reflects improved performance under those specific environmental conditions. The observed trends emphasize the importance of tuning inductance values according to seasonal variations to ensure optimal MPPT controller operation.

Figure 3 presents an analysis of how power output varies with changes in capacitance while keeping inductance constant. The investigation was carried out under two distinct irradiation levels: 2,720 W/m^2 (representing winter conditions) and 7,320 W/m^2 (representing summer conditions). These specific values were selected to simulate realistic seasonal solar irradiance levels typically observed in St. John's, Newfoundland, and Kaptai, Chittagong, respectively—allowing for comparative analysis of system behavior across different climatic scenarios. Figure 3 shows a general trend of increasing power output with rising capacitance values, although the output exhibits fluctuations that suggest additional influencing factors. In the lower capacitance range between 0 and 150 µF, power output remains relatively stable, fluctuating between

4,900 W and 5,400 W, indicating that initial increases in capacitance have a limited effect on performance. After this point, the system shows a temporary decline in power output, suggesting that capacitance beyond 150 μF may cause impedance mismatches or increased dielectric losses, thereby reducing efficiency.

However, a significant upward trend re-emerges between 300 μF and 700 μF, culminating in a peak power output of approximately 13,000 W at 600 μF. This peak highlights the presence of an optimal capacitance value that maximizes power output under the given conditions. Beyond 600 μF, the output begins to decline again, with visible fluctuations, possibly due to instability or diminishing returns from excess energy storage. The system performs notably better under summer irradiation, likely due to reduced dielectric and resistive losses at elevated temperatures, which enhance energy transfer and efficiency. In contrast, winter conditions may exacerbate dielectric losses and impair capacitor performance, resulting in lower and more erratic power output across the measured capacitance values.

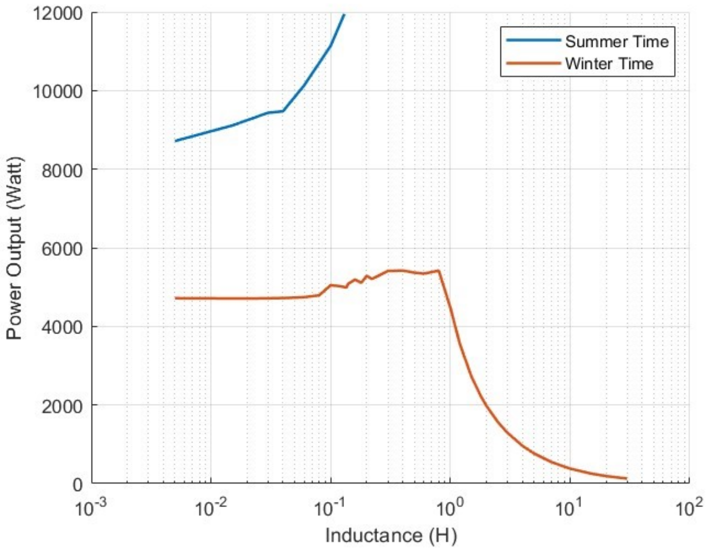

Figure 2. Power output varying inductance

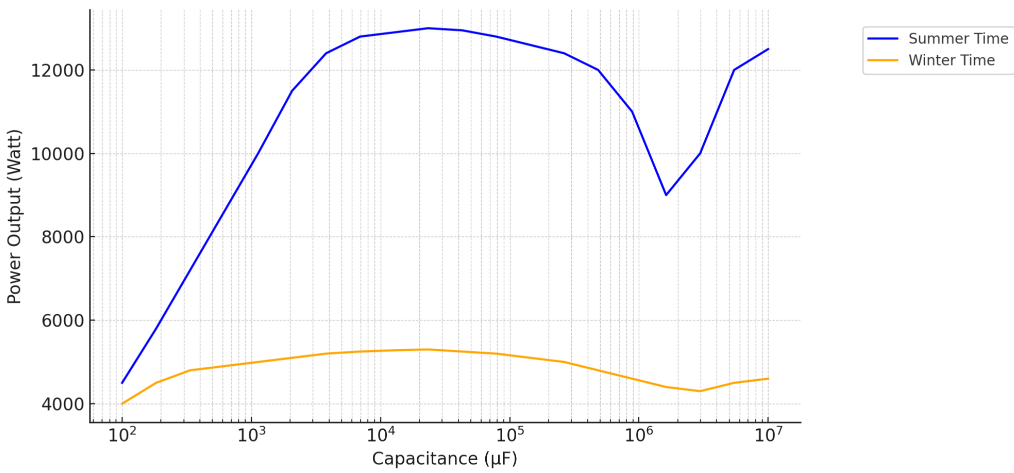

Figure 3. Power output varying capacitance

5.2 *Results obtained for Kaptai, Chittagong, Bangladesh*

Figure 4 illustrates the effect of varying inductance (in millihenries, mH) on power output (in watts) under two seasonal irradiation conditions: 4,300 W/m^2 during summer and 5,840 W/m^2 during winter, with capacitance held constant throughout. Figure 4 reveals a clear trend in both conditions power output initially increases sharply with inductance, peaks at a low inductance value (approximately 50–100 mH), and then rapidly declines as inductance continues to increase. Specifically, the peak power output approaches nearly 9,500 W in winter and 8,500 W in summer, highlighting that a relatively small inductance value can significantly enhance system performance. After the peak, a steep drop-off is observed for both seasons, suggesting that higher inductance values cause increased energy losses due to greater magnetic impedance or delayed current response. This behavior is particularly important in MPPT design, as it emphasizes the need for precise tuning of inductance to maximize efficiency. Interestingly, despite higher irradiation in winter (5,840 W/m^2), the power output in the post-peak region converges closely with summer output, indicating that beyond a certain inductance threshold, the irradiation benefit diminishes due to system inefficiencies. This figure demonstrates that inductance plays a crucial role in regulating power output, and improper selection may drastically reduce system performance. Therefore, identifying and operating near the optimal inductance value is essential for reliable and efficient solar energy harvesting in both seasonal conditions

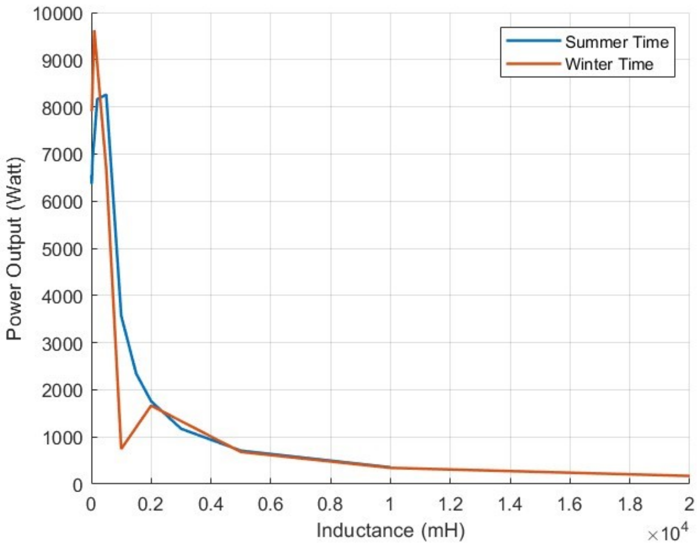

Figure 4. Power output varying inductance

Figure 5 illustrates the variation of power output (in watts) with respect to capacitance (in microfarads, µF) under constant inductance conditions for both summer and winter scenarios. In summer, the irradiation level was 4,300 W/m^2, while in winter, it was 5,840 W/m^2. The data show that in both seasons, power output is low and unstable at low capacitance values (below approximately 10 µF), particularly in summer where sharp fluctuations are observed. As capacitance increases beyond 100 µF, power output begins to rise steadily for both seasons. In winter, a smooth and continuous increase in power output is observed from 100 µF up to approximately 3,000 µF, after which it reaches a plateau at around 11,000 W and remains stable. In contrast, the summer curve shows a more abrupt rise in power between 100 µF and 3,000 µF, reaching a maximum output of approximately 8,400 W, which remains relatively stable beyond this range. These observations suggest that the system achieves optimal energy transfer above 3,000 µF, where impedance matching and energy storage capability are likely optimized. The difference in peak output levels between seasons may be attributed to temperature-dependent dielectric behavior of the capacitors and reduced resistive losses in winter. Notably, the winter condition supports higher and more stable power output, while summer conditions introduce variability at lower capacitance, likely due to resonance sensitivity or thermal effects on system components

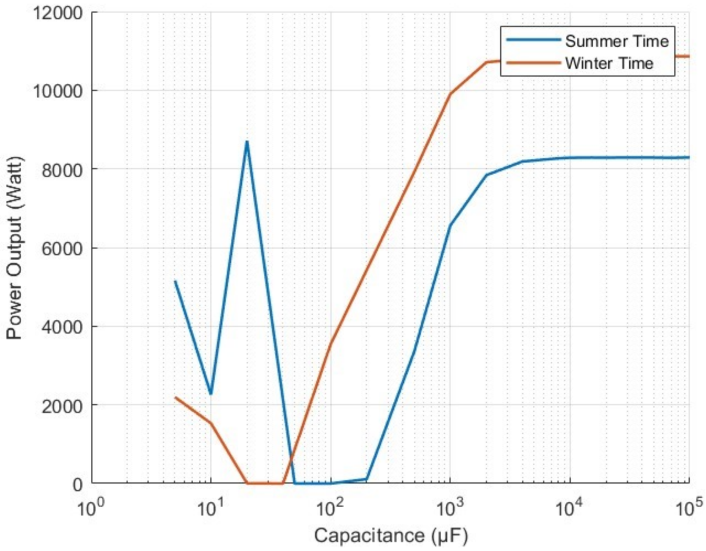

Figure 5. Power output varying capacitance

5.3 *Results obtained from reliability analysis*

Figure 6 shows the PDF for different power outputs of the MPPT charge controller. The PDF histogram provides a visualization of the probability density of the power output values around the mean power output of 10,805.24 W. The PDF histogram shows a shape centered around the mean power output value. With a standard deviation of 2,164.2109 W, the PDF histogram will likely show a spread of power output values around the mean, with most values concentrated near the mean and fewer in the distribution's tails. The shape of the PDF histogram reflects the variability and likelihood of different power output levels, with higher bars indicating higher probability density for certain power output values. Between 1,000 W and 1,200 W, the highest PDF is 2.25×10^{-4}.

An MPPT charge controller is designed to optimize power output from a PV system by adjusting the electrical operating point of the modules. Under standard operating conditions, the MPPT will track the maximum power point, resulting in power outputs that are clustered around an average or peak value. This consistent tracking leads to higher occurrences near the central power output value. The slight spread around the central peak (and the symmetrical bell shape) may result from variations in sunlight intensity, temperature, and other environmental conditions. On a typical day, sunlight intensity fluctuates due to passing clouds, changing sunlight angles, and temperature variations. These factors create a range of power outputs, with the most frequent values centered around the optimal output for the given conditions.

MPPT systems are usually efficient and stable, operating close to the maximum power point for various conditions. This efficiency contributes to a high frequency of power outputs near the peak value. However, due to occasional environmental or load fluctuations, the power output may shift slightly, resulting in the spread on either side of the peak, creating the bell shape. Since the histogram is symmetrical, it suggests that the power output deviations above and below the mean (peak) are equally likely. This symmetry indicates that the variations in power output are due to random environmental fluctuations rather than any systematic drift in the MPPT's performance. The frequency decreases at the tails of the distribution (lower and higher power outputs), indicating that extreme power outputs (very low or very high) are less common. This makes sense as the MPPT charge controller usually operates within a specific range and rarely experiences extreme conditions (e.g., very low sunlight or exceptionally bright conditions) that would cause it to deviate significantly from the central power output value.

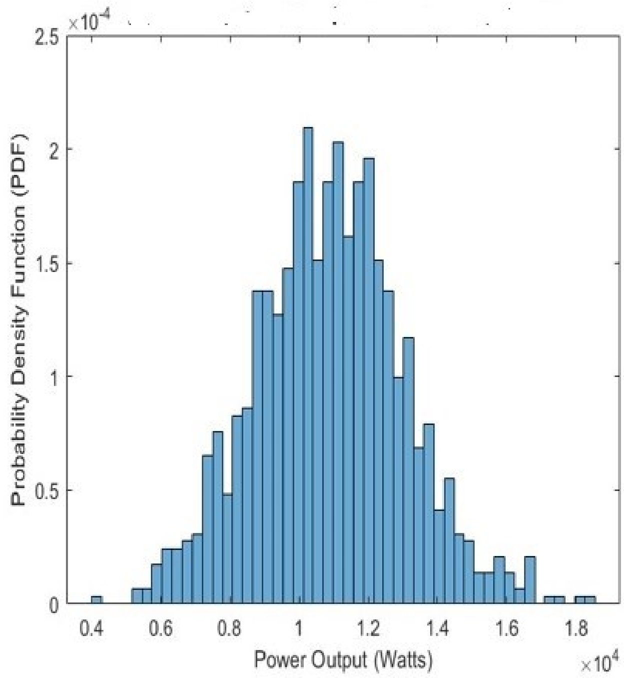

Figure 6. PDF versus power output of the MPPT

Figure 7 illustrates the cumulative probability distribution of the power output data, showcasing how the probability of observing a power output value less than or equal to a specific value changes across the range of power output values. At the beginning of the CDF graph, the cumulative probability will start at zero and gradually increase as the power output values increase. The trend of the CDF graph is expected to show a monotonically increasing curve, reflecting the accumulation of probabilities as the power output values move towards higher values. The curve's steepness in the CDF graph indicates the rate at which the cumulative probability increases with increasing power output values. The highest cumulative probability of 1.0 is observed when the output power is 1,800 watts. Since the histogram of the power output (in the previous analysis) resembled a normal distribution, the CDF will naturally have an S-shaped curve. The cumulative probability function shows the probability that the power output is less than or equal to a given value. This results in a smooth, S-shaped curve for a normally distributed variable where the cumulative probability gradually increases as you move from the lower to the higher end of the distribution.

At the lower end, on the left side of the curve, the cumulative probability starts at near zero. This reflects that very few data points are observed at lower power outputs, which are below 6,000 watts. Thus, the cumulative probability remains low in this range. In the central part of the curve (around 8,000–14,000 W), there is a steep increase in cumulative probability. This range corresponds to the most frequent power output values observed in the PDF. The cumulative probability quickly increases as you move through this central range because most power output values fall within this interval.

The cumulative probability approaches one at the curve's higher end (right side). This indicates that nearly all observed power output values are below this level (around 18,000 W). Beyond this point, there are few data points, so the cumulative probability reaches its maximum and flattens. The S-curve flattens at both the low and high extremes. This saturation effect reflects the cumulative nature of the graph, where, once nearly all values have been accounted for, the extremes, the cumulative probability does not change significantly with further increases in power output.

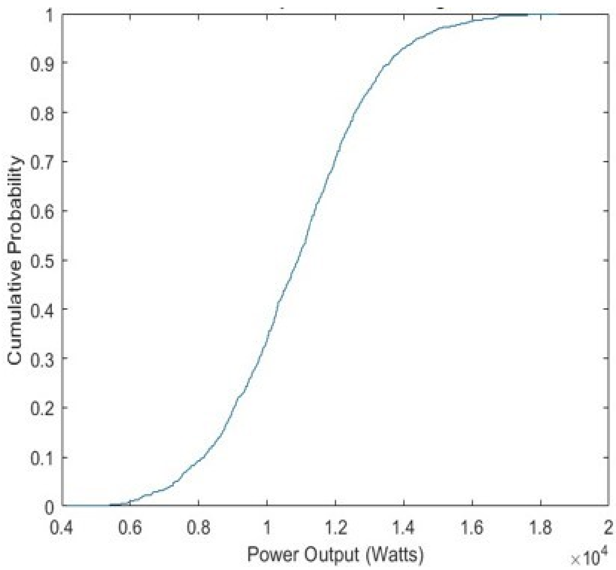

Figure 7. CDF distribution versus power output of the MPPT

6. Conclusion

This study evaluates the influence of inductance and capacitance on the performance of MPPT charge controllers under varying environmental conditions using MATLAB Simulink simulations across two locations—St. John's, Newfoundland, and Kaptai, Chittagong.

- Power Output vs. Inductance: At a constant capacitance, the highest power output of approximately 9,300 W was achieved at an inductance of 50 mH in summer conditions. Power output declined to below 500 W as inductance increased beyond 1,000 mH, indicating a strong inverse relationship beyond the optimal range.
- Power Output vs. Capacitance: With constant inductance, the system achieved peak performance at a capacitance of 0.6 F (600,000 µF) in summer, producing up to 13,000 W, while in winter, the optimal capacitance shifted to around 10^6 µF, with a peak power of 10,800 W. This demonstrates how seasonal temperature variations affect dielectric efficiency and resonance behavior.
- Location-Based Performance: Simulations reveal that Kaptai, with irradiation levels of up to 7,320 W/m^2, consistently yielded higher power outputs than St. John's, which received up to 2,720 W/m^2, indicating that geographic solar potential significantly affects MPPT efficiency.
- Reliability Metrics: The MTTF of the MPPT controller was found to be approximately 21,666.67 hours. The failure rate was calculated as 0.000114 h^{-1}, confirming long-term operational stability. The PDF and CDF curves exhibit a near-normal distribution, with most power values concentrated around the optimal peak outputs.
- Controller Configuration Sensitivity: Seasonal variations altered optimal component values. For example, inductance of 50 mH and capacitance of 0.6 F yielded best summer results, whereas winter required higher values to maintain comparable efficiency, confirming the need for adaptive tuning based on temperature and irradiation levels.

Overall, this study underscores the necessity of carefully selecting and optimizing inductance and capacitance values in MPPT charge controllers to improve solar energy harvesting, especially in diverse and challenging environmental conditions. The insights gained here are crucial for developing more reliable and adaptable renewable energy systems. The findings of this study provide actionable guidance for engineers and system designers. By identifying optimal inductance and capacitance ranges for different seasonal and geographic conditions, MPPT controllers can be designed with adaptive or tunable components to sustain high efficiency year-round. In practice, this means integrating temperature- and irradiance-sensitive tuning algorithms into controller firmware, selecting capacitors with stable dielectric properties across varying climates, and designing inductors that avoid saturation at higher power outputs. These strategies can help reduce energy losses, extend controller lifespan, and improve the cost-effectiveness of solar installations, particularly in hybrid or floating PV systems deployed in resource-constrained regions. While the present work is based on simulation models, future research will focus on experimental validation of the proposed configurations. Building and testing a prototype MPPT controller under controlled laboratory and field conditions will allow us to compare measured outputs with simulation results. This will not only strengthen the reliability of the findings but also reveal practical challenges such as thermal effects, component tolerances, and real-time controller response. Further investigations may also explore adaptive algorithms that automatically adjust inductance and capacitance in response to fluctuating environmental conditions, thereby bridging the gap between theoretical modeling and real-world deployment.

Author contributions

Conceptualization, S.M.T.A.; methodology, S.M.T.A.; software, S.M.T.A.; validation, S.M.T.A.; formal analysis, S.M.T.A.; investigation, S.M.T.A., A.E.; resources, S.M.T.A., A.E.; data curation, S.M.T.A.; writing—original draft preparation, S.M.T.A.; writing—review and editing, A.E., S.M.T.A.; supervision, A.E.; project administration, A.E.; funding acquisition, A.E. All authors have read and agreed to the published version of the manuscript

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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