International Journal of Engineering, Science and Mathematics
Vol. 12 Issue 6, June 2023,
ISSN: 2320-0294 Impact Factor: 6.765
Journal Homepage: http://www.ijesm.co.in, Email: editorijmie@gmail.com
Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

Review of MPPT-Based Grid-Connected Hybrid Renewable Energy Systems: Performance and Optimization

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ABSTRACT

Hybrid renewable energy systems (HRES) with energy storage are gaining popularity as sustainable solutions to meet increasing energy demand while reducing greenhouse gas emissions. This research proposes a grid-connected HRES with energy storage, consisting of a solar photovoltaic (PV) array, a wind turbine, and a battery bank. The integration of these renewable energy sources with the grid is achieved using power electronics-based interfaces. Additionally, maximum power point tracking (MPPT) algorithms, specifically Perturb and Observe (P&O) and Incremental Conductance, are applied to optimize power generation.

INTRODUCTION

In recent years, there has been a growing emphasis on harnessing renewable energy sources to meet the increasing global energy demand while mitigating the negative environmental impacts of traditional fossil fuel-based power generation. Among the various renewable energy technologies, hybrid renewable energy systems have gained significant attention due to their ability to combine multiple renewable energy sources to ensure a reliable and sustainable power supply. A grid-connected hybrid renewable energy system refers to a system that integrates multiple renewable energy sources, such as solar, wind, and hydro, with the utility grid. This integration allows for the efficient utilization of renewable energy resources and enables the system to provide a continuous power supply even in the absence of sufficient renewable energy generation. One critical component of a grid-connected hybrid renewable energy system is the Maximum Power Point Tracking (MPPT) technique. MPPT is an algorithm-based technology that optimizes the power output from the renewable energy sources by continuously tracking and adjusting the operating point to maximize the energy extraction. MPPT plays a vital role in enhancing the overall performance and efficiency of the hybrid system by extracting the maximum available power from the renewable energy sources under varying environmental conditions. The study aims to assess the system's efficiency, reliability, and power quality while considering the intermittent nature of renewable energy sources and the dynamic characteristics of the grid. The research will investigate the MPPT algorithms and control strategies employed to extract maximum power from each renewable energy source and their impact on the overall system performance. this study will also explore the various components and their interactions within the grid-connected hybrid system. The integration of different renewable energy sources, energy storage systems, power converters, and grid interface equipment will be analyzed to determine their impact on system efficiency, stability, and reliability.

The Need for Renewable Energy

The need for renewable energy is primarily driven by the urgent need to mitigate climate change. The burning of fossil fuels, such as coal, oil, and natural gas, for energy production releases substantial amounts of greenhouse gases (GHGs) into the atmosphere. These GHGs, particularly carbon dioxide (CO_2), trap heat and contribute to the warming of the planet, leading to adverse effects like rising sea levels, extreme weather events, and disruptions to ecosystems. Renewable energy sources, such as solar power, wind energy, and hydropower, offer a clean alternative as they produce little to no greenhouse gas emissions during operation. By transitioning to renewable energy, we can significantly reduce carbon emissions and limit the severity of climate change impacts.

Another crucial reason for embracing renewable energy is to enhance energy security and independence. Reliance on fossil fuels makes nations vulnerable to price fluctuations and supply disruptions, often resulting from geopolitical tensions or natural disasters. In contrast, renewable energy sources are abundant and widely available, reducing the dependence on imported fossil fuels and improving energy security. Furthermore, the decentralized nature of renewable energy allows for the development of local energy systems, empowering communities and reducing their vulnerability to external factors. By diversifying our energy sources with renewables, we can achieve greater energy independence and stability.

Preserving the environment is a compelling argument for the widespread adoption of renewable energy. The extraction, transportation, and combustion of fossil fuels result in severe environmental degradation. For instance, coal mining leads to deforestation, habitat destruction, and soil and water pollution. On the other hand, renewable energy technologies have significantly lower environmental impacts. Solar and wind farms have a smaller land footprint, and hydropower projects can provide multiple benefits like flood control and water management. By embracing renewables, we can protect ecosystems, conserve biodiversity, and ensure a cleaner and healthier environment for future generations.

Different Sources of Renewable Energy

Renewable energy refers to energy derived from naturally replenishing sources that are not depleted with use. Here are some of the different sources of renewable energy:

Solar Energy: Solar energy harnesses the power of the sun by converting sunlight into electricity through photovoltaic (PV) panels or concentrating solar power (CSP) systems. Solar energy is abundant, widely available, and can be harnessed both for large-scale power generation and decentralized applications like rooftop solar panels.

Wind Energy: Wind energy utilizes the kinetic energy of wind to generate electricity. Wind turbines, usually installed in wind farms, capture the wind's energy and convert it into electrical power. Wind energy is a mature and rapidly growing renewable energy source, with onshore and offshore wind farms becoming increasingly common.

Hydropower: Hydropower harnesses the energy of flowing water, such as rivers and dams, to generate electricity. Water turbines are used to convert the potential and kinetic energy of water into mechanical energy, which is then transformed into electrical energy by generators. Hydropower is a reliable and widely deployed renewable energy source, with large-scale hydroelectric plants and smaller run-of-river systems.

Geothermal Energy: Geothermal energy taps into the heat stored beneath the Earth's surface. It utilizes the natural heat from the Earth's core and geothermal reservoirs to generate electricity or provide direct heating and cooling for buildings. Geothermal power plants use steam or hot water from underground sources to drive turbines and produce electricity.

Biomass Energy: Biomass energy is derived from organic materials, such as wood, crop residues, agricultural waste, and dedicated energy crops. Biomass can be burned directly to produce heat or converted into biogas or biofuels through processes like anaerobic digestion or bioconversion. Biomass energy provides a versatile renewable energy source for heat, electricity, and transportation fuels.

Tidal Energy: Tidal energy captures the energy of ocean tides and currents to generate electricity. Tidal power plants use turbines that are driven by the ebb and flow of tides, converting the kinetic energy of water into electrical energy. Tidal energy has the advantage of being predictable and consistent, as tides follow predictable patterns.

Wave Energy: Wave energy harnesses the power of ocean waves to generate electricity. Wave energy converters capture the energy from the up-and-down motion of waves and convert it into electrical power. Wave energy is an emerging renewable energy source with significant potential, although it is still in the early stages of commercial development.

Each of these renewable energy sources offers unique advantages and can contribute to a more sustainable and diversified energy mix. By harnessing and utilizing these sources effectively, we can reduce our reliance on fossil fuels, mitigate climate change, and ensure a cleaner and more sustainable energy future.

The Concept of Micro-grids

Microgrids are localized energy systems that operate independently or in coordination with the main power grid. They are designed to provide electricity to a specific geographical area, such as a community, campus, or industrial facility, and can function both in grid-connected and islanded modes. Here are the key concepts of microgrids:

Decentralized Generation: Microgrids incorporate decentralized generation sources, including renewable energy systems like solar panels, wind turbines, and small-scale hydroelectric generators. These local energy sources help reduce transmission losses, improve energy efficiency, and enhance the overall resilience of the system.

Energy Storage: Microgrids often integrate energy storage technologies, such as batteries, flywheels, or pumped hydro storage, to store excess energy produced during periods of low demand and supply it during peak demand or when renewable energy sources are not available. Energy storage enables the efficient use of renewable energy and ensures a stable power supply.

Control and Management Systems: Microgrids employ advanced control and management systems to monitor and regulate the flow of electricity within the system. These systems optimize energy generation, storage, and consumption, and facilitate smooth transitions between grid-connected and islanded modes of operation. They also enable microgrid operators to manage the energy supply and demand in real-time, ensuring reliability and stability.

Grid Integration and Islanding Capability: Microgrids can operate in grid-connected mode, exchanging electricity with the main grid, or in islanded mode, where they can disconnect from the main grid and operate autonomously. Grid-connected microgrids allow for the exchange of excess electricity with the main grid, while islanded microgrids provide power during grid outages or in remote areas without access to the central grid.

Resilience and Energy Security: Microgrids enhance the resilience and energy security of local communities and critical facilities. In case of grid failures or natural disasters, microgrids can continue to provide reliable electricity, ensuring essential services such as hospitals, emergency response centers, and communication networks remain operational. The ability to operate independently increases energy security and reduces vulnerability to external disruptions.

Demand Response and Energy Efficiency: Microgrids often incorporate demand response programs and energy efficiency measures to optimize energy consumption and reduce peak demand. Demand response enables consumers to adjust their electricity usage in response to price signals or grid conditions, while energy efficiency measures promote the efficient use of energy, reducing overall demand and strain on the system.

Integration of Electric Vehicles (EVs): Microgrids can support the integration of electric vehicles by providing charging infrastructure and managing their charging and discharging patterns. EVs can act as mobile energy storage devices, contributing to the stability and balancing of the microgrid by supplying or absorbing electricity as needed.

Microgrids offer several benefits, including increased reliability, improved energy efficiency, reduced greenhouse gas emissions, and enhanced resilience. They empower local communities to generate their own clean energy, reduce dependency on centralized power grids, and contribute to a more sustainable and decentralized energy system.

LITERATURE REVIEW

Over the past ten years, low and medium energy storage has become tied to new active systems. Wind turbines, power generators, biomass and geothermal manufacturers, solar systems, fuel cells, storage, and other tools to improve the quality of energy are all part of these new active systems. Almost all of these new pieces of hardware are connected to each other through voltage source filters (VSI) and filters. Most of the time, these devices are needed to give the target the right amount of active and reactive power, which requires a good tracking system. The main focus of this piece is on how to handle the dynamic and reactive energy of the related VSI. After a quick look at some of the more common ways to control things, the next topic will be control tactics, which are a new way to control things. It depends on the user knowing where the line bend is and what the current velocity vector is. The main goal of this work is to come up with a general method for solving asymmetrical transients analytically based on the Clarke transformation. The Clarke change will be used to make this happen. Because the basic use of the Clarke transformation does not result in the diagonalization of system matrices, special theoretical work is needed to explain the difference between the three stages. Because of the phase asymmetry, analytical answers in closed form can be found by making sense of how Clarke modal circuits (i.e.,,, and 0 circuits) interact with each other.

Jinsong Kang et al. (2019), the growth of renewable energy sources like hydrogen energy has led to the DC Microgrid including renewable energy supply as a key part. Monitoring and power control in similar situations have become the focus of a lot of research in recent years. The Microgrid DC photovoltaic / fuel / DC energy storage in this article includes photovoltaic (PV), fuel cells, lithium-ion batteries, and supercapacitors, as well as DC / DC and DC / AC converters. To ensure the stability of the photovoltaic / fuel cell / hybrid DC microgrid energy storage. This paper presents a control and energy management system. The proposed power control and management system effectively controls the cost of the bus and balances the power by automatically controlling the power of each model. Under the power control and management system, when the load changes suddenly, the bus load stays stable, and the power supply remains balanced. The effectiveness of the proposed method was verified by simulation.

Sheik Mohammed et al. (2019) DC Microgrid with photovoltaics. Controlled energy storage systems include batteries, supercapacitors, DC loads, electric motors, and energy management systems (EMS). The main goal is to manage the demand for goods effectively. Simple adaptive energy management control is achieved. In MATLAB/Simulink, the system is set up with different inputs and loads, and then the outputs are gotten. Based on what was found, the DC Microgrid that uses the energy control system can meet all of the standards.

Li Jing et al. (2016) batteries and supercapacitors have the advantage of high energy content and high power density. Combining them in a hybrid energy storage system (HESS) can meet a variety of microgrids requirements. A balanced system power supply and DC bus power supply can be achieved by implementing a power management strategy. The HESS control strategy is designed to satisfy the required / discharge requirements and minimize battery damage caused by frequent discharge waves. Based on the HESS DC microgrid system model of the Matlab / Simulink platform, the simulation results validate the feasibility of the control strategy**.** Solar and wind energy are the primary sources of renewable energy. Researchers work hard on both sides to get as much energy as possible. Many algorithms have been developed to work with energy conversion systems from solar or wind to maximum power (MPP).

Mohammed et al. (2012) The Perturb and Observe method was thought of as a way to get the most power out of a photovoltaic solar system. It is a simple programme that doesn't require you to know anything about the PV system or have any experience with it. The use of this method makes it easy to use analogue systems. The algorithm moves the operating point of a photovoltaic (PV) system by slowly changing the values of the control parameters, which can be positive or negative. Mohammed et al. (2012) say that if you turn up the voltage, the turbulence will keep going in the same way. If the power doesn't go up, the turbulence will keep going the other way. The P&O method has a number of benefits, some of which are fewer control parameters, easy implementation, and a simple algorithm. The problem with this method is that it changed when the MPP came, and it can't be used properly when the conditions are different.

Yuxiang Shi et al. (2016) The photovoltaic solar system is linked to the load by two bridge converters that are working with a number of inverters at the moment.. In this embodiment, the small capacitors in the film replace the high-voltage capacitors that are common in the system. Even under rapidly changing conditions, this program can provide high efficiency. The 5kW PV converter was developed to test the efficiency of the algorithm. The control of both active bridges and multilevel inverters is the disadvantage of this approach.

Markus Andresen (2016) The MPPT tracking method could be helpful for solar PV systems. This method takes into account the stress that the semiconductor switch puts on the converter in terms of heat. Because of this, there is less waste and more total efficiency. Climate change is making the world change, which makes the algorithm work better.

Chun Wei et al. (2016) MPPT is an algorithm that was made for use in energy transfer systems. To get to the highest energy point, you need to mix the artificial neural network and the Q learning algorithm. Always use the power level that makes the rotor spin the fastest. With the help of the data and tests shown here, the ANN-based MPPT control algorithm made for a 5MW wind-to-wind energy conversion system (WECS) is proven to work. The artificial neural networks will need more time to learn the smaller chemical WECS.

Yipeng& Heng (2015) The author put forward a flexible control method for wind energy systems that change over time. Imagine that two converters, say an edge converter and a rotor edge converter, are both working to reach the maximum power point (MPP). This method is used when the parameters are inconsistent or wrong. One of the perks of using this technology is that it cuts down on harmonics that could be dangerous.

Yinru Bai et al. (2015) designed a wind turbine generator system for an outdoor generation. A standard buck/boost wind energy conversion system will be used to obtain the maximum power point. But in this structure, there is no power electronic converter required. It is highly reliable for outdoor use. A prototype of this structure is developed and tested. The disadvantage of this scheme is the design of this particular generator. Each of the above-mentioned methods has its own unique problems to solve before it can reach its full power. So, three different MPPT methods have been made to get the most power from systems that convert solar and wind energy into electricity.

Mohamed AL-Emam et al. (2018) When trying to get more use out of a solar (PV) model, it is very important to stay true to its maximum power point (MPP). When the conditions are called "partial shade," the P-V graph has a lot of peaks. Therefore, the function of state-of-the-art technology (MPPT) is to monitor the location of the global power supply and prevent running over the top of the city. Especially in partial shadow situations, one of the most effective methods is logic control flooring (FLC) technology.

MAXIMUM POWER POINT TRACKING ALGORITHMS

Maximum Power Point Tracking (MPPT) algorithms play a crucial role in optimizing the performance of renewable energy systems, particularly those utilizing solar photovoltaic (PV) panels or wind turbines. The primary objective of MPPT algorithms is to track and maintain the operating point at which the renewable energy source operates at its maximum power output, maximizing energy extraction and system efficiency.

Renewable energy sources such as solar and wind are characterized by variable and non-linear power generation characteristics, making it essential to continuously track the maximum power point (MPP) to ensure optimal energy conversion. MPPT algorithms enable the renewable energy system to dynamically adjust its operating parameters, such as voltage or rotor speed, to maintain the system at or near the MPP, even under changing environmental conditions.

Various MPPT algorithms have been developed and implemented to achieve accurate and efficient power tracking. These algorithms differ in their control strategies, computational complexity, convergence speed, and robustness. Some of the commonly used MPPT algorithms include Perturb and Observe (P&O), Incremental Conductance (IC), Fractional Open-Circuit Voltage (FOCV), and Fuzzy Logic Control (FLC), among others.

The P&O algorithm is one of the simplest and widely adopted MPPT techniques. It perturbs the operating point and observes the resulting power change to determine the direction of the MPP. The IC algorithm, on the other hand, utilizes the incremental change in conductance to track the MPP. FOCV algorithm calculates the MPP based on the fractional open-circuit voltage and its derivatives. FLC algorithm employs fuzzy logic to adaptively adjust the operating point towards the MPP.

The selection of an appropriate MPPT algorithm depends on factors such as system requirements, environmental conditions, computational resources, and cost considerations. Each algorithm has its advantages and limitations, and their performance may vary under different operating conditions. MPPT algorithms are essential for optimizing the performance of renewable energy systems by enabling accurate and efficient tracking of the MPP. The choice of MPPT algorithm depends on various factors, and ongoing research aims to develop advanced algorithms that offer improved accuracy, faster convergence, and robustness to further enhance the efficiency of renewable energy systems.

Hill-climbing techniques

Hill-climbing techniques are optimization algorithms used to find the maximum or minimum of a function by iteratively adjusting the solution towards the direction of improvement. These techniques derive their name from the analogy of climbing a hill, where the goal is to reach the highest point (maximum) or the lowest point (minimum) on the landscape of the objective function.

Hill-climbing algorithms start with an initial solution and repeatedly modify it by making small adjustments or "climbs" to reach a better solution. The search process involves evaluating the objective function at each iteration and comparing the current solution with its neighbors to determine the direction of improvement. The solution is updated by moving towards the neighbor with the highest or lowest objective function value, depending on whether the algorithm is aiming for a maximum or minimum.

One of the simplest forms of hill-climbing is the basic hill-climbing algorithm, also known as the steepest ascent/descent algorithm. It takes a single step in the direction of the steepest ascent (for maximum) or descent (for minimum) in each iteration. However, this approach may get stuck in local optima, where the algorithm reaches a suboptimal solution that is not the global maximum or minimum.

To overcome the limitation of getting trapped in local optima, variations of hill-climbing techniques have been developed. These include:

Random-restart hill climbing: This approach performs multiple independent hill climbs from different starting points. By randomly selecting initial solutions, the algorithm explores different regions of the search space, increasing the chances of finding the global optimum.

Simulated annealing: Simulated annealing incorporates probabilistic acceptance of solutions that are worse than the current solution. Initially, the algorithm allows for more exploration, but as it progresses, it gradually reduces the acceptance of worse solutions, mimicking the annealing process in metallurgy. This helps the algorithm escape local optima and converge towards the global optimum.

Genetic algorithms: Genetic algorithms use a population-based approach inspired by biological evolution. The algorithm maintains a population of candidate solutions and applies genetic operators like mutation and crossover to generate new solutions. This allows for a more extensive exploration of the search space and facilitates the discovery of better solutions.Hill-climbing techniques have found applications in various domains, including optimization problems, machine learning, and artificial intelligence. They offer a simple and intuitive approach to finding local optima, but care must be taken to handle issues such as local optima, convergence to suboptimal solutions, and proper exploration of the search space to improve their effectiveness.

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