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Design and Implementation of a Smart Grid System for Efficient Energy Distribution in Rural Areas

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Abstract

Automating these substations' operations and facilitating communication between substations and control centers are key components of the transmission sector's modernization and automation. Monitoring the electricity transmission network in real time for the best possible control and security is another facet of automation. The power distribution network requires the same substation automation requirements as well as grid monitoring, control, and protection. Formerly mostly centralized and bulk, generation is now a combination of centralized and distributed, including the possibility of distributed energy storage. In order to realize the idea of micro grids, the technology also focuses on developing more dispersed generating facilities that integrate electrical energy from renewable resources. Since technology has made it possible for dispersed generation to be successfully and smoothly integrated into the grid, consumers are turning into prosumers by pursuing import-export deals with the grid on the one hand and owning captive Renewable Energy (RE) power plants on the other. The development of an efficient smart energy monitoring system (SEMS) requires several technologies.

Keywords: Smart Grids, Renewable Energy, Microgrids, Cloud Computing.

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Introduction

When we talk about the Smart Grid, we're really referring to the whole electrical system. In addition to the activities, markets, and service providers that contribute to the grid becoming "smarter," this encompasses everything from generation and transmission to distribution and the end users. The greatest and most complex component of this entire structure is the distribution system, which normally runs at either 25 kV or 15 kV. Surprisingly, when it comes to planning, operations, and maintenance, this aspect of the system is frequently disregarded by certain major metropolitan utilities that simultaneously oversee transmission and generating. On the other hand, it typically receives a lot more attention from smaller rural utilities (Colak et al., 2020). Many people think that Smart Grid technologies aren't applicable in rural areas, yet if we're talking about Smart Cities, why not apply the same idea to rural areas as well? A rural smart grid entails putting creative ideas for electricity production in rural areas into practice. Local rural communities or the departments of agriculture and the environment are supporting many of these initiatives (Paul et al., 2014). All in all, implementing SSTs can transform the grid into a more intelligent, compact, reliable, and safe system. To keep things straightforward, this case study offers a simplified version of the proposed system. Here, we assume that the dataset we've gathered reflects the electricity consumption patterns of different homes throughout a specific city. Additionally, we've included 20% of the data entries as malicious to illustrate instances of electric theft happening in the area. In order to effectively simulate this case study, we've taken into account various assumptions, which are outlined below:

- We're looking at a distribution station that can generate 2MW of power, which is set up as a power generation (PG) unit. This setup aligns with the total electricity usage in the city, taking into account the transmission and distribution (T&D) losses.
- The typical electric distribution network for the city is shown in the illustration. From what we can see, there's a PG unit linked to two transmission lines (TL), and each of those lines connects to two distribution stations (DS). Each DS is then tied to two transformers (T), which deliver electricity to various neighborhoods. We're assuming that each neighborhood has about 140 houses.
- The 2MW PG unit sends 1MW of power to each of the connected TLs. In turn, these TLs share their power with the DSs, meaning each DS gets 500kW. This power is then distributed among the transformers at 250kW each, not accounting for any losses along the way.

We've set up an experiment using a 200W polycrystalline solar panel along with two identical simple mirrors equipped with MPPT. The dual tracking for the solar panel with mirrors was done manually (Brown, 2008).

Literature Review

People all around the globe are showing a keen interest in the benefits of smart grids. These grids have a wide range of applications, which have been detailed in various presentations. El-Hawary (2014) aims to shed light on the technical, socio-economic, environmental, and other less tangible advantages that smart grids offer to society (Lo & Ansari, 2011). The real-time implementation of this infrastructure is designed to respond instantly and take proactive measures to tackle the challenges posed by future power systems.

The author shared these insights during a presentation at Dalhousie University in Nova Scotia, Canada. Meanwhile, Chen Shu-Yong and colleagues (2008) conducted a survey focusing on smart grid technology, specifically analyzing China's smart microgrid. In another paper, Hassan Farhangi and his team (2010) explored the evolution of the smart grid. They pointed out that rising energy costs, the widespread electrification of daily life, and climate change are key factors that will influence how quickly these transformations take place.

They discussed how rapidly various services are adopting smart grid concepts, technologies, and systems, all agreeing on the inevitability of this significant shift. S. Massoud Amin and his co-authors (2005) wrote an article about energy delivery for the twenty-first century, addressing the unpredictable challenges faced by smart grids while considering multiple performance parameters like agility, robustness, security, and reliability (Vijayapriya & Kothari, 2011). Notably, the same author has also worked on F-15 fault tolerance for aircraft control systems, earning praise for his contributions to flight reconfiguration. Lastly, Nigam and his team (2019) emphasized the traditional grid's ability to navigate the barriers posed by smart grids, focusing on key topics such as demand-side management and load forecasting.

Methodology

The quality of manufacturing a solar panel plays a crucial role in how well it performs. But it's not just about the panel itself; its output is also influenced by its positioning in relation to the Sun. Ideally, the panel should be oriented at a

90-degree angle or parallel to the Sun to capture the maximum sunlight (Moslehi & Kumar, 2010). To achieve this, solar panels often use trackers that follow the Sun's movement across the sky. The Sun's position is measured using azimuth and zenith angles, where the azimuth essentially tells us the compass direction of the Sun as it travels from east to west each day. Some solar cells are equipped with dual-axis trackers that utilize Maximum Power Point Tracking (MPPT) and specular reflection, along with a non-reflective path. It's important to note that as the temperature of a photovoltaic (PV) panel rises, energy is lost due to heat, which can reduce the panel's efficiency during peak sunlight hours. A parabolic reflector solar tracker can increase efficiency by employing two less reflectors. Solar panels can track the Sun's passage from east to west using single-axis tracking devices, which revolve around a single midway (Bayindir et al., 2016). The slanted single-axis system, the vertical single-axis system, and the horizontal single-axis system are the three different varieties of single-axis tracking systems. When you look at a horizontal setup, you'll notice that each component's face is lined up parallel to the horizontal rotational axis, which doesn't really take the ground into account. The surface of a module is tilted at a certain angle in relation to how the system operates, with the rotational axis standing vertical to the earth. In a vertical system, similar to a horizontal tracker, the rotational axis remains horizontal, again ignoring the ground, and the component's face stays aligned parallel to the rotation. One major downside of a single-axis tracker is that it can't keep up with the Sun's daily path, only its yearly journey. Because this single-axis system can only track the east-west direction in four different positions during cloudy weather, its overall effectiveness takes a hit.

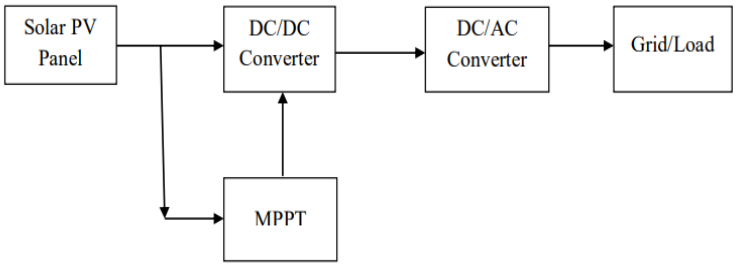


Fig. 1: Block diagram of MPPT system

Using MPPT is the smartest way to boost the efficiency of a solar photovoltaic (SPV) plant while keeping costs down. By ensuring that the PV modules operate at their ideal voltage, or maximum power point, MPPT aims to maximize the power that the modules can produce. In essence, MPPT finds the optimal power level the PV module can produce to charge the battery by monitoring the module's output and comparing it to the battery voltage. To guarantee that the maximum current enters the battery, it also modifies the voltage. Additionally, any DC load connected to the battery can be powered directly by it.

Case Study

In order to compare the solar panel's output power and efficiency, we used experimental data—such as readings and graphs—collected using four distinct techniques.

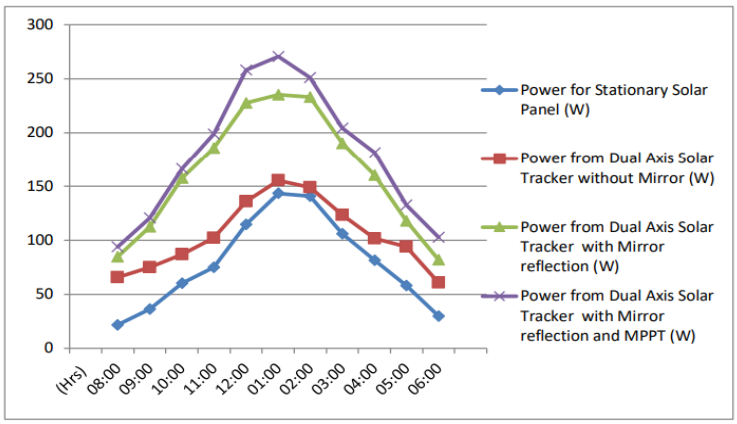


Fig. 2: Power characteristic curve and comparison of static solar panel, dual axis solar tracker and dual axis solar tracker with mirror and MPPT

The shift towards sustainable energy systems is all about embracing advanced technologies such as smart grids (SGs), management systems, and renewable energy generation and storage solutions. In this era of big data, wireless connectivity, and the Internet of Things (IoT), advanced sensors and smart meters are essential data sources that must be integrated and coordinated in order to manage the operation of these complex systems (Tuballa & Abundo, 2016).

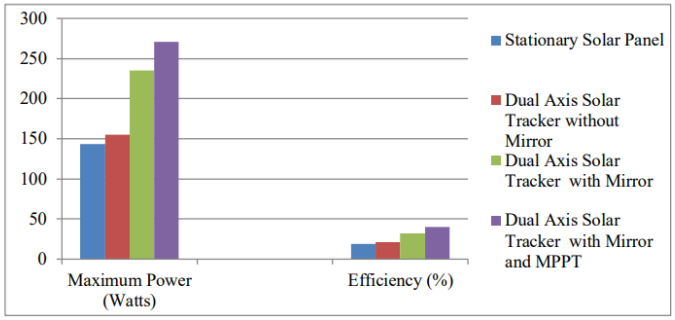


Fig. 3: Graph showing the comparison analyses of maximum power and efficiency

The data we gather needs to be stored, processed, and analyzed to produce the necessary outputs for the smooth deployment of smart grids and the operation of power stations, balancing demand and supply while incorporating renewable energy and clean energy sources, along with demand-side management strategies. In today's power systems, energy efficiency, cutting down emissions, and minimizing waste are absolutely crucial. The advantages of a modern grid include improved asset management, better operational planning, enhanced monitoring and control, fewer instances of voltage instability, more accurate predictions, and quicker fault detection within the power system. However, implementing such an advanced system does come with its own set of challenges, particularly concerning data uncertainty, security, quality, and complexity.

Conclusion

The experiment's results highlight a notable boost in both power output and efficiency for the stationary solar panel. By combining a stationary solar panel with a dual tracker—both with and without mirrors—and utilizing Maximum Power Point Tracking (MPPT), we find these methods to be incredibly effective for enhancing solar panel efficiency. A scalable method for incorporating renewable energy sources into the smart grid is presented in this research. The objective is to address the persistent difficulties in maintaining reliable and seamless operations in smart grids that are being populated with a significant number of renewable energy sources and technologies. New complexity and architectural problems arise when sources, loads, and utility operators integrate a sensing-actuation system. Implementing cutting-edge control, communication, and monitoring technologies that enable intelligent and scalable power management is crucial for achieving high performance, economic viability, and sustainability in addition to efficiency and dependability.

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