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Comparative Study of Performance Metrics for Smart Inverter Control in Solar PV-Based EV Charging Stations

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Abstract: **-** Photovoltaic (PV) panels harness sunlight as a clean and renewable energy source, providing a sustainable alternative to fossil fuels. In India, PV technology is gaining traction due to its environmental benefits and governmental support. This study analyzes typical PV generation profiles, identifying daily and seasonal variations influenced by factors like cloud cover. Additionally, it investigates the effectiveness of three EV charging strategies—uncontrolled, smart, and vehicle-to-home (V2H)—using rule-based and Model Predictive Control (MPC) algorithms. Simulations reveal that MPC consistently outperforms rule-based control in reducing household costs, with V2H charging showing potential for cost savings during peak electricity pricing. However, the efficacy of control strategies varies across seasons, suggesting the need for adaptive optimization approaches.

Keywords: Service Learning, Digital Literacy, Marginalized Communities, Malaysia, ICT Training, Empowerment

Introduction

One common argument against the idea that electric vehicles (EVs) are truly clean is that they are frequently charged with electricity generated from fossil fuels. However, studies have consistently shown that, regardless of the power source, electrification of transport significantly reduces carbon emissions and air pollution.

The emergence of solar-powered EV charging stations represents a promising solution that aligns with the concept of green mobility. As India gears up to accommodate an estimated 102 million EVs on its roads by 2030, the need for 2.9 million public charging stations becomes increasingly apparent.

Solar-powered charging stations offer several advantages. Firstly, they are environmentally friendly, as they rely on renewable energy sources. Secondly, they are cost-effective, reducing the burden on consumers and the economy.

India's vast potential for solar power, with an estimated capacity of 749 GW, far surpasses its current installed capacity. Therefore, investing in solar-powered EV charging stations represents a significant, untapped opportunity that not only supports India's climate goals but also promotes sustainable economic development. This initiative is gradually gaining momentum and has the potential to revolutionize India's transportation sector.

Figure 1. Solar Power EV charging Station

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Benefits of solar charging stations

These EV charging stations use solar panels to generate electricity, which makes them eco-friendly. A study by The Energy and Resources Institute (TERI) shows that the per-unit cost of electricity generated from solar panels ranges between Rs 2.50 to Rs 3.50,(which will be significantly lower by 2030) whereas the per-unit cost of electricity from grid power ranges between Rs 6 to Rs 7. This can translate to lower per unit charging costs for consumers, which can further bring down the total cost of ownership of EVs. Another study shows that electric vehicle charging stations with solar rooftop photovoltaic are economically more viable than charging stations sourcing electricity from the grid. The mismatch between solar energy generation and consumption (from charging) can be solved by deploying net metering at charging stations.

Another benefit of these stations is that they can also be set up in remote areas, which lack access to grid power. This can help promote EV adoption in rural areas, where the cost of setting up traditional charging stations can be high due to the absence of grid power. According to an International Energy Agency (IEA) report, around 50% of India's population lives in rural areas, and the adoption of EVs can help promote sustainable mobility in these areas.

These stations are also a potential source of job creation, as highlighted by a recent report by CEEW, which shows that the installation of 1 million EV charging stations in India can create up to 46,000 jobs, including those in the manufacturing, installation, and maintenance of charging infrastructure, thus helping boost the country's economy.

And lastly, their contribution to reducing carbon emissions and dependence on fossil fuels will be immense. In 2019-20, India's crude oil imports amounted to $102.5 billion, accounting for around 2.8% of its GDP. The adoption of EV and solar-powered charging infrastructure can help reduce India's dependence on imported oil and promote energy security.

Research Methodology

Sunlight possesses an incredible potential as a clean and renewable energy source, and photovoltaic (PV) panels harness this power by converting sunlight directly into electricity without emitting pollutants. This technology has gained significant traction globally, including in India, where it's not only recognized for its environmental benefits but also supported through subsidies.

PV panels play a crucial role in India's energy landscape, offering a sustainable alternative to traditional fossil fuels. As a populous nation with a rapidly growing economy, India faces the dual challenge of meeting its energy demands while minimizing environmental impact. PV generation stands out as a promising solution, as it produces electricity without contributing to air or water pollution, unlike coal or oil-based power plants.

We observed a typical photovoltaic (PV) generation profile during data analysis, as shown in Figure 2. The profile illustrates the maximum, minimum, and median generation profiles. PV generation typically begins in the morning, gradually increasing until it reaches its peak around noon. Afterward, the power output gradually decreases, reaching zero by the end of the day. This daily pattern of power generation corresponds to the sun's rising and setting. The time of year influences the amount of power generated, with the summer producing more than the winter.

Occasional disturbances in the PV generation profile are observed, primarily caused by the presence of clouds, which reduce PV generation. Because these disturbances are highly localized, the production profile tends to be smoother on a larger PV generation surface and more erratic on a smaller surface. Considering the standard sizing of a PV panel (1 m × 1.65 m), the maximum power output per panel during the year is approximately 220 W.

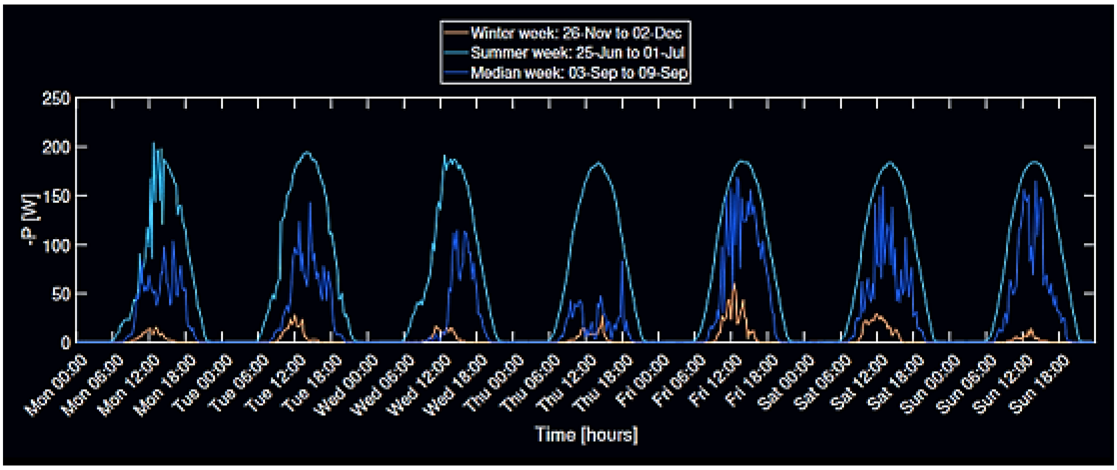

Figure 2. Analyzing PV Panel Production: Peak, Median, and Minimum Weekly Output

The study aims to assess the effectiveness of three charging strategies—uncontrolled charging, smart charging, and vehicle-to-home (V2H) charging—in reducing household costs. To do so, simulations are conducted using a rule-based controller and the Model Predictive Control (MPC) algorithm. Two scenarios are considered: one with perfect information and another with certainty-equivalent conditions. The simulation period spans two weeks, including weekends, while keeping computation time manageable.

Seasonal variations in variables like photovoltaic (PV) generation and household loads are factored in. Three seasons are defined: summer (maximal PV generation, minimal household demand), winter (minimal PV generation, maximal household loads), and median (average PV generation and household load, representative of spring or autumn). It's important to note that the simulations model extreme cases, acknowledging that PV generation may not be consistently high during summer days.

We use Matlab R2017a software to conduct simulations and solve the Mixed Integer Linear Programming (MILP) problem. This approach enables efficient optimization of the control problem while taking into account the system's dynamic nature and the constraints imposed by the available data.

Result and Discussion

Table 1 presents simulation results for different charging strategies in a microgrid during the summer season. The strategies include uncontrolled charging, smart charging, and vehicle-to-home (V2H) charging, each employing either rule-based or Model Predictive Control (MPC) with perfect information (PI) or certainty equivalent (CE). The table compares total microgrid costs, including electricity costs, distributed system operator (DSO) costs due to peak power demand, and costs associated with EVs leaving charging poles with incomplete battery charges. The comparison allows for an analysis of the overall performance of the control strategies and their effectiveness in improving household costs within the microgrid system.

Table 1. Summer Season EV Charging Strategies

	Smart		**Uncontrolled**	**V2H**	
	MPC			MPC	
	CE	PI		CE	PI
Total costs	2958	2925	14091	2968	2904
Electricity Cost	2512	2480	2619	2518	2454
Economical Cost	3256	3197	3429	3283	3210
Peak Power(kW)	258	232	319	273	265
Mean EV departure	.0040	.0041	0	.0032	.0034

Cost Comparison

The study reveals that implementing smart charging or vehicle-to-home (V2H) charging using rule-based control leads to higher total costs compared to uncontrolled charging. This is primarily because the rule-based control method is less efficient in charging electric vehicles (EVs) to 100% state of charge (SOC) before departure, unlike uncontrolled charging. With uncontrolled charging, the mean EV departure shortage is always zero because the arrival and departure times at the charging pole are scheduled to ensure the EV has enough time to charge its daily energy demand.

When comparing total costs, the Model Predictive Control (MPC) algorithm consistently outperforms the rule-based control algorithm for both smart charging and V2H charging. The perfect information model, facilitated by the MPC algorithm, demonstrates the best performance. V2H charging, which allows bidirectional power flow through the EV's power converter, offers potential cost savings by discharging EVs to support household loads during peak electricity pricing. However, this benefit can only be effectively realized if the control algorithm accurately forecasts uncertain variables like photovoltaic (PV) generation, household loads, and electricity prices.

According to the study, V2H rule-based control implementation performs worse than its smart charging counterpart because it does not consider forecasts of uncertain variables. Although the MPC algorithm considers the expected developments of uncertain variables, the results indicate that even in the certainty equivalent case, it fails to outperform its smart charging counterpart in reducing total costs. The summer simulations show that the certainty equivalent MPC V2H charging works better than both the rule-based and certainty equivalent MPC smart charging implementations. This is based on the assumption that the EV power conversion is 100% efficient, meaning that no energy is lost during charging or discharging.

Figure 3 presents the results of smart charging, which significantly reduces economic costs compared to uncontrolled charging during the summer season. Interestingly, the implementation of rule-based control for smart charging shows a greater economic cost decrease compared to the certainty-equivalent Model Predictive Control (MPC) implementation. However, when it comes to vehicle-to-home (V2H) charging, the rule-based approach performs less effectively than the certainty-equivalent MPC implementation.

It's important to note that the superiority of either rule-based control or certainty-equivalent MPC implementation varies across different seasons. We attribute this variation to the objective function of the MPC algorithm.

One way to potentially enhance the economic cost decrease of the MPC algorithm is by fine-tuning the weights in the objective function. By adjusting these weights, more emphasis can be placed on reducing economic costs rather than solely maximizing the state of charge (SOC) of the electric vehicle (EV) at the charging pole departure.

Furthermore, the mean values of uncertain variables in the MPC objective function, such as electricity prices and household loads, fluctuate throughout the year. These fluctuations impact the ratio between different costs in the objective function, subsequently affecting the optimization priorities.

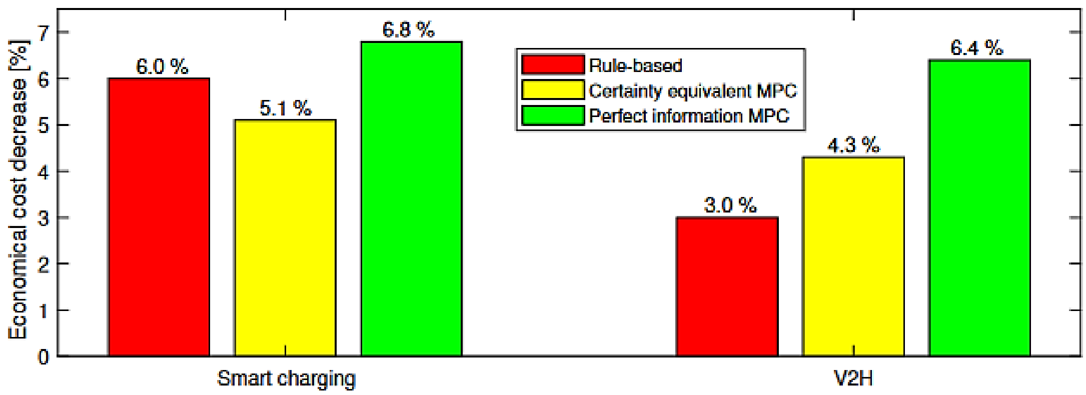

Figure 3. Summer Season Economic Savings with Controlled Charging

Conclusion

The study underscores the significance of PV technology in India's energy landscape and its potential to mitigate environmental impacts. It highlights the importance of advanced control algorithms, particularly MPC, in optimizing EV charging strategies to minimize household costs within microgrid systems. While smart charging demonstrates economic benefits, V2H charging offers additional savings during peak pricing periods. However, the effectiveness of control strategies varies across seasons, necessitating adaptive optimization methods. Future research should focus on refining control algorithms and considering dynamic factors to maximize the economic and environmental benefits of PV integration and EV charging in India's energy transition.

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