

Grid-Supportive Inverter Technologies for Power Quality Improvement

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Abstract. This paper offers a comprehensive review of grid-supportive inverter technologies aimed at enhancing power quality. One area of exploration presents a two-stage three-phase three-wire solar photovoltaic (SPV) system. This system utilises a boost converter for optimal power point tracking and a three-leg voltage source converter to channel the harnessed SPV energy. Distinctively, this approach provides harmonics elimination, grid current balancing, and compensation for the nonactive portion of load currents, going beyond traditional solar inverter functionalities. An innovative adjustable step adaptive neuron-based control method is employed to gauge the genuine power reflecting segment of the load current, ensuring swift dynamic adaptability to environmental shifts. Another focal point addresses the complexities introduced by the rising integration of microgrid systems within the AC distribution framework. Highlighting the imperative of maintaining voltage and frequency, the narrative accentuates the pivotal role of energy storage systems (ESS) for the proficient operation of sensitive loads. A grid adaptive power management strategy (GA-PMS) is proposed, orchestrating the current references for renewable energy sources, ESS, and microgrid-connected converters. This strategy guarantees uninterrupted microgrid functionality, priority-driven load shedding, and the maintenance of power quality standards at the local bus. Both areas significantly contribute to the evolution of grid-supportive inverter technologies and their potential in power quality betterment.

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1 Introduction

Electricity stands as a cornerstone of modern human existence, with its demand witnessing a relentless surge. Traditional fuels, once the stalwarts of electricity generation, are now dwindling, and their environmental ramifications have become a pressing concern. Consequently, the spotlight has shifted towards renewable energy systems, such as solar thermal, wind power, and notably, Solar Photovoltaic (SPV). SPV, in particular, is gaining traction, especially as it inches closer to grid parity.

Grid-connected solar PV systems, which eschew the need for battery energy storage, are becoming increasingly popular. These systems harness power directly from solar panels and feed it into the grid, eliminating the need for substantial energy storage. However, the nonlinear characteristics of solar PV mean that peak power can only be extracted at a unique voltage, necessitating sophisticated techniques like Maximum Power Point Tracking (MPPT). While some MPPT techniques, like the Perturb and Observe (P&O) method, are straightforward, they suffer from drawbacks such as poor dynamic response and oscillations near the Maximum Power Point (MPP).

On the other hand, the proliferation of nonlinear loads using power electronic converters is evident, given their high efficiency and compactness. Yet, they introduce harmonics that can wreak havoc on distribution systems, leading to issues like transformer derating, increased distribution losses, and distortion at the Common Connection Point (CCP). Solutions like the Distribution Static Compensator (D-STATCOM) have emerged to counter these power quality challenges. Furthermore, the integration of grid-supportive solar PV generation systems has been explored, with algorithms being developed to ensure seamless power transfer and quality.

The rapid integration of distributed energy resources (DERs) into traditional distribution networks poses challenges for the safe and consistent operation of power systems. The unpredictable nature of Renewable Energy Sources (RESs) combined with the erratic behaviour of loads can destabilise voltage and frequency profiles. This unpredictability underscores the importance of energy storage units, which can act as a temporary power source or sink, ensuring stability. The present review delves into these intricate dynamics, exploring the advancements in grid-supportive inverter technologies and their pivotal role in power quality enhancement.

The relevance of this study to our review article is manifold. As we navigate through an era of energy transition, the integration of renewable energy sources into the grid becomes not just an option but a necessity. Our review article aims to shed light on the advancements in grid-supportive inverter technologies that are instrumental in enhancing power quality. The two focal areas—solar photovoltaic systems with advanced control algorithms and the role of energy storage systems in microgrids—directly tie into the challenges and solutions outlined in the text. These areas are crucial for addressing the complexities of grid integration, power quality, and system reliability. By reviewing these advancements, we aim to provide a comprehensive understanding that could serve as a foundation for future innovations in this field. Thus, this study serves as a timely and pertinent contribution to the ongoing discourse on sustainable and reliable energy systems.

2 Review and discussion

In a study by Singh et al. (2017), the importance of grid-supportive solar photovoltaic (SPV) generation systems was highlighted, especially in relation to distributed SPV generation and the enhancement of power quality [1]. The study delved deeply into these systems, proposing a novel adjustable step adaptive neuron method for control, which was subsequently put to the test through practical experiments. The findings from the study are tabulated below for a comprehensive understanding [2-5]:

Table 1. Key insights from the study on grid-supportive SPV generation systems

Key Findings	Details	Additional Information
Grid Supportive SPV Generation System	A system was proposed that aimed at supporting the grid.	This system had the dual purpose of distributed SPV generation and the betterment of power quality.
Control Approach	The study introduced a novel adjustable step adaptive neuron method.	This method's efficacy was confirmed through hands-on experimentation.
Power Quality and Distribution Losses	The potential for a marked reduction in distribution losses was highlighted.	This reduction was attributed to the enhanced power quality with grid-supportive PV systems.
Case Study	A practical example within an academic institution's building was presented.	This detailed the potential reduction in distribution losses.
Savings from Local Generation	The study estimated a potential reduction in power loss due to local solar generation.	This equated to a saving of 31.34 kW.
Harmonics Mitigation Savings	The presence of harmonics in the system was identified as a concern.	By mitigating these harmonics, the study estimated a saving of 423,181.5 units over 25 years.
Night Time Harmonics Compensation	It was noted that 40% of the nonlinear load operates at night.	By compensating for these harmonics, potential units saved could amount to 169,272.6.
Commercial Savings	The average cost of a commercial unit was identified as INR 10.	With the multifunctional attributes of VSC, a potential saving of INR 8,886,801 over 25 years was projected.
Increase in VSC Rating	The study emphasised the benefits of a modest increase in the VSC rating.	An increase by 4.67% could notably reduce harmonic losses in the current system.

Singh et al. (2017)'s research serves as a cornerstone for our review article, shedding light

on the intricate balance between distributed SPV generation and power quality enhancement. The tabulated findings offer a nuanced understanding of how grid-supportive SPV systems can be optimised for multiple functionalities, including but not limited to, harmonic loss reduction and local power generation. These insights are particularly pertinent to our discussion on the evolution of sustainable energy systems and their integration into existing power grids.

Moreover, the study's focus on the financial viability of such systems, demonstrated through a detailed case study, aligns seamlessly with our review's objective to explore not just the technical but also the economic aspects of renewable energy solutions. The quantifiable benefits, such as the reduction in distribution losses and the subsequent financial savings, serve as compelling arguments for the broader adoption of these technologies.

In essence, the meticulous findings from Singh et al. (2017) enrich our review article by providing empirical evidence and practical examples, thereby substantiating our arguments for the multifunctional capabilities and economic benefits of grid-supportive SPV systems.

Another study conducted by Korada et al. (2016) delves deep into the complexities of grid-assistive systems and their behaviour under varied scenarios [6]. Here are the pivotal findings from this in-depth research:

- **Simulation Approach:** The researchers employed MATLAB/Simulink as their primary tool for simulation, aiming to assess the dynamic response and adaptability to frequency changes of the proposed GA-PMS.
- **Evaluation Criteria:** The simulations were executed under two specific frequency conditions, namely G-DPM and G-EPM. The Hybrid Energy Storage System (HESS) had its State of Charges (SoCs) deliberately adjusted, and power levels were modified to examine both surplus and deficit modes.
- **Performance Observations:**
 - Under the G-DPM setting, the system showcased a robust operation for both alternating and direct current loads amidst transient phases. The ultracapacitor units exhibited a dynamic reaction to abrupt load shifts, ensuring uninterrupted power transitions.
 - In the G-EPM setting, the system rigorously regulated the voltage with the aid of HESS. The ultracapacitor units remained consistently engaged, providing transient power throughout their operation.
- **Experimental Design:** A condensed experimental model was crafted, encompassing battery and ultracapacitor units, two-way converters, and a microgrid Voltage Source Converter (μ G-VSC).
- **Case Analysis:**
 - The research presented a triad of distinct scenarios to validate their control strategy. The initial scenario assessed the GA-PMS's behaviour under diverse operational conditions, the second delved into the smooth transition of modes under fluctuating grid frequencies, and the third scrutinised the battery and grid's dynamic performance across varied battery SoC states.
- **Efficiency Metrics:** Drawing from both simulated and hands-on experiments, the system's overall efficiency was gauged to lie between 81% and 91% [7-9].

In our review article, we aim to shed light on the advancements and intricacies of grid-assistive systems and their potential in modern energy landscapes. The study by Korada et

al. (2016) serves as a cornerstone in our research, offering a meticulous exploration of the dynamic behaviour of these systems under varied conditions. Their comprehensive simulation and experimental approaches provide a tangible blueprint, enabling us to understand the practical implications and real-world adaptability of such systems. By integrating their findings, we can present a more holistic view of the current state of grid-assistive technologies, their efficiencies, and their potential pitfalls. This not only enriches our review's content but also ensures that our readers are presented with a well-rounded perspective, grounded in empirical research.

3 Future scope of research

The realm of grid-assistive systems is rapidly evolving, with technological advancements paving the way for innovative solutions. As we transition towards a more sustainable and efficient energy landscape, it's imperative to explore the potential avenues that can shape the future of energy systems. Here are some promising directions for future research:

- **Integration with Emerging Technologies:** As technology evolves, there's potential to integrate grid-assistive systems with other emerging energy solutions, such as hydrogen fuel cells or advanced nuclear reactors, to create hybrid systems that maximise efficiency and sustainability.
- **Decentralised Energy Systems:** Investigate the feasibility of decentralised energy grids, where localised communities or regions generate and manage their own power, reducing transmission losses and increasing resilience against large-scale outages.
- **Advanced Energy Storage:** Delve into the development of next-generation energy storage solutions, beyond batteries and ultracapacitors, to enhance the efficiency and longevity of grid-assistive systems.
- **AI and Machine Learning:** Harness the power of artificial intelligence and machine learning to predict energy demand, optimise energy distribution, and enhance the adaptability of grid-assistive systems to changing conditions.
- **Environmental Impact Assessment:** Conduct comprehensive studies on the environmental footprint of large-scale deployment of grid-assistive systems, considering factors like resource extraction, system lifespan, and end-of-life disposal.
- **Economic Modelling:** Develop detailed economic models to understand the long-term financial viability of these systems, considering factors like initial investment, maintenance costs, and potential returns from energy sales.

4 Knowledge gaps

While the benefits and potential of grid-assistive systems are evident, there remain certain areas where our understanding is limited or nascent. Acknowledging these gaps is crucial, not just for academic pursuits but also for practical implementations and policy-making. Here are some of the key knowledge gaps that need attention:

- **Long-Term Durability:** While we have insights into the immediate benefits of grid-assistive systems, there's limited data on their long-term durability and performance over decades.

- **Interplay with Renewable Sources:** The dynamics between grid-assistive systems and varying renewable energy sources, such as wind or tidal energy, remain underexplored.
- **Regulatory Challenges:** There's a lack of comprehensive understanding regarding the regulatory and policy challenges that might arise with widespread adoption of these systems.
- **Socio-economic Impacts:** The broader socio-economic implications of transitioning to grid-assistive systems, especially in regions heavily reliant on traditional energy sources, are not yet fully understood.
- **Infrastructure Adaptability:** The adaptability of current infrastructure to accommodate advanced grid-assistive systems, without significant overhauls, remains a grey area.
- **Consumer Behaviour:** As these systems become more prevalent, there's a need to understand consumer behaviour better, especially in terms of energy consumption patterns and adaptability to new technologies.

By addressing these future research avenues and acknowledging the existing knowledge gaps, our review article can provide a comprehensive roadmap for scholars and industry professionals looking to delve deeper into the realm of grid-assistive systems.

5 Conclusion

As we draw our exploration to a close, it's evident that grid-assistive systems and their integration with renewable energy sources are pivotal for the future of sustainable energy. The intricate interplay of technology, environmental considerations, and economic feasibility has been the cornerstone of our review. Reflecting upon the insights gleaned from the studies we've dissected; the following key findings emerge:

- **Holistic Benefits:** Grid-assistive systems, especially when integrated with solar photovoltaic (SPV) setups, not only augment power generation but also significantly enhance power quality, as underscored by Singh et al.'s study.
- **Technological Advancements:** Advanced tools and methodologies, such as MATLAB/Simulink simulations, have proven instrumental in understanding the dynamic performance and adaptability of grid-supportive systems, as highlighted by Korada et al. (2016)
- **Energy Storage Evolution:** The role of hybrid energy storage systems, encompassing batteries and ultracapacitors, is paramount. Their ability to dynamically respond to sudden load changes and maintain grid stability is a game-changer for future energy systems.
- **AI and Predictive Analysis:** The potential of artificial intelligence in predicting energy demand and optimising distribution is vast, promising a future where energy systems are not only efficient but also highly adaptive.
- **Regulatory and Socio-economic Considerations:** As we transition to more sustainable energy solutions, understanding the regulatory landscape and socio-economic implications will be crucial for seamless integration and public acceptance.
- **Future Research Avenues:** While the current research provides a solid foundation, there's a vast expanse of uncharted territory, from exploring new energy storage solutions to understanding the long-term environmental impact of these systems.

In alignment with our review, these findings reiterate the significance of grid-assistive systems in the broader narrative of sustainable energy. As the world grapples with the dual challenges of energy demand and environmental conservation, the insights from our review offer a beacon of hope and direction. The journey towards a sustainable energy future is intricate, but with continuous research and innovation, it's a horizon within reach.

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