

Review Article

Demand-Side Management in Smart Grids Using Power Electronics Technologies: A Review

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A B S T R A C T

Demand-Side Management (DSM) is a crucial component of modern smart grids, enabling efficient energy utilization, load balancing, and grid stability while reducing operational costs and minimizing environmental impact. With the rapid growth of renewable energy sources (RES), the increasing penetration of electrified transportation, and the shift towards decentralized power generation, DSM strategies have become essential in ensuring a reliable and resilient power grid.

Power electronics technologies play a pivotal role in DSM by facilitating real-time load control, dynamic energy optimization, and seamless integration of distributed energy resources (DERs). This review explores the advancements in power electronic converters, energy storage systems (ESS), and demand response (DR) strategies, which collectively enhance DSM capabilities. Various converter topologies, such as bidirectional converters, multilevel inverters, and soft-switching techniques, are examined for their ability to optimize power flow and improve grid efficiency. Additionally, the integration of solid-state transformers (SSTs), hybrid energy storage systems, and vehicle-to-grid (V2G) technologies is discussed as enablers of an interactive and flexible demand-side infrastructure.

Furthermore, artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT)-based control strategies are emerging as key trends in DSM, enabling predictive analytics, adaptive demand response, and real-time grid optimization. These technologies enhance consumer participation, improve energy efficiency, and support autonomous decision-making in DSM programs.

This study highlights the impact of power electronics-driven DSM solutions on improving power quality, reducing peak demand, minimizing total harmonic distortion (THD), and ensuring grid resilience. The review also addresses challenges related to high implementation costs, cybersecurity risks, and the need for regulatory frameworks to support DSM adoption. Ultimately, the advancements in power electronics-based DSM contribute to the development of a sustainable, intelligent, and future-ready power network, paving the way for next-generation energy management solutions.

Keywords: Demand-Side Management (DSM), Electrified Transportation, Real-Time Load Control

Introduction

The evolution of power grids from traditional centralized generation systems to decentralized smart grids has introduced new challenges in energy management, grid stability, and load optimization. The increasing integration of renewable energy sources (RES), electric vehicles (EVs), and distributed energy resources (DERs) has further complicated the dynamics of electricity distribution and consumption. To address these challenges, Demand-Side Management (DSM) has emerged as a key strategy, focusing on controlling and optimizing electricity consumption at the consumer level to enhance grid efficiency and reliability.¹

DSM programs are designed to:

- Reduce peak demand and prevent grid overload by shifting or curtailing loads during high-demand periods.
- Enhance energy efficiency through optimized power consumption and improved load management strategies.
- Facilitate seamless integration of renewable energy sources (RES) while ensuring grid stability and reliability.
- Enable demand response (DR) programs, allowing consumers to adjust electricity usage based on real-time electricity prices, grid conditions, and incentive mechanisms.
- Support electrification initiatives, including the deployment of smart appliances, EV charging infrastructure, and industrial automation, to create a more responsive and efficient grid.

Power electronics technologies play a pivotal role in DSM by providing efficient energy conversion, real-time load control, and grid-interactive solutions. Traditional grid infrastructure relies on passive components for energy regulation, whereas modern power electronic devices—such as bidirectional converters, multilevel inverters, solid-state transformers (SSTs), and smart inverters—enable dynamic load control, voltage regulation, and power factor correction. These technologies facilitate the seamless integration of DERs, battery storage systems, and controllable loads into the grid, ensuring a flexible and adaptive energy network.²

Additionally, emerging technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) are being incorporated into DSM frameworks to enable real-time energy optimization, predictive analytics, and automated control mechanisms. Smart meters, IoT-enabled appliances, and AI-based forecasting tools allow both utilities and consumers to make data-driven energy decisions, further enhancing DSM effectiveness.

This review explores the contributions of power electronics-based solutions to DSM, focusing on:

- Advanced converter topologies for improved efficiency and controllability.

- Integration of energy storage systems to provide grid stability and load balancing.
- Intelligent control techniques leveraging AI and real-time monitoring for optimized DSM implementation. By examining these aspects, the study highlights the critical role of power electronics in shaping the next generation of smart, flexible, and energy-efficient power grids.³

Power Electronics Technologies for DSM

Power electronics technologies play a crucial role in demand-side management (DSM) by enabling flexible, real-time control of electrical loads and energy flow within smart grids. These technologies provide high-efficiency energy conversion, grid stabilization, and intelligent power management, ensuring optimal utilization of distributed energy resources (DERs). Several key innovations contribute to enhancing DSM capabilities by improving power quality, reducing transmission losses, and supporting renewable energy integration.⁴

Power Electronic Converters

Converters form the backbone of power electronics-based DSM by facilitating energy conversion, voltage regulation, and dynamic grid interaction. Advanced power converters help in optimizing power flow, managing bidirectional energy exchange, and ensuring stable operation under varying load conditions. Commonly used converter topologies in DSM include:

- **Bidirectional DC-DC Converters:** Essential for integrating energy storage systems (ESS), these converters enable efficient power exchange between batteries, the grid, and connected loads, allowing dynamic energy management and peak load shifting.
- **Multilevel Converters:** Provide high power quality, lower switching losses, and reduced total harmonic distortion (THD), making them ideal for grid-connected renewable energy systems, electric vehicle (EV) chargers, and industrial DSM applications.
- **Solid-State Transformers (SSTs):** Act as intelligent energy routers, optimizing power flow across different voltage levels and enhancing grid flexibility, fault isolation, and demand response capabilities. SSTs also enable high-frequency operation, reducing transformer size and improving efficiency.
- **Matrix Converters:** Enable direct AC-AC power conversion without requiring a DC-link capacitor, reducing component size and improving system efficiency and reliability in DSM applications.⁵

Smart Inverters

Modern grid-interactive inverters equipped with advanced control algorithms play a critical role in DSM by:

- Enabling real-time load shifting and voltage regulation to manage power demand dynamically.
- Supporting reactive power compensation to enhance grid stability and power factor correction, reducing system-wide energy losses.
- Facilitating seamless integration of distributed generation (DG) sources, such as solar PV and wind turbines, into the grid.
- Integrating demand response (DR) functionalities, allowing appliances and industrial loads to adjust power consumption dynamically in response to electricity prices and grid conditions.
- Enhancing islanding detection and microgrid operation, ensuring uninterrupted power supply during grid disturbances.⁶

Energy Storage Systems (ESS)

Energy storage plays a pivotal role in DSM by balancing supply and demand, reducing peak loads, and enhancing grid resilience. Power electronics technologies enable efficient energy storage integration, ensuring reliable charging, discharging, and power conversion. Some key ESS technologies used in DSM include:

- **Lithium-Ion Battery Systems:** Widely used in residential, commercial, and industrial DSM programs, offering high energy density, fast response times, and long cycle life for peak shaving and load leveling applications.
- **Supercapacitors:** Provide rapid energy buffering to mitigate short-term power fluctuations and stabilize voltage variations, making them suitable for grid frequency regulation and high-power demand applications.
- **Flywheel Energy Storage:** Offers high-speed energy discharge, providing an effective solution for grid frequency stabilization, voltage support, and emergency power backup.
- **Hydrogen-Based Energy Storage:** Emerging as a promising long-term storage solution, enabling power-to-gas (P2G) conversion, where excess renewable energy is converted into hydrogen for later use in fuel cells or power generation.
- **Pumped Hydro Storage:** Although mainly used at the utility scale, advances in modular hydro storage systems enable its application in localized DSM programs to support energy balancing and load-following capabilities.⁷

Role of Power Electronics in Grid-Interactive DSM

The integration of power electronics with DSM strategies enables:

- Dynamic load regulation through voltage and frequency control.
- Seamless integration of decentralized energy resources (DERs) into smart grids.

- Automated peak shaving and valley filling to reduce grid congestion.
- Real-time optimization of energy demand, improving overall system efficiency.
- Grid-to-vehicle (G2V) and vehicle-to-grid (V2G) interactions, allowing electric vehicles to participate in DSM.

With continuous advancements in semiconductor technologies, digital controllers, and AI-driven predictive analytics, power electronics is set to play an even greater role in enhancing demand-side management capabilities in next-generation smart grids.⁸

Demand Response Strategies in DSM

Demand Response (DR) is a critical component of Demand-Side Management (DSM) that enables flexible load control based on real-time grid conditions, energy prices, and power availability. By dynamically adjusting energy consumption patterns, DR helps utilities maintain grid stability, reduce peak demand, and integrate renewable energy sources efficiently.

Power electronics technologies play a key role in DR implementation by providing precise control over load variations, improving energy efficiency, and enabling seamless communication between consumers and the grid. Advanced DR strategies leverage smart meters, IoT-enabled appliances, and AI-driven automation to optimize energy usage in residential, commercial, and industrial sectors.⁹

Direct Load Control (DLC)

Direct Load Control (DLC) is a real-time DR mechanism that allows utilities to adjust controllable loads remotely to balance supply and demand dynamically. Power electronics technologies enable DLC by integrating real-time monitoring, load modulation, and automated control systems. Some key applications of DLC include:

- **Smart HVAC Systems:** Heating, ventilation, and air conditioning (HVAC) units equipped with power electronics-based controllers adjust temperature settings based on grid demand, weather conditions, and occupancy patterns, improving energy efficiency while reducing peak load stress.
- **Electric Vehicle (EV) Charging Stations:** Smart EV chargers adapt charging rates dynamically based on grid load, energy availability, and dynamic pricing signals, ensuring optimized charging schedules that prevent overloading the power system.
- **Industrial Motors and Variable-Speed Drives (VSDs):** Power electronics-controlled variable-frequency drives (VFDs) and motor control units regulate industrial loads to reduce energy consumption during peak demand hours, improving operational efficiency.

- **Smart Appliances:** Devices such as washing machines, refrigerators, and water heaters equipped with intelligent load control systems modify their operation to align with grid availability and electricity pricing signals.
- **Microgrid Integration:** Power electronics coordinate load sharing between microgrids and the main grid, ensuring optimal energy distribution during peak periods.

By enabling automated and remote load management, DLC strategies help utilities and consumers reduce electricity costs, enhance energy efficiency, and improve grid stability.¹⁰

Price-Based Demand Response

Price-Based Demand Response (PBDR) utilizes dynamic electricity pricing to encourage consumers to shift their energy usage from peak periods to off-peak hours, optimizing overall grid performance. Power electronics technologies, in combination with smart metering infrastructure and AI-driven energy management, facilitate automated responses to real-time electricity price variations.

Key pricing strategies include:

- **Time-of-Use (TOU) Pricing:** Consumers pay different electricity rates depending on predefined time slots, incentivizing them to shift energy-intensive activities to lower-cost periods.
- **Real-Time Pricing (RTP):** Electricity prices fluctuate based on real-time demand-supply conditions, allowing responsive consumers to adjust their energy consumption dynamically.
- **Critical Peak Pricing (CPP):** Utilities apply higher charges during extreme peak demand events, motivating consumers to reduce consumption during critical periods.
- **Peak Time Rebates (PTRs):** Consumers are rewarded for voluntarily reducing their energy usage during peak hours, promoting grid-friendly energy consumption behaviors.

Power electronics-enabled smart meters, automated demand controllers, and home energy management systems (HEMS) play a crucial role in executing price-based DR by:

- Communicating real-time electricity prices to consumers and energy management systems.
- Automatically adjusting power consumption of smart appliances and industrial loads.
- Coordinating load scheduling based on electricity tariffs and grid conditions.
- Integrating distributed energy resources (DERs) to optimize self-consumption and minimize costs.

By leveraging price-based DR, utilities can reduce peak loads, enhance energy efficiency, and integrate renewables seamlessly, while consumers benefit from lower electricity bills and improved energy management.¹¹⁻¹⁵

AI and Machine Learning-Based Demand Response

The integration of Artificial Intelligence (AI) and Machine Learning (ML) into DR strategies revolutionizes DSM by enabling self-learning, predictive analytics, and real-time energy optimization. AI-driven demand response leverages big data, IoT sensors, and advanced control algorithms to automate and optimize energy consumption decisions.

Key AI and ML applications in DR include:

Predicting Load Patterns: AI models analyze historical energy consumption data, weather forecasts, and user preferences to predict demand patterns and suggest optimal energy usage schedules.

- **Real-Time Grid Optimization:** ML algorithms dynamically adjust power consumption, storage dispatch, and load balancing based on grid conditions, preventing overloads and ensuring stable operation.
- **Adaptive Control Strategies:** AI-driven DSM systems continuously learn from consumer behavior and grid interactions, refining energy management strategies for maximized efficiency.
- **Autonomous Demand Response:** AI-enabled smart controllers automatically adjust household and industrial loads in response to real-time electricity price signals, peak demand alerts, and renewable energy availability.
- **Blockchain-Based DR Transactions:** AI and blockchain technologies enable secure peer-to-peer (P2P) energy trading, allowing consumers to buy and sell electricity dynamically based on real-time demand and supply conditions.

With AI-powered demand response, DSM systems can:

- Enhance load forecasting accuracy, enabling better planning for utilities.
- Increase automation levels, reducing the need for manual intervention.
- Improve grid resilience, ensuring efficient handling of peak demand events and renewable energy fluctuations.
- Reduce electricity costs for consumers while enhancing overall system efficiency.

Role of Power Electronics in Demand Response

Power electronics plays a crucial role in enabling and optimizing DR strategies by:

- Ensuring fast load response times through intelligent converters and controllers.
- Providing real-time voltage and frequency regulation for stable grid operation.
- Facilitating bidirectional energy flow between DERs, storage systems, and the grid.
- Enhancing efficiency in automated demand-side control systems, reducing energy waste.

- Integrating renewable energy sources seamlessly into DR programs.¹⁶

Applications of Power Electronics-Based DSM

The integration of power electronics with DSM is transforming multiple sectors, including:

Residential Energy Management

- Smart home automation systems use PFC-based converters to optimize energy consumption.
- Home battery storage and solar PV inverters enhance self-consumption and peak shaving.

Industrial Load Management

- Adjustable speed drives (ASDs) optimize industrial motors for energy savings.
- Power quality conditioners ensure stable voltage and harmonic mitigation.

Electric Vehicle (EV) Integration

- Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) systems allow EVs to act as distributed energy resources.
- Fast-charging stations with bidirectional converters support grid balancing.

Renewable Energy Grid Integration

- Smart inverters for PV and wind power ensure seamless DSM participation.
- Hybrid energy storage systems provide backup power and frequency regulation.

Challenges and Future Trends

Despite the benefits of power electronics-based DSM, several challenges remain:

- High Initial Costs – Advanced converters and smart inverters involve high capital investment.
- Grid Compatibility Issues – DSM solutions must be compatible with existing grid infrastructure and communication protocols.
- Cybersecurity Risks – Increased connectivity introduces vulnerabilities to cyberattacks and data breaches.

Future Trends

- Wide-Bandgap (WBG) Semiconductors – Silicon Carbide (SiC) and Gallium Nitride (GaN) technologies are improving the efficiency and power density of DSM solutions.
- Blockchain-Based Energy Trading – Decentralized energy markets are emerging, enabling peer-to-peer (P2P) electricity exchange.
- 5G and IoT-Enabled Smart Grids – Ultra-fast data communication enhances real-time DSM decision-making.

Conclusion

Power electronics technologies are revolutionizing Demand-Side Management (DSM) by providing flexible, intelligent, and highly efficient energy control solutions in modern smart grids. With the increasing complexity of electric power systems and the rapid adoption of distributed energy resources (DERs), DSM has emerged as a key enabler of grid stability, load optimization, and energy efficiency. The integration of bidirectional converters, solid-state transformers (SSTs), smart inverters, and AI-driven demand response (DR) strategies has significantly enhanced the ability of power grids to balance supply and demand dynamically while reducing peak loads and improving overall power quality.

Furthermore, the synergy between power electronics and digital technologies has enabled the real-time monitoring, control, and automation of energy usage. Advanced energy storage systems (ESS), such as lithium-ion batteries, supercapacitors, and flywheels, have further strengthened DSM by providing fast-response energy buffering and grid stabilization capabilities. Additionally, AI and machine learning algorithms have introduced self-learning, adaptive demand-side management techniques, optimizing energy consumption based on predictive analytics, pricing signals, and user behavior. These developments have empowered consumers to actively participate in DSM programs, ensuring a more interactive, cost-effective, and sustainable power grid.

As renewable energy penetration increases and the electrification of transportation accelerates, the role of power electronics in DSM will continue to expand. Future advancements will focus on:

- Cost-effective and highly efficient power electronic converters to reduce system losses and enhance performance.
- Cybersecurity measures to protect DSM infrastructure from potential cyber threats and ensure secure communication between smart grid components.
- AI-integrated energy management platforms capable of autonomously optimizing demand-side operations and providing real-time adaptive control based on grid conditions and energy prices.
- Scalable DSM solutions that can accommodate the evolving energy landscape, including electric vehicle-to-grid (V2G) systems, community energy storage, and microgrid-based DSM.

By addressing these challenges and leveraging emerging power electronics innovations, DSM can pave the way for a more resilient, sustainable, and intelligent energy future.

The continued integration of smart grid technologies, AI-driven analytics, and energy-efficient power electronics will be crucial in achieving global energy sustainability goals while ensuring grid reliability and economic efficiency.

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