IAES Journal of Electrical and Electronics Engineering
Vol. 12, No. 1, June 2025, pp. 7~12
ISSN: 2338-7432, DOI: 10.11591/jeee.v12i1.pp7-12

Smart plugs for industrial and laboratory equipment management: a review of equipment monitoring, operational scheduling, and load coordination

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Article Info

Article history:

Received Sep 22, 2022
Revised Jul 7, 2023
Accepted Jan 11, 2024

Keywords:

Equipment monitoring
Industrial energy management
Laboratory equipment
Load coordination
Operational scheduling
Smart plugs

ABSTRACT

Industrial and laboratory facilities operate diverse electrical equipment with different power demands, operating schedules, and availability requirements. Conventional energy monitoring often provides limited visibility into the consumption of individual devices, making it difficult to identify unnecessary operation, standby losses, and opportunities for coordinated load management. Smart plugs offer a practical device-level interface for measuring electrical parameters, transmitting operating data, and remotely controlling compatible equipment. This review examines their potential contribution to equipment monitoring, operational scheduling, and electrical load coordination in industrial and laboratory environments. The discussion integrates research on smart plugs, industrial smart metering, energy monitoring, demand response, and energy-aware production scheduling published up to 2021. Particular attention is given to equipment-level measurement, operating-state identification, time-based control, peak-demand reduction, and communication with centralized energy management platforms. The review also identifies technical limitations involving electrical ratings, measurement accuracy, communication reliability, cybersecurity, and process safety. The findings indicate that smart plugs can support more transparent and coordinated electricity use, provided that their deployment is matched to equipment characteristics and integrated with appropriate industrial protection and control systems.

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1. INTRODUCTION

Industrial facilities and laboratories use a wide range of electrical equipment, including computers, test instruments, pumps, fans, heaters, compressors, and auxiliary machines. Their electricity consumption is influenced not only by rated power but also by operating duration, standby conditions, experimental requirements, and production schedules. In many facilities, energy measurements are collected at the building or distribution-panel level, making it difficult to identify the contribution of individual devices. Device-level monitoring can therefore provide information needed to improve energy efficiency, identify abnormal consumption, and support operational decisions [1], [2].

Smart plugs provide a potential solution by combining electrical measurement, switching, and communication functions in a compact device. Depending on their design, they can measure voltage, current,

active power, and accumulated energy while transmitting measurements to a gateway or management platform. Their switching capability can also support remote operation and scheduled disconnection of compatible loads. Research on distributed smart-plug monitoring and industrial smart metering provides a technical foundation for extending these capabilities beyond residential applications [1]–[4].

However, industrial and laboratory deployment involves requirements that differ substantially from ordinary household use. Equipment may have high starting currents, inductive loads, sensitive electronic components, continuous operating requirements, or safety-critical functions. A smart plug that is suitable for a low-power office device may be inappropriate for a laboratory oven, industrial motor, or high-power instrument. This review therefore examines the opportunities and limitations of smart plugs as components of a broader equipment and energy management system.

2. SMART-PLUG ARCHITECTURE AND MANAGEMENT FUNCTIONS

A smart-plug management system generally consists of a measurement and switching unit, a communication interface, a data-processing platform, and a user interface. The measurement unit records electrical parameters, while the switching element enables authorized control of the connected equipment. Communication technologies transfer measurement data and control commands to local gateways or centralized platforms. Such architectures are consistent with distributed smart-plug monitoring and internet of things (IoT)-based energy management approaches [2]-[4].

The principal contribution of a smart plug is the provision of equipment-level information that can be associated with a particular device or operational task. This information can help facility managers distinguish between productive consumption, standby consumption, and unexpected operating patterns. When several smart plugs are deployed, their measurements can be aggregated to describe the energy profile of a laboratory room, production area, or equipment group. Industrial smart-metering research similarly emphasizes the value of detailed consumption information for identifying efficiency opportunities and improving operational decisions [1], [5].

A practical implementation should connect smart plugs to an energy management platform rather than treat each device as an isolated control point. The platform can store measurements, display equipment status, generate reports, and apply scheduling rules. It may also exchange information with building management systems or industrial supervisory platforms through suitable communication interfaces. This architecture creates an opportunity to coordinate device-level actions with broader facility requirements [6], [7].

3. EQUIPMENT MONITORING IN LABORATORIES AND INDUSTRIAL FACILITIES

Equipment monitoring is one of the most direct applications of smart plugs because electrical consumption provides an observable indication of equipment activity. Measurements of power and energy can reveal operating duration, idle periods, and differences between expected and actual consumption. For example, laboratory computers, oscilloscopes, electronic test instruments, and auxiliary equipment may continue consuming electricity after experiments have finished. Monitoring these devices can help identify avoidable energy use and establish more accurate equipment utilization records [2], [8].

In industrial environments, equipment-level power data can support energy reporting, optimization, fault detection, and predictive maintenance investigations. Changes in electrical consumption may indicate altered operating conditions, increased mechanical resistance, or an unexpected process state. Henning et al. demonstrated the value of analyzing power consumption data at machine level and identified real-time processing, multi-level monitoring, anomaly detection, forecasting, and visualization as useful analytical measures [9]. Nevertheless, electrical consumption alone cannot reliably diagnose every mechanical or electrical fault, so smart-plug measurements should be interpreted alongside equipment sensors and process information.

Monitoring also supports equipment inventory and utilization management. A facility can associate each smart plug with an equipment identifier, location, rated capacity, and responsible department. The resulting records can help identify devices that are frequently unused, operated outside approved periods, or responsible for unusually high energy consumption. These functions are particularly relevant to laboratories where equipment is shared between research groups and where usage patterns may vary considerably throughout the week [5], [9].

4. OPERATIONAL SCHEDULING AND AUTOMATED CONTROL

Operational scheduling determines when electrical equipment should be switched on, maintained in standby, or disconnected. Smart plugs can implement simple schedules based on working hours, laboratory

access periods, production shifts, or predefined experimental requirements. Such scheduling is most suitable for equipment whose operation can be interrupted without affecting safety, measurement integrity, or production continuity. Building energy management research demonstrates that scheduling, optimization, and model predictive control can contribute to improved energy management when operational constraints are properly considered [6], [10].

In laboratories, scheduling can be applied to non-critical auxiliary equipment such as selected lighting systems, computers, display devices, and peripheral instruments. A laboratory management platform could automatically disconnect approved devices after working hours while preserving power to equipment requiring continuous operation. For example, a temperature-controlled storage unit or long-duration experiment must not be switched off merely because a general shutdown schedule has started. Equipment classification and user authorization are therefore essential elements of safe scheduling.

Industrial scheduling requires a closer relationship between electricity management and production planning. Some equipment can be operated during lower-demand periods, while other machines must follow production sequences, material availability, and process constraints. Research on energy-efficient production scheduling shows that energy objectives can be incorporated into manufacturing decisions without treating electricity consumption as an isolated problem [11], [12]. Smart plugs may support this approach for compatible auxiliary loads, but major production machinery generally requires appropriately rated industrial control equipment rather than plug-level switching.

5. ELECTRICAL LOAD COORDINATION AND DEMAND MANAGEMENT

Load coordination involves managing several electrical devices so that their combined demand remains within operational or electrical limits. When multiple devices start simultaneously, their combined demand may create short-duration peaks or increase the maximum demand recorded during a billing period. Smart plugs can provide the individual load measurements needed to identify such events and coordinate selected loads. Industrial demand response research highlights the importance of flexibility, monitoring, and control while emphasizing that industrial reliability and production continuity must remain protected [13], [14].

A coordinated system can classify equipment into priority groups according to operational importance. Essential equipment may remain continuously supplied, while flexible auxiliary loads can be delayed or temporarily disconnected when the facility approaches a predefined demand threshold. The management platform can use measurement data and operating schedules to determine which devices are eligible for load shifting. This approach is consistent with demand-side management and optimal load scheduling methods discussed in the smart-grid literature [15], [16].

Table 1 summarizes the principal applications of smart plugs in industrial and laboratory environments. It links the management objective to representative equipment, the relevant smart-plug function, and the expected operational benefit. The table also distinguishes between monitoring applications and switching actions that require explicit operational approval. This distinction is important because the ability to measure a device does not automatically mean that the device can be safely switched remotely.

Table 1. Potential smart-plug applications in industrial and laboratory equipment management

Management objective	Representative equipment	Smart-plug function	Potential benefit
Energy monitoring	Computers, test instruments, auxiliary devices	Power and energy measurement	Device-level consumption visibility
Utilization monitoring	Laboratory instruments, workshop equipment	Operating-time and energy logging	Identification of idle or underused equipment
Standby reduction	Displays, office equipment, selected peripherals	Scheduled disconnection	Reduction of unnecessary standby consumption
Operational scheduling	Compatible auxiliary equipment	Time-based switching	Better alignment with working schedules
Peak-demand management	Flexible auxiliary loads	Coordinated switching and load prioritization	Reduction of avoidable simultaneous demand
Anomaly identification	Pumps, fans, selected machines	Consumption trend analysis	Early indication of unusual operating patterns
Energy reporting	Equipment groups and laboratory rooms	Data aggregation and visualization	Improved energy accountability

6. COMMUNICATION, DATA ANALYTICS, AND SYSTEM INTEGRATION

Communication is essential because the value of smart plugs increases when measurements can be accessed by a shared management platform. Depending on the deployment environment, communication may use Wi-Fi, Ethernet, Zigbee, or other suitable wireless and wired technologies. The selection should consider

coverage, interference, latency, network security, and the number of connected devices. Research on IoT-based energy management and smart energy monitoring identifies communication and data-processing infrastructure as important components of intelligent energy systems [3], [17].

Data analytics can convert raw measurements into information that supports operational decisions. Descriptive analysis can summarize energy consumption, while forecasting can estimate future demand and anomaly detection can identify unusual operating patterns. Smart-meter data analytics research organizes these capabilities around load analysis, forecasting, and load management [18]. In industrial environments, multi-level monitoring and real-time processing can further connect device-level measurements with production areas and facility-wide energy performance [9].

Integration should also consider the existing building management system and industrial automation infrastructure. Smart plugs can serve as supplementary monitoring and control points, while supervisory systems retain responsibility for process sequencing, interlocks, and safety-related control. Standardized data exchange and consistent equipment identification can reduce fragmentation between monitoring platforms. This arrangement allows smart plugs to contribute useful information without replacing established industrial automation systems [7], [9].

7. TECHNICAL CHALLENGES AND IMPLEMENTATION CONSIDERATIONS

Electrical compatibility is a fundamental requirement for smart-plug deployment. Each device must be selected according to rated voltage, current, switching capacity, load type, and expected operating conditions. Motor-driven equipment and other inductive loads may produce starting currents that exceed normal operating values, while some electronic devices have specific power-quality or uninterrupted-supply requirements. Consequently, smart plugs should not be used with equipment whose electrical characteristics exceed the manufacturer's specifications or whose operation requires dedicated industrial switching and protection devices [19], [20].

Measurement accuracy is another important consideration because poor-quality data can lead to incorrect scheduling and misleading energy reports. Calibration, measurement resolution, sampling frequency, and long-term stability should be evaluated before measurements are used for operational decisions. Communication interruptions can also prevent timely delivery of measurements or switching commands. Local fallback rules and safe default operating states are therefore necessary, particularly when equipment operation must not depend on continuous cloud connectivity.

Cybersecurity and access control become increasingly important as the number of connected devices grows. Unauthorized switching, weak authentication, and insecure communication can create operational disruptions or expose facility information. A deployment should therefore use controlled device enrollment, secure communication, role-based permissions, and event logging. Industrial energy management studies also indicate that successful implementation requires organizational processes and management commitment, not merely the installation of monitoring hardware [12], [17].

8. RESEARCH GAPS AND FUTURE DIRECTIONS

A major research gap concerns the limited number of studies that directly evaluate smart plugs under industrial and laboratory operating conditions. Much of the relevant literature addresses smart metering, distributed monitoring, building energy management, and industrial demand response rather than plug-level deployment on specific equipment. Future research should therefore conduct controlled experiments in laboratories, workshops, and production facilities to evaluate measurement accuracy, switching reliability, communication performance, and long-term durability. Such studies should also compare smart-plug measurements with calibrated reference instruments and existing energy meters.

Another important direction is the development of equipment-aware scheduling and load coordination. Rather than switching devices solely according to fixed time schedules, future systems could consider equipment priority, operating state, production requirements, experimental duration, and electricity demand. Machine learning and predictive analytics may help identify consumption patterns and recommend more appropriate operating schedules. However, automated decisions should remain subject to user authorization and safety constraints, particularly when connected equipment supports experiments or industrial processes [9], [11], [18].

Future deployments should also examine interoperability and scalable system architecture. A large facility may contain equipment from different manufacturers, communication technologies, and automation platforms. Common data models and reliable interfaces would simplify the integration of smart plugs into facility-wide energy management systems. Research should ultimately evaluate not only electricity savings but also equipment availability, operational productivity, maintenance implications, cybersecurity, and lifecycle cost.

9. CONCLUSION

Smart plugs offer a practical opportunity to improve the visibility and management of electrical equipment in industrial and laboratory environments. Their principal contributions include device-level energy monitoring, operating-time analysis, scheduled control of compatible loads, and the provision of data for coordinated demand management. When integrated with centralized platforms, these functions can help identify unnecessary consumption, improve equipment utilization, and support more informed operational decisions. Their value is therefore greatest when they form part of a broader energy management architecture rather than operate as isolated switching devices.

However, successful implementation depends on careful equipment selection, accurate measurement, reliable communication, cybersecurity, and appropriate operational rules. Smart plugs should be restricted to compatible loads and must not replace certified electrical protection, industrial motor controls, emergency systems, or safety interlocks. Future research should prioritize field validation in laboratories and industrial facilities, with particular attention to equipment-aware scheduling and coordinated load control. With these safeguards, smart plugs can become useful supplementary components in the development of more efficient, observable, and intelligently managed electrical facilities.

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