Energy Efficiency and Operational Reliability of Motor Control Centres in Industrial Manufacturing Plants

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Abstract

This review examines the relationship between electrical energy performance and operational dependability in motor control centres serving industrial manufacturing plants. It aims to identify the principal determinants of energy consumption and equipment failure, evaluate established improvement practices, and assess the potential of emerging monitoring and automation technologies. A structured narrative synthesis of technical standards and published research through 2022 was organised around control centre architecture, industrial loading conditions, electrical protection, efficiency optimisation, maintenance, and digital innovation.

The review identifies motor oversizing, inappropriate operating schedules, inefficient speed regulation, voltage disturbances, deteriorating electrical connections, and inadequate maintenance as important contributors to avoidable energy use and production disruption. Appropriate motor and drive selection, feeder-level metering, coordinated protection, and load-responsive control can improve performance when matched to actual process requirements. Condition monitoring, thermal inspection, and reliability-centred maintenance provide complementary means of detecting deterioration and prioritising interventions before equipment failure. Intelligent sensors, predictive analytics, and digital twins offer further opportunities for integrating energy management with asset reliability, although their implementation depends on data quality, cybersecurity, technical expertise, and investment capacity.

The review concludes that efficiency and reliability should be assessed jointly rather than managed as separate operational objectives. It recommends periodic energy audits, documented protection coordination, systematic condition assessment, workforce training, and phased adoption of interoperable monitoring systems. Particular attention should be given to facilities facing unstable electricity supplies and constrained maintenance resources. Future plant-based studies should quantify energy savings, downtime reduction, lifecycle costs, and safety outcomes using

comparable performance indicators, thereby strengthening evidence-based investment decisions and sustainable industrial manufacturing practice.

Keywords: Motor Control Centres; Energy Efficiency; Operational Reliability; Industrial Manufacturing; Predictive Maintenance; Intelligent Motor Control.

DOI: 10.18091/ijsts.v6i1.09

1. Introduction

1.1 Background of Industrial Motor Control Systems

Industrial motor control systems constitute an essential component of modern manufacturing infrastructure, providing the electrical coordination required to operate machinery, regulate production processes, and sustain continuous industrial activities. Electric motors drive numerous manufacturing applications, including conveyor systems, pumps, compressors, mixers, ventilation equipment, and material-handling installations. Their substantial contribution to industrial electricity demand makes effective control and energy management critical considerations in manufacturing operations. Waide and Brunner (2011) established the considerable global electricity consumption associated with motor-driven systems, demonstrating the importance of improving their efficiency through coordinated technological and operational interventions.

Motor Control Centres (MCCs) provide centralised assemblies through which electrical power is distributed, controlled, and protected across multiple motor-driven applications. Conventional MCCs typically incorporate busbars, circuit breakers, fuses, contactors, overload relays, motor starters, and associated control equipment. These components facilitate equipment isolation, motor starting, operational switching, and protective responses to abnormal electrical conditions. The IEEE (2014) established important guidance concerning MCC design and electrical safety, emphasising appropriate equipment configuration, protective arrangements, and practices intended to reduce electrical hazards. Such considerations are particularly important in manufacturing facilities where equipment availability and personnel safety directly influence operational continuity.

The historical development of motor control technology reflects the transition from predominantly electromechanical switching arrangements towards increasingly sophisticated electronic and automated systems. Traditional contactor-based control provides comparatively straightforward motor operation, whereas modern configurations can incorporate programmable logic controllers,

soft starters, variable-frequency drives, and industrial communication interfaces. Sunday and Omoegun (2022) examined integrated industrial automation through Siemens Totally Integrated Automation Portal, highlighting the importance of coordinated control engineering, system interoperability, and real-time operational monitoring. These developments provide a technological foundation for integrating MCCs into wider industrial automation networks.

Energy efficiency represents another major consideration in the evolution of motor control systems. Conventional fixed-speed motor operation can lead to avoidable energy consumption when mechanical output substantially exceeds process requirements. Variable-frequency drives provide opportunities to regulate motor speed according to changing operational demands, particularly in suitable pump and fan applications. Du Plessis, Liebenberg and Mathews (2013) demonstrated the energy-saving potential of variable-speed technology within South African mine cooling installations, illustrating how improved motor control can reduce electricity consumption while maintaining operational requirements.

Alongside efficiency, the operational reliability of MCCs depends on the integrity of electrical connections, protective devices, insulation systems, and environmental operating conditions. Deteriorating components, excessive temperatures, inadequate maintenance, and electrical disturbances can compromise equipment performance and increase the probability of unplanned shutdowns. Bugaris and Doan (2014) investigated variations in arc-flash incident energy across low-voltage MCC configurations, demonstrating the significance of internal equipment arrangements for electrical hazard exposure. Their findings reinforce the necessity of incorporating safety considerations into MCC design and operational assessment.

Technological improvements have also expanded opportunities for identifying developing faults before catastrophic equipment failure occurs. Advanced monitoring techniques can detect electrical abnormalities associated with insulation degradation and thermal deterioration, supporting proactive maintenance interventions. Kay et al. (2016) examined preemptive arc-fault detection methods involving sensor technologies and signal processing, establishing the relevance of early fault identification to the protection of industrial electrical equipment. Similarly, Seera et al. (2014) demonstrated the potential of intelligent condition-monitoring approaches for identifying induction motor abnormalities, strengthening the technological basis for predictive equipment maintenance.

The increasing convergence of automation, instrumentation, and industrial data analytics is consequently reshaping expectations concerning motor control performance. Kusiak (2018) identified intelligent monitoring, interconnected production assets, and predictive engineering as important characteristics of smart manufacturing. Within MCC applications, these developments create opportunities for continuous operating-condition assessment, improved maintenance decisions, and closer coordination between electrical control infrastructure and production requirements. The historical progression of industrial motor control systems therefore provides an

essential foundation for examining how energy efficiency and operational reliability can be jointly addressed within contemporary manufacturing plants.

1.2 Energy Consumption in Industrial Manufacturing Plants

Energy consumption in industrial manufacturing plants constitutes a fundamental determinant of production efficiency, operating expenditure, and equipment sustainability. Manufacturing operations depend extensively on electricity to power motor-driven machinery, automated production lines, material-handling equipment, ventilation systems, and auxiliary installations. Within these environments, Motor Control Centres (MCCs) coordinate electrical distribution and motor operation, making their configuration and control performance important considerations in managing industrial electricity demand. Saidur (2010) examined industrial motor energy consumption and identified motor efficiency, operating conditions, power-factor improvement, and variable-speed applications as important opportunities for reducing avoidable electrical losses.

Industrial electricity demand varies considerably according to manufacturing processes, production capacity, operating schedules, and equipment utilisation. Continuous-process facilities generally exhibit sustained electrical demand, whereas batch manufacturing operations experience fluctuations associated with machine starting, intermittent loading, and production transitions. These variations influence motor loading, distribution requirements, and the effectiveness of energy-management interventions. Renna and Materi (2021) examined energy efficiency and sustainability across manufacturing systems, emphasising the importance of integrating energy considerations into production planning, operational scheduling, and resource management.

The contribution of motor-driven equipment to industrial energy expenditure also necessitates systematic assessment of electrical and mechanical inefficiencies. Oversized motors, inefficient operating practices, deteriorating components, and inappropriate control strategies can increase electricity consumption without producing corresponding improvements in manufacturing output. Trianni, Cagno, and Accordini (2019) classified motor-system efficiency measures into equipment improvements, drive technologies, plant-level management, and power-quality interventions. These considerations are particularly relevant to MCC-managed installations, where coordinated starting, switching, protection, and speed regulation influence the operating characteristics of connected motors.

Manufacturing energy consumption additionally reflects broader industrial structures and regional operating conditions. In South Africa, Olanrewaju (2019) employed logarithmic mean Divisia index analysis to distinguish the contributions of industrial activity, manufacturing structure, and energy intensity to consumption patterns. Such distinctions demonstrate the importance of evaluating electricity demand against production activity rather than interpreting aggregate consumption independently. Similarly, Kan, Mativenga and Marnewick (2020) investigated manufacturing energy consumption and associated environmental implications in South Africa,

highlighting the significance of understanding consumption drivers when developing industrial efficiency strategies.

Electricity supply reliability introduces further complexity in developing manufacturing economies. Nigerian industries frequently encounter supply constraints that encourage alternative generation arrangements and increase the importance of coordinating industrial electrical loads. Sunday and Omoegun (2018) examined solar power integration in Nigerian small-scale manufacturing, identifying decentralised generation as a potential means of improving energy availability and operational sustainability. Nevertheless, incorporating alternative electricity sources requires appropriate coordination between generation capacity, plant demand, and motor starting requirements.

The interaction between supply variability and manufacturing loads therefore creates a practical need for intelligent electrical distribution. Sunday and Omoegun (2019) investigated optimisation approaches for hybrid solar electricity systems, emphasising load allocation, energy-management coordination, and operational adaptability. Within MCC-equipped manufacturing plants, these principles support examination of feeder-level metering, demand prioritisation, motor-control scheduling, and power-quality monitoring. Assessing electricity consumption at both equipment and distribution levels consequently provides a stronger basis for identifying energy losses, understanding production-related demand variations, and evaluating the operational implications of motor-control strategies.

1.3 Significance of Motor Control Centre Reliability

Operational reliability constitutes a fundamental requirement for Motor Control Centres (MCCs) because their performance directly influences manufacturing continuity, equipment availability, electrical safety, and production efficiency. MCCs serve as centralised interfaces for distributing and controlling electrical power supplied to industrial motors. Consequently, failures involving protective devices, electrical connections, control circuits, or associated components may interrupt multiple production processes simultaneously. Sauve et al. (2019) emphasised the importance of appropriate MCC design, equipment selection, and installation practices in reducing electrical hazards and improving operational safety.

The reliability of MCC installations depends substantially on electrical protection integrity and effective fault management. Insulation deterioration, inadequate grounding, excessive current, and defective connections can compromise electrical equipment performance and increase the likelihood of hazardous operating conditions. Adeniji et al. (2020) examined grounding-system optimisation in medium-voltage distribution networks, highlighting the importance of balancing equipment protection, operational reliability, and safety requirements. These considerations are particularly significant in industrial facilities where electrical disturbances can propagate through interconnected distribution and motor-control infrastructure.

Manufacturing productivity is equally dependent on the continuous availability of connected motor-driven machinery. Unexpected motor failures may interrupt sequential manufacturing operations, increase maintenance expenditure, and generate production losses. Zhang et al. (2019) demonstrated the importance of induction motor condition monitoring for sustainable manufacturing, particularly through data-driven techniques capable of identifying developing equipment abnormalities. Integrating such diagnostic information with MCC operational monitoring offers opportunities to improve maintenance decisions and minimise unexpected machinery interruptions.

Effective reliability management also requires identifying equipment deterioration before operational failure occurs. Gangsar and Tiwari (2020) reviewed signal-based diagnostic approaches for induction motors, demonstrating the applicability of vibration and electrical-current analysis in detecting abnormal operating conditions. These techniques provide valuable diagnostic information that can complement MCC-based electrical protection and monitoring arrangements, particularly where continuous machine operation is essential.

Maintenance strategies represent another important determinant of industrial electrical infrastructure reliability. In South African industrial processing operations, Ngoma, Mativenga and Pretorius (2020) investigated condition-based maintenance using sensor measurements and statistical assessment techniques. Their findings highlighted opportunities for identifying equipment deterioration and supporting maintenance interventions before functional failures disrupt production activities. Such approaches offer a practical foundation for improving maintenance scheduling across MCC-controlled manufacturing equipment.

Advancements in diagnostic instrumentation have further strengthened the relationship between equipment condition assessment and industrial reliability. Kudelina et al. (2021) reviewed electrical-machine fault-detection techniques, including thermal, electrical, and mechanical monitoring methods. Their findings underscore the importance of selecting appropriate diagnostic indicators for different failure mechanisms. Within manufacturing plants, combining these monitoring approaches with effective MCC protection coordination, documented maintenance procedures, and operational performance assessment can strengthen electrical asset management while supporting safer and more consistent production operations.

1.4 Review Objectives, Scope, and Methodology

This review critically examines the relationship between energy efficiency and operational reliability in Motor Control Centres (MCCs) deployed across industrial manufacturing plants. Its primary objective is to evaluate how MCC design characteristics, electrical control strategies, maintenance practices, and emerging technologies influence energy consumption, equipment availability, and manufacturing continuity. Particular attention is directed towards identifying operational inefficiencies, common failure mechanisms, and engineering interventions capable of

improving electrical system performance without compromising safety or production requirements.

The review encompasses conventional and intelligent MCC configurations, including motor starters, protective devices, variable-frequency drives, power distribution arrangements, and integrated monitoring systems. It further considers the effects of industrial loading conditions, electrical losses, equipment deterioration, and maintenance effectiveness on overall system performance. The discussion incorporates manufacturing environments characterised by continuous and intermittent operations, recognising differences in technological infrastructure, electricity supply reliability, and resource availability across developed and developing economies.

Methodologically, the study adopts a structured narrative literature review, drawing upon relevant peer-reviewed journal articles, technical publications, and established electrical engineering standards published through 2022. Literature is examined thematically to identify established engineering principles, documented technological developments, operational challenges, and practical improvement strategies. Particular emphasis is placed on evaluating the relationship between energy-saving interventions and equipment reliability, while distinguishing demonstrated findings from broader technological possibilities.

The synthesis integrates evidence concerning electrical efficiency optimisation, fault detection, reliability-centred maintenance, industrial automation, and intelligent monitoring technologies. Through this approach, the review seeks to establish a coherent understanding of MCC performance determinants, identify limitations within existing research, and formulate technically grounded recommendations for improving energy utilisation, operational resilience, maintenance effectiveness, and long-term manufacturing productivity across diverse industrial operating environments.

2. Motor Control Centre Architecture and Operations

2.1 Components and Configurations of Motor Control Centres

Motor Control Centres (MCCs) constitute integrated electrical assemblies designed to centralise the distribution, protection, and operational control of multiple electric motors within industrial manufacturing facilities. Their fundamental architecture comprises interconnected compartments containing power distribution busbars, circuit breakers, motor starters, contactors, overload relays, control transformers, and terminal connections. The selection and arrangement of these components depend on motor ratings, production requirements, operating environments, and electrical protection considerations. Durocher and Hussey (2019) examined technological

developments in low-voltage MCC configurations, demonstrating how equipment modernisation can accommodate changing industrial loads while improving functionality and operational flexibility.

The power distribution arrangement typically incorporates incoming supply terminals, horizontal and vertical busbars, and individual motor-control units. These components establish electrical pathways between incoming feeders and connected machinery, while protective devices provide isolation during abnormal operating conditions. Motor-control assemblies may employ direct-on-line starters, reduced-voltage starting equipment, soft starters, or variable-frequency drives, depending on starting-current limitations and process requirements. Collins, Farr and Durocher (2016) examined the installation of a medium-voltage MCC incorporating improved sensing and protective arrangements, illustrating the importance of selecting suitable configurations for industrial expansion and equipment modernisation.

Protection and control components also determine the functional integrity of individual motor circuits. Contactors facilitate switching operations, overload relays respond to sustained excessive currents, and circuit breakers provide appropriate fault interruption capabilities. In Nigeria, Orovwode et al. (2021) developed a three-phase induction motor starter incorporating protective mechanisms against abnormal operating conditions, demonstrating the practical importance of integrating sensing, control, and disconnection functions within motor-control equipment.

MCC configurations may incorporate fixed-mounted or withdrawable functional units, with different arrangements offering distinct maintenance, accessibility, and installation characteristics. Modular construction facilitates equipment expansion and adaptation to changing production requirements. Saraf, Marquardt and Kerr (2019) investigated alternative modular MCC arrangements for hazardous industrial environments, highlighting the significance of equipment placement and installation architecture.

Contemporary MCCs increasingly incorporate digital relays, networked instrumentation, communication interfaces, and intelligent motor-management devices. Bayer et al. (2019) explored intelligent MCC technologies, identifying opportunities for improved equipment information, operational monitoring, and industrial connectivity. These developments support the integration of electrical control infrastructure with broader manufacturing automation platforms.

System configuration additionally influences the effectiveness of supervisory monitoring and operator decision-making. Hugo and Holm (2020) examined Industry 4.0 control-room architectures, demonstrating the significance of integrated information systems and intelligent operational interfaces. Within MCC-equipped manufacturing plants, appropriately configured communication and monitoring arrangements can therefore support coordinated equipment supervision, timely fault identification, and informed maintenance planning.

2.2 Electrical Protection, Control, and Power Distribution

Electrical protection, control, and power distribution constitute interconnected functions determining the efficiency, safety, and operational reliability of Motor Control Centres (MCCs) in industrial manufacturing plants. MCCs distribute electrical power through coordinated arrangements of busbars, feeders, switching devices, and motor-control units while providing protective mechanisms against abnormal operating conditions. Their effectiveness depends on appropriate component selection, fault discrimination, and compatibility between electrical supply characteristics and connected motor loads. The International Electrotechnical Commission (IEC, 2020) establishes technical requirements for semiconductor motor controllers and soft starters, providing an essential framework for equipment performance, electrical safety, and operational coordination.

Protective systems within MCCs typically incorporate circuit breakers, fuses, overload relays, earth-fault protection, and associated monitoring equipment. These devices must distinguish normal motor-starting currents from overloads and short-circuit conditions to prevent unnecessary equipment disconnection. Effective discrimination requires carefully selected protection settings and coordinated operating characteristics. Khond and Dhomane (2019) investigated optimised directional overcurrent relay coordination, demonstrating the significance of systematic relay-setting determination in improving fault isolation and maintaining electrical distribution reliability.

Fault-clearing performance additionally influences equipment damage, thermal exposure, and manufacturing continuity. Prolonged short-circuit currents generate substantial thermal energy that can deteriorate conductors, insulation, and electrical connections. Slabbert, Bansal, and Naidoo (2018) examined let-through energy associated with overcurrent protection, emphasising the relationship between fault magnitude, clearing duration, and conductor exposure. These considerations are relevant when evaluating MCC short-circuit withstand ratings and protective-device coordination.

Power distribution reliability also depends on the ability of protection systems to accommodate changing operating configurations. Industrial facilities increasingly incorporate alternative power sources, interconnected feeders, and varying electrical demands. Samadi and Chabanloo (2020) proposed adaptive overcurrent protection coordination using independently adjustable relay-setting groups, illustrating opportunities for maintaining protection selectivity under changing network conditions.

In South African electricity distribution applications, Thomas et al. (2019) investigated recloser placement and fault-energy exposure, demonstrating how protection arrangements influence equipment damage and network reliability. Although industrial MCCs differ from utility distribution systems, appropriate fault isolation and protective coordination remain essential engineering considerations.

Digital control technologies have further expanded the interaction between MCCs and supervisory power-management infrastructure. Intelligent relays, programmable controllers, and communication networks support equipment-status monitoring, remote supervision, and operational data acquisition. Shittu et al. (2022) examined blockchain-assisted information exchange in SCADA-controlled power systems, highlighting data integrity and cybersecurity considerations in interconnected electrical infrastructure. Such developments reinforce the importance of secure communication between industrial control systems and electrical distribution equipment while preserving independent, dependable operation of time-critical protective functions.

2.3 Operating Conditions and Industrial Load Characteristics

Operating conditions and industrial load characteristics fundamentally influence the energy efficiency, electrical performance, and operational reliability of Motor Control Centres (MCCs) in manufacturing facilities. Industrial motors operate under diverse loading arrangements determined by production intensity, process requirements, equipment characteristics, and operational schedules. These conditions produce variations in current demand, motor temperature, starting frequency, and mechanical output. Consequently, effective MCC performance assessment requires consideration of electrical load behaviour alongside the manufacturing processes responsible for generating demand. Gao et al. (2020) established the importance of energy-aware production scheduling in managing industrial electricity consumption while maintaining manufacturing productivity.

Industrial motor loads are commonly classified according to their torque-speed characteristics, duty cycles, and operating continuity. Pumps and centrifugal fans typically exhibit variable-torque characteristics, whereas conveyors, positive-displacement equipment, and material-handling machinery frequently require approximately constant torque. These differences influence motor starting requirements, drive selection, and power consumption under changing operating conditions. Quispe et al. (2018) demonstrated that electrical supply imbalance affects induction motor current, losses, efficiency, and power factor, reinforcing the importance of evaluating motor performance under realistic operating conditions.

Temperature also represents a critical operating parameter because excessive thermal exposure accelerates insulation deterioration and increases the likelihood of premature equipment failure. Industrial motors exposed to fluctuating loads, repeated starting, and electrical disturbances may experience irregular heating patterns that influence maintenance requirements. Tabora et al. (2020) investigated voltage imbalance across different induction motor efficiency classes, demonstrating significant variations in operating current and temperature. These findings highlight the relevance of electrical condition monitoring to MCC reliability assessment.

Manufacturing production schedules introduce additional variation in electrical demand. Simultaneous operation of multiple motor-driven machines can produce concentrated loading periods, particularly during production commencement and equipment changeovers. Chou, Yang and Wu (2020) developed an energy-aware scheduling approach incorporating maximum power constraints, demonstrating how production scheduling can influence demand peaks and overall energy performance.

Production organisation also determines the frequency and duration of motor operation. In Nigerian manufacturing applications, Akanbi, Ganiu and Sunday (2022) examined workforce-centred line balancing within multi-shift production environments, emphasising the effects of operational variability on production coordination. These considerations provide context for understanding changes in equipment utilisation and associated electrical demand across manufacturing shifts.

Time-dependent electricity costs further influence industrial operating decisions. Aghelinejad, Ouazene and Yalaoui (2018) examined production scheduling involving machine operating states and variable electricity prices, demonstrating opportunities to coordinate manufacturing activities with energy-cost considerations. Similarly, Masmoudi, Delorme and Gianessi (2019) incorporated peak-power limitations into job-shop scheduling, illustrating the relationship between electrical demand management and production constraints.

Electrical supply interruptions create additional operational challenges, especially where manufacturing systems depend on continuous machine availability. In South Africa, Dewa, van der Merwe and Matope (2020) investigated production scheduling under frequent load-shedding conditions, identifying practical strategies for managing production interruptions and maintaining manufacturing performance.

The integration of operational feedback into production planning can improve responses to changing manufacturing conditions. Xu and Wang (2017) demonstrated the usefulness of feedback-based scheduling for coordinating energy consumption and production completion requirements. Within MCC-equipped facilities, such principles support improved motor utilisation, load monitoring, and coordinated equipment operation.

Table 1. Industrial operating conditions and their implications for MCC performance

Operating condition	Electrical load characteristics	Implications for MCC efficiency and reliability
Continuous production	Sustained motor loading and extended operating periods	Requires thermal stability, continuous monitoring, and dependable protective coordination

Intermittent production	Repeated starting, stopping, and fluctuating demand	Increases switching operations and may contribute to contact wear and thermal cycling
Variable-torque applications	Power demand changes with speed and process requirements	Creates opportunities for energy savings through appropriate variable-speed control
Constant-torque applications	Relatively stable torque requirements across operating speeds	Requires suitable drive sizing and adequate current-carrying capacity
Simultaneous motor starting	Temporary concentration of starting currents	Can cause voltage depression and requires coordinated starting and protection settings
Supply voltage imbalance	Unequal phase currents and additional motor losses	Can increase operating temperatures and reduce motor efficiency
Multi-shift manufacturing	Changing equipment utilisation and production intensity	Requires load profiling and coordinated operation across shifts
Unstable electricity supply	Interruptions, voltage fluctuations, and restart transients	Can cause unexpected shutdowns and necessitates appropriate restart procedures and protection

Source: Author's synthesis of established motor operating characteristics, industrial scheduling principles, and electrical engineering considerations. The table is qualitative and does not represent measured performance data from a particular manufacturing plant.

3. Energy Efficiency Assessment and Optimization Strategies

Energy efficiency assessment in Motor Control Centres (MCCs) requires systematic examination of electrical losses, motor operating characteristics, control strategies, and manufacturing load requirements. Although MCC assemblies primarily provide electrical distribution and motor control rather than mechanical energy conversion, their configuration influences the efficiency of connected motor-driven systems. Accordingly, performance assessment should distinguish losses occurring within MCC components from those associated with motors, drives, and mechanical equipment. Trianni, Cagno, and Accordini (2019) classified industrial motor-system efficiency measures according to equipment characteristics, drive technologies, operational management, and power quality, establishing a useful framework for identifying improvement opportunities across manufacturing facilities.

Effective assessment begins with establishing an electrical energy baseline using measurements of voltage, current, active power, reactive power, power factor, and operating duration. Feeder-level

measurements should be associated with individual motor loads and corresponding production output to identify inefficient equipment operation. ISO (2018) emphasises systematic energy-performance evaluation, measurable indicators, and continual improvement, providing a structured basis for energy management within industrial installations. Relevant MCC performance indicators include electricity consumption per production unit, feeder losses, motor loading, peak demand, and energy consumption during nonproductive operation.

Motor speed regulation represents an important optimisation strategy, particularly for variable-torque applications involving centrifugal pumps and fans. Variable-frequency drives permit motor speed adjustment according to process requirements, potentially reducing unnecessary energy consumption associated with fixed-speed operation. Gouws (2015) investigated induction motor efficiency in a South African hot rolling mill, demonstrating how appropriately coordinated torque, flux, and speed control can improve energy performance under changing production conditions.

Control optimisation must nevertheless account for motor characteristics, process stability, and the limitations of individual applications. Sunday et al. (2019) examined adaptive control strategies and thermodynamic efficiency in electrically driven cooling systems, highlighting the relevance of coordinated control in reducing energy demand. Within manufacturing facilities, such principles inform the evaluation of process-responsive motor control, particularly where mechanical output varies throughout operating cycles.

Statistical monitoring provides an additional mechanism for detecting inefficient operating conditions. Akanbi, Ganiu and Sunday (2022) examined statistical process control methods for managing manufacturing process variability. Applying comparable statistical principles to MCC energy measurements can help identify abnormal consumption patterns, persistent deviations from established baselines, and changes in equipment operating behaviour.

Real-time monitoring further strengthens energy optimisation by enabling timely identification of deviations from expected performance. Bonfá et al. (2019) demonstrated the application of intelligent monitoring and control methods to industrial compressed-air systems, incorporating operational measurements and statistical analysis to support energy assessment. Similar monitoring arrangements can facilitate MCC load profiling, equipment-status evaluation, and identification of inefficient operating periods.

Economic considerations are equally important when selecting efficiency interventions. Zuberi, Tijdink and Patel (2017) evaluated energy-saving opportunities in Swiss industrial motor systems, demonstrating the importance of assessing investment costs against achievable electricity savings. MCC modernisation should therefore prioritise interventions according to technical feasibility, capital expenditure, expected savings, operational compatibility, and lifecycle costs.

Implementation may be constrained by limited investment resources, inadequate technical expertise, and organisational resistance. Singh and Lalk (2016) identified barriers affecting energy-efficiency adoption in South African manufacturing firms, reinforcing the need for coordinated technical and managerial approaches.

Broader electricity-supply arrangements can also influence industrial energy-management decisions. Shittu et al. (2019) examined hydrogen integration within electricity networks, providing context for future energy-system flexibility. However, supply-side diversification must be distinguished from improvements in MCC electrical efficiency, which require direct assessment of internal distribution losses and connected motor-system performance.

Table 2. Energy efficiency assessment and optimization strategies for industrial MCCs

Assessment area	Performance indicators	Optimization strategy	Expected operational benefit
Motor loading	Load factor, active power, operating hours	Motor right-sizing and load matching	Reduced unnecessary motor losses
Variable-speed operation	Motor speed, torque, power demand	Appropriate variable-frequency drive control	Lower consumption under variable-load conditions
Electrical distribution	Feeder current, voltage drop, thermal losses	Connection maintenance and conductor assessment	Reduced resistive losses and overheating
Power quality	Power factor, harmonics, voltage imbalance	Power-factor correction and harmonic mitigation	Improved electrical performance and reduced disturbances
Production scheduling	Peak demand, idle time, load diversity	Coordinated motor operation and demand management	Reduced peak demand and avoidable consumption
Energy monitoring	kWh per unit output, baseline deviation	Feeder-level metering and statistical monitoring	Earlier identification of inefficiencies
Equipment upgrading	Lifecycle cost, annual savings, payback	Targeted replacement of inefficient components	Improved investment effectiveness
Maintenance management	Operating temperature, deterioration trends	Preventive and condition-based maintenance	Sustained efficiency and equipment availability

Source: Author's synthesis of electrical engineering principles and the reviewed literature. Expected benefits are qualitative; actual energy savings must be established through plant-specific measurements and analysis.

4. Operational Reliability, Failure Mechanisms, and Maintenance Practices

Operational reliability is fundamental to the performance of Motor Control Centres (MCCs), particularly in industrial manufacturing plants where electrical disturbances can interrupt interconnected production processes. MCC reliability depends on the integrity of power distribution components, switching mechanisms, protective devices, insulation systems, and associated motor-control equipment. Failures may arise through progressive deterioration or sudden electrical disturbances, making systematic maintenance essential for sustaining equipment availability. Jardine, Lin, and Banjevic (2006) established the importance of condition-based maintenance through diagnostic evaluation, prognostic modelling, and informed maintenance decisions, providing a framework for assessing industrial electrical equipment deterioration.

Electrical failure mechanisms commonly involve insulation degradation, loose connections, contact deterioration, excessive loading, and abnormal operating temperatures. These conditions may increase contact resistance, accelerate component ageing, and compromise protective performance. Infrared thermography offers a non-invasive approach for identifying thermal abnormalities within electrical installations. Ferreira et al. (2019) investigated measurement uncertainties affecting infrared diagnosis of electrical components, emphasising the influence of surface emissivity and environmental conditions on temperature interpretation.

Thermal monitoring is particularly valuable for identifying developing abnormalities in busbar joints, cable terminations, switching contacts, and associated MCC connections. Nevertheless, accurate diagnosis requires consideration of equipment loading and normal operating temperatures. Xia et al. (2021) reviewed infrared thermography applications in electrical equipment diagnostics, demonstrating the importance of temperature distribution assessment and intelligent image interpretation for identifying potential equipment defects.

Maintenance strategy selection also influences the frequency, duration, and consequences of equipment failures. Reactive maintenance addresses faults after breakdown, whereas preventive maintenance involves scheduled inspection and component replacement. Predictive maintenance instead evaluates equipment condition to identify developing abnormalities before functional failure occurs. Sunday et al. (2020) examined the transition towards predictive maintenance in mechanical systems, highlighting the importance of condition monitoring, operational data, and proactive intervention in reducing maintenance-related disruption.

The effectiveness of maintenance planning depends on the quality of equipment information and the ability to prioritise critical assets. Ozor, Nwobodo-Anyadiegwu and Mbohwa (2020) investigated computerised maintenance information management in a South African manufacturing environment, identifying opportunities to improve maintenance policies through systematic data analysis. Within MCC installations, comparable information systems can support

fault-history documentation, inspection scheduling, component replacement planning, and maintenance-performance evaluation.

Condition-monitoring information must also be sufficiently reliable to support defensible maintenance decisions. In South African industrial applications, de Meyer et al. (2021) examined the reliability of condition-based maintenance data, demonstrating the importance of contextual equipment characteristics when interpreting operational measurements. This consideration is relevant to MCC monitoring because variations in electrical loading, ambient temperature, and operating schedules can influence diagnostic indicators.

Intelligent maintenance systems increasingly incorporate statistical modelling and machine-learning techniques for identifying abnormal equipment behaviour. Carvalho et al. (2019) reviewed machine-learning applications in predictive maintenance, demonstrating opportunities for equipment fault identification and maintenance decision support. Within MCC environments, these techniques may facilitate analysis of electrical current, thermal measurements, switching frequency, and equipment deterioration patterns.

Maintenance optimisation must nevertheless balance technological sophistication with implementation feasibility. Selcuk (2017) emphasised the significance of integrating predictive techniques with established maintenance practices to improve equipment availability, efficiency, and operational safety. Successful adoption therefore requires trained personnel, dependable instrumentation, appropriate diagnostic thresholds, and clearly defined maintenance responsibilities.

Reliability-centred maintenance provides a systematic approach for identifying equipment functions, evaluating failure consequences, and selecting appropriate maintenance interventions. Olutimehin and Ganiu (2022) examined the integration of reliability-centred maintenance with Lean Six Sigma, emphasising coordinated improvement in manufacturing reliability and operational performance. For MCC-equipped manufacturing plants, this approach supports prioritising critical motor circuits, reducing recurrent failures, and aligning maintenance expenditure with equipment risk and production requirements.

5. Emerging Technologies, Implementation Challenges, and Future Directions

The advancement of industrial automation has accelerated the development of intelligent Motor Control Centres (MCCs) capable of integrating electrical distribution, equipment monitoring, and automated control within interconnected manufacturing environments. Emerging technologies, including the Industrial Internet of Things (IIoT), artificial intelligence, digital twins, and cyber-physical systems, offer opportunities to improve energy management, fault detection, and operational reliability. However, their effectiveness depends on appropriate technological integration, dependable communication infrastructure, and compatibility with existing electrical

equipment. Lee, Bagheri, and Kao (2015) proposed a cyber-physical architecture for intelligent manufacturing, demonstrating how interconnected physical equipment and computational systems can support real-time monitoring, information analysis, and adaptive operational decisions.

Sensor-based monitoring represents an important development in intelligent motor-control infrastructure. Modern MCCs can incorporate temperature sensors, current transducers, voltage monitors, and intelligent protective relays to continuously assess equipment conditions. Such arrangements facilitate the identification of abnormal loading, overheating, and developing electrical faults. Sunday and Omoegun (2022) examined intelligent fault detection using sensor-based monitoring and data-driven analytics, highlighting opportunities for recognising equipment abnormalities and improving maintenance responsiveness. Applying these principles to MCC installations requires careful sensor selection, reliable measurements, and diagnostic models appropriate to electrical failure mechanisms.

Digital twin technology offers additional opportunities for modelling MCC operating conditions and evaluating alternative maintenance strategies. By establishing a virtual representation informed by operational measurements, digital twins can support simulation, equipment-condition assessment, and performance optimisation. Tao et al. (2019) examined industrial digital twin applications, identifying their potential for integrating physical equipment with computational models across manufacturing operations. For MCCs, these capabilities may support thermal assessment, load-distribution evaluation, and predictive analysis of component deterioration.

The effectiveness of digital twins nevertheless depends on data accuracy, model calibration, and continuous interaction with physical equipment. Cimino, Negri and Fumagalli (2019) identified limitations in manufacturing digital twin implementations, particularly regarding the provision of comprehensive services and effective communication between virtual and physical systems. These limitations indicate the importance of validating MCC models against measured electrical performance before adopting automated operational recommendations.

Predictive maintenance scheduling represents another promising application. Rather than relying exclusively on predetermined maintenance intervals, intelligent systems can evaluate equipment conditions alongside production requirements to identify appropriate intervention periods. Assad Neto et al. (2021) developed a digital twin-driven maintenance scheduling framework demonstrating how manufacturing downtime opportunities can support preventive maintenance decisions. Similar approaches could improve the coordination of MCC inspections, component replacement, and production availability.

Industrial digitalisation also introduces substantial cybersecurity considerations. Networked MCCs may become vulnerable to unauthorised access, communication disruption, and manipulation of operational information. Abosata et al. (2021) investigated cybersecurity threats affecting industrial IoT systems, emphasising the importance of authentication, secure

communication, and effective intrusion detection. Accordingly, intelligent MCC implementation should incorporate network segmentation, access control, and cybersecurity measures without compromising independent electrical protection functions.

The integration of decentralised energy resources introduces further opportunities for coordinated industrial energy management. Shittu et al. (2021) investigated blockchain-based energy trading in renewable microgrids, highlighting potential applications involving secure transactions, distributed energy coordination, and transparent information exchange. Within manufacturing environments, such developments may support broader energy-management infrastructure connected to MCC-monitored industrial loads.

Implementation challenges remain particularly significant in developing manufacturing economies. Maisiri, van Dyk and Coetzee (2021) identified infrastructure limitations, technological affordability, skills shortages, and organisational barriers affecting Industry 4.0 adoption in South Africa. These constraints demonstrate the importance of adapting intelligent MCC solutions to local manufacturing conditions rather than assuming uniform technological readiness.

Future research should therefore prioritise affordable sensor integration, interoperable communication architectures, explainable fault-detection algorithms, and reliable cybersecurity frameworks. Moktadir et al. (2018) identified technological infrastructure and implementation complexity as important obstacles to industrial digital transformation. Addressing these challenges through phased modernisation, workforce development, and field validation could facilitate the adoption of intelligent MCC technologies while maintaining electrical safety, measurable energy performance, and dependable manufacturing operations.

Conclusion and Recommendations

This review has critically examined the interconnected roles of energy efficiency and operational reliability in industrial motor control infrastructure, establishing how electrical system design, operating conditions, protective mechanisms, and maintenance strategies influence manufacturing performance. By evaluating conventional and intelligent Motor Control Centre configurations, the study has fulfilled its objectives of identifying major energy consumption determinants, investigating prevalent failure mechanisms, and assessing technological and operational interventions capable of improving equipment efficiency, safety, and availability.

The findings demonstrate that inefficient motor loading, inappropriate control configurations, electrical disturbances, deteriorating connections, and inadequate maintenance contribute to avoidable energy consumption and operational interruptions. Effective motor selection, variable-frequency drive applications, coordinated protection systems, and systematic energy monitoring offer significant opportunities for improving electrical performance. Furthermore, the review

establishes that reliability-centred and predictive maintenance approaches strengthen equipment condition assessment, facilitate early fault identification, and reduce the likelihood of unexpected manufacturing downtime.

Emerging technologies, particularly intelligent monitoring systems, digital twins, industrial automation, and data-driven diagnostics, present additional opportunities for integrating energy optimisation with proactive asset management. Nevertheless, implementation remains constrained by infrastructure deficiencies, technological costs, cybersecurity vulnerabilities, limited technical expertise, and compatibility challenges, particularly within resource-constrained manufacturing environments.

Based on these findings, industrial operators should prioritise comprehensive energy audits, appropriate motor and protective-device selection, routine thermal inspections, and performance-based maintenance programmes. Manufacturing facilities should establish measurable energy and reliability indicators, strengthen workforce technical competencies, and progressively integrate intelligent monitoring technologies according to operational requirements and financial feasibility. Regulatory institutions and industry stakeholders should encourage compliance with recognised electrical safety standards and promote accessible industrial energy-management practices.

Future investigations should undertake longitudinal, plant-level evaluations to quantify energy savings, failure reduction, maintenance costs, and lifecycle benefits associated with MCC modernisation. Such evidence would strengthen technology selection and investment decisions. Ultimately, sustainable manufacturing performance requires an integrated engineering approach in which efficient electricity utilisation, dependable equipment operation, and continuous reliability improvement are treated as mutually reinforcing operational priorities.

References

1. Abosata, N., Al-Rubaye, S., Inalhan, G. and Emmanouilidis, C. (2021) ‘Internet of Things for system integrity: A comprehensive survey on security, attacks and countermeasures for industrial applications’, Sensors, 21(11), Article 3654. DOI: 10.3390/s21113654.
2. Adeniji, I.O., Shittu, H., Elumilade, R.A., Opara, I.S. and Shittu, M.A. (2020) ‘Grounding system design optimization for medium-voltage distribution networks in emerging power markets’, IRE Journals, 3(11), pp. 547–565. DOI: 10.64388/IREV3I11-1714040.
3. Aghelinejad, M.M., Ouazene, Y. and Yalaoui, A. (2018) ‘Production scheduling optimisation with machine state and time-dependent energy costs’, International Journal of Production Research, 56(16), pp. 5558–5575. DOI: 10.1080/00207543.2017.1414969.
4. Akanbi, O., Ganiu, O.S. and Sunday, E.A. (2022) ‘A workforce-centric line-balancing model for throughput maximization in multi-shift operations’, Shodhshauryam: International Scientific Refereed Research Journal, 5(3), pp. 439–464. DOI: 10.32628/SHISRRJ.

5. Akanbi, O., Ganiu, O.S. and Sunday, E.A. (2022) 'Comprehensive review of statistical process control (SPC) for precision weight management in global food manufacturing', Gyanshauryam: International Scientific Refereed Research Journal, 5(3), pp. 433–461. Available at: https://gisrrj.com/paper/GISRRJ225387.pdf
6. Assad Neto, A., Carrijo, B.S., Brock, J.G.R., Deschamps, F. and Pinheiro de Lima, E. (2021) 'Digital twin-driven decision support system for opportunistic preventive maintenance scheduling in manufacturing', Procedia Manufacturing, 55, pp. 439–446. DOI: 10.1016/j.promfg.2021.10.060.
7. Bayer, M.R., Stewart, B.G., Venne, B.K., Mazur, D.C. and Kay, J.A. (2019) 'Intelligent motor control centers: Defining the benefits to petroleum and chemical industries', IEEE Industry Applications Magazine, 25(5), pp. 47–56. DOI: 10.1109/MIAS.2018.2875205.
8. Bonfá, F., Benedetti, M., Ubertini, S., Introna, V. and Santolamazza, A. (2019) 'New efficiency opportunities arising from intelligent real-time control tools applications: The case of compressed air systems' energy efficiency in production and use', Energy Procedia, 158, pp. 4198–4203. DOI: 10.1016/j.egypro.2019.01.809.
9. Bugaris, R.M. and Doan, D.R. (2014) 'Arc-flash incident energy variations: A study of low-voltage motor control center unit configurations and incident energy exposure', IEEE Industry Applications Magazine, 20(3), pp. 40–45. DOI: 10.1109/MIAS.2013.2288386.
10. Carvalho, T.P., Soares, F.A.A.M.N., Vita, R., Francisco, R.P., Basto, J.P. and Alcalá, S.G.S. (2019) 'A systematic literature review of machine learning methods applied to predictive maintenance', Computers & Industrial Engineering, 137, Article 106024. DOI: 10.1016/j.cie.2019.106024.
11. Chou, Y.-L., Yang, J.-M. and Wu, C.-H. (2020) 'An energy-aware scheduling algorithm under maximum power consumption constraints', Journal of Manufacturing Systems, 57, pp. 182–197. DOI: 10.1016/j.jmsy.2020.09.004.
12. Cimino, C., Negri, E. and Fumagalli, L. (2019) 'Review of digital twin applications in manufacturing', Computers in Industry, 113, Article 103130. DOI: 10.1016/j.compind.2019.103130.
13. Collins, C., Farr, L.B. and Durocher, D.B. (2016) 'Process modernization upgrade: Selecting and installing a new medium-voltage motor control center', 2016 IEEE Industry Applications Society Annual Meeting, Portland, OR, USA, 2–6 October, pp. 1–9. IEEE. DOI: 10.1109/IAS.2016.7731922.
14. de Meyer, J.N., Goosen, P., van Rensburg, J.F., du Plessis, J.N. and van Laar, J.H. (2021) 'Estimating the reliability of condition-based maintenance data using contextual machine-specific characteristics', South African Journal of Industrial Engineering, 32(3), pp. 173–184. DOI: 10.7166/32-3-2625.
15. Dewa, M., van der Merwe, A. and Matope, S. (2020) 'Production scheduling heuristics for frequent load-shedding scenarios: A knowledge engineering approach', South African Journal of Industrial Engineering, 31(3), pp. 110–121. DOI: 10.7166/31-3-2422.

16. Du Plessis, G.E., Liebenberg, L. and Mathews, E.H. (2013) 'The use of variable speed drives for cost-effective energy savings in South African mine cooling systems', Applied Energy, 111, pp. 16–27. DOI: 10.1016/j.apenergy.2013.04.061.
17. Durocher, D.B. and Hussey, M.R. (2019) 'Advancing technology in upgrading or replacing vintage low-voltage motor control centers', IEEE Transactions on Industry Applications, 55(6), pp. 6576–6584. DOI: 10.1109/TIA.2019.2934073.
18. Ferreira, R.A.M., Silva, B.P.A., Teixeira, G.G.D., Andrade, R.M. and Porto, M.P. (2019) 'Uncertainty analysis applied to electrical components diagnosis by infrared thermography', Measurement, 132, pp. 263–271. DOI: 10.1016/j.measurement.2018.09.036.
19. Gangsar, P. and Tiwari, R. (2020) 'Signal-based condition monitoring techniques for fault detection and diagnosis of induction motors: A state-of-the-art review', Mechanical Systems and Signal Processing, 144, Article 106908. DOI: 10.1016/j.ymssp.2020.106908.
20. Gao, K., Huang, Y., Sadollah, A. and Wang, L. (2020) 'A review of energy-efficient scheduling in intelligent production systems', Complex & Intelligent Systems, 6, pp. 237–249. DOI: 10.1007/s40747-019-00122-6.
21. Gouws, R. (2015) 'Efficiency analysis of an induction motor with direct torque and flux control at a hot rolling mill', Journal of Energy in Southern Africa, 26(3), pp. 111–115. DOI: 10.17159/2413-3051/2016/v26i3a2150.
22. Hugo, E.L. and Holm, J.E.W. (2020) 'Synthesis and evaluation of an Industry 4.0 control room', South African Journal of Industrial Engineering, 31(3), pp. 1–12. DOI: 10.7166/31-3-2423.
23. Institute of Electrical and Electronics Engineers (IEEE) (2014) IEEE guide for motor control centers rated up to and including 600 V AC or 1000 V DC with recommendations intended to help reduce electrical hazards. IEEE Std 1683-2014. New York: IEEE. Available at: https://standards.ieee.org/ieee/1683/5847/
24. International Electrotechnical Commission (IEC) (2020) Low-voltage switchgear and controlgear – Part 4-2: Contactors and motor-starters – Semiconductor motor controllers, starters and soft-starters. IEC 60947-4-2:2020. 4th edn. Geneva: International Electrotechnical Commission. Available at: https://webstore.iec.ch/en/publication/60981 (Accessed: 28 October 2026).
25. International Organization for Standardization (ISO) (2018) Energy management systems: Requirements with guidance for use. ISO 50001:2018. 2nd edn. Geneva: International Organization for Standardization. Available at: https://www.iso.org/standard/69426.html
26. Jardine, A.K.S., Lin, D. and Banjevic, D. (2006) 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', Mechanical Systems and Signal Processing, 20(7), pp. 1483–1510. DOI: 10.1016/j.ymssp.2005.09.012.
27. Kan, K., Mativenga, P. and Marnewick, A. (2020) 'Understanding energy use in the South African manufacturing industry', Procedia CIRP, 91, pp. 445–451. DOI: 10.1016/j.procir.2020.02.197.

28. Kay, J.A., Hussain, G.A., Lehtonen, M. and Kumpulainen, L. (2016) 'New preemptive arc-fault detection techniques in medium-voltage switchgear and motor controls', IEEE Transactions on Industry Applications, 52(1), pp. 740–750. DOI: 10.1109/TIA.2015.2466620.
29. Khond, S.V. and Dhomane, G.A. (2019) 'Optimum coordination of directional overcurrent relays for combined overhead/cable distribution system with linear programming technique', Protection and Control of Modern Power Systems, 4, Article 9. DOI: 10.1186/s41601-019-0124-6.
30. Kudelina, K., Asad, B., Vaimann, T., Rassõlkin, A., Kallaste, A. and Khang, H.V. (2021) 'Methods of condition monitoring and fault detection for electrical machines', Energies, 14(22), Article 7459. DOI: 10.3390/en14227459.
31. Kusiak, A. (2018) 'Smart manufacturing', International Journal of Production Research, 56(1–2), pp. 508–517. DOI: 10.1080/00207543.2017.1351644.
32. Lee, J., Bagheri, B. and Kao, H.A. (2015) 'A cyber-physical systems architecture for Industry 4.0-based manufacturing systems', Manufacturing Letters, 3, pp. 18–23. DOI: 10.1016/j.mfglet.2014.12.001.
33. Maisiri, W., van Dyk, L. and Coetzee, R. (2021) 'Factors that inhibit sustainable adoption of Industry 4.0 in the South African manufacturing industry', Sustainability, 13(3), Article 1013. DOI: 10.3390/su13031013.
34. Masmoudi, O., Delorme, X. and Gianessi, P. (2019) 'Job-shop scheduling problem with energy consideration', International Journal of Production Economics, 216, pp. 12–22. DOI: 10.1016/j.ijpe.2019.03.021.
35. Moktadir, M.A., Ali, S.M., Kusi-Sarpong, S. and Shaikh, M.A.A. (2018) 'Assessing challenges for implementing Industry 4.0: Implications for process safety and environmental protection', Process Safety and Environmental Protection, 117, pp. 730–741. DOI: 10.1016/j.psep.2018.04.020.
36. Ngoma, W.J., Mativenga, P.T. and Pretorius, J. (2020) 'Enabling condition-based maintenance in a precious metal processing plant', Procedia CIRP, 91, pp. 893–898. DOI: 10.1016/j.procir.2020.04.138.
37. Olanrewaju, O.A. (2019) 'Multiplicative LMDI approach to South Africa's industrial energy consumption', South African Journal of Industrial Engineering, 30(1), pp. 69–77. DOI: 10.7166/30-1-2037.
38. Olutimehin, A.O. and Ganiu, O.S. (2022) 'Integrating Lean Six Sigma with reliability-centered maintenance: A unified framework for manufacturing excellence', International Journal of Multidisciplinary Research and Growth Evaluation, 3(6), pp. 983–996. DOI:10.54660/.IJMRGE.2022.3.6.983-996.
39. Orovwode, H., Matthew, S., Agbetuyi, A.F., Adoghe, U.A. and Amuta, E. (2021) 'Development of a starter with protective systems for a three-phase induction motor', Journal of Engineering, 2021, Article 3163046, pp. 1–8. DOI: 10.1155/2021/3163046.

40. Ozor, P.A., Nwobodo-Anyadiegwu, E.N. and Mbohwa, C. (2020) 'Computerised software systems in replacement maintenance information management: A South African case study', South African Journal of Industrial Engineering, 31(3), pp. 36–43. DOI: 10.7166/31-3-2420.
41. Quispe, E.C., López, I.D., Ferreira, F.J.T.E. and Sousa, V. (2018) 'Unbalanced voltages impacts on the energy performance of induction motors', International Journal of Electrical and Computer Engineering, 8(3), pp. 1412–1422. DOI: 10.11591/ijece.v8i3.pp1412-1422.
42. Renna, P. and Materi, S. (2021) 'A literature review of energy efficiency and sustainability in manufacturing systems', Applied Sciences, 11(16), Article 7366. DOI: 10.3390/app11167366.
43. Saidur, R. (2010) 'A review on electrical motors energy use and energy savings', Renewable and Sustainable Energy Reviews, 14(3), pp. 877–898. DOI: 10.1016/j.rser.2009.10.018.
44. Samadi, A. and Chabanloo, R.M. (2020) 'Adaptive coordination of overcurrent relays in active distribution networks based on independent change of relays' setting groups', International Journal of Electrical Power & Energy Systems, 120, Article 106026. DOI: 10.1016/j.ijepes.2020.106026.
45. Saraf, N., Marquardt, J. and Kerr, S. (2019) 'Modularization of low-voltage motor control centers: Exploring alternative electrical system designs for hazardous location applications', IEEE Industry Applications Magazine, 25(3), pp. 24–31. DOI: 10.1109/MIAS.2018.2875215.
46. Sauve, T.R., Anderson, R., Bower, T. and Mickler, K.R. (2019) 'Using IEEE Standard 1683 in designing and specifying motor control centers: Helping to ensure safe performance and reducing hazards and risks', IEEE Industry Applications Magazine, 25(3), pp. 32–43. DOI: 10.1109/MIAS.2018.2875186.
47. Seera, M., Lim, C.P., Nahavandi, S. and Loo, C.K. (2014) 'Condition monitoring of induction motors: A review and an application of an ensemble of hybrid intelligent models', Expert Systems with Applications, 41(10), pp. 4891–4903. DOI: 10.1016/j.eswa.2014.02.028.
48. Selcuk, S. (2017) 'Predictive maintenance, its implementation and latest trends', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(9), pp. 1670–1679. DOI: 10.1177/0954405415601640.
49. Shittu, H., Opara, I.S., Elumilade, R.A. and Adeniji, I.O. (2019) 'Hydrogen as a secondary energy carrier: Modeling its integration in national grids', IRE Journal, 3(1), pp. 628–643. DOI: 10.64388/IREV3I1-1713909.
50. Shittu, H.A., Shittu, M.A., Adeleke, O.J. and Adedokun, O.J. (2021) 'Blockchain-based energy trading models for peer-to-peer renewable microgrids', International Journal of Research in Electrical and Electronics Engineering, 4(3), pp. 1–19. DOI: 10.34218/IJREEE_04_03_001.

51. Shittu, M.A., Adeniji, I.O., Shittu, H. and Opara, I.S. (2022) 'Blockchain-assisted secure data exchange architectures for SCADA-controlled power systems', IRE Journals, 6(3), pp. 359–380. DOI: 10.64388/IREV6I3-1714041.
52. Singh, R. and Lalk, J. (2016) 'An investigation into the barriers to energy efficiency within medium to large manufacturing firms operating within the eThekwini municipal area', South African Journal of Industrial Engineering, 27(3), pp. 287–302. DOI: 10.7166/27-3-1658.
53. Slabbert, M.J., Bansal, R.C. and Naidoo, R. (2018) 'Application of let-through energy to back-up over-current protection on high-voltage feeders', IET Generation, Transmission & Distribution, 12(19), pp. 4341–4347. DOI: 10.1049/iet-gtd.2018.6190.
54. Sunday, E.A. and Omoegun, G.O. (2018) 'Integrating solar power solutions in small-scale manufacturing industries in Nigeria', International Journal of Scientific Research in Science, Engineering and Technology, 4(8), pp. 832–853. Available at: https://ijsrset.com/paper/14141.pdf.
55. Sunday, E.A. and Omoegun, G.O. (2019) 'Optimizing electrical load distribution for hybrid solar installations in developing economies', International Journal of Scientific Research in Mechanical and Materials Engineering, 3(6), pp. 27–47. Available at: https://ijsrmme.com/IJSRMME19349.
56. Sunday, E.A. and Omoegun, G.O. (2022) 'Automation of process control systems using Siemens TIA Portal: A case study approach', International Journal of Scientific Research in Mechanical and Materials Engineering, 6(5), pp. 30–55. Available at: https://ijsrmme.com/IJSRMME18210
57. Sunday, E.A. and Omoegun, G.O. (2022) 'Smart fault detection in HVAC systems using sensor-based monitoring', International Journal of Scientific Research in Science, Engineering and Technology, 7(4), pp. 380–403. DOI: 10.32628/IJSRSET229473.
58. Sunday, E.A., Omoegun, G.O., Essien, M.A. and Oluokun, O.A. (2019) 'Thermodynamic efficiency and control strategies in residential air conditioning systems', International Journal of Scientific Research in Civil Engineering, 3(3), pp. 52–76. DOI: 10.32628/IJSRCE19339.
59. Sunday, E.A., Omoegun, G.O., Essien, M.A. and Oluokun, O.A. (2020) 'Transitioning from reactive to predictive maintenance in mechanical systems', International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 6(6), pp. 425–447.
60. Tabora, J.M., Tostes, M.E.L., Matos, E.O., Soares, T.M., Andrade, V. and Morais, I. (2020) 'Voltage unbalance impacts on temperature of IE2, IE3 & IE4 class induction motors', Congresso Brasileiro de Automática, 2(1). DOI: 10.48011/asba.v2i1.1049.
61. Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2019) 'Digital twin in industry: State-of-the-art', IEEE Transactions on Industrial Informatics, 15(4), pp. 2405–2415. DOI: 10.1109/TII.2018.2873186.

62. Thomas, R., van Zyl, S., Naidoo, R.M., Bansal, R.C., Mbungu, N.T. and Bipath, M. (2019) 'Recloser-based energy exposure assessment of a distribution network', Journal of Energy in Southern Africa, 30(4), pp. 41–50. DOI: 10.17159/2413-3051/2019/v30i4a2486.
63. Trianni, A., Cagno, E. and Accordini, D. (2019) 'A review of energy efficiency measures within electric motor systems', Energy Procedia, 158, pp. 3346–3351. DOI: 10.1016/j.egypro.2019.01.964.
64. Trianni, A., Cagno, E. and Accordini, D. (2019) 'Energy efficiency measures in electric motor systems: A novel classification highlighting specific implications in their adoption', Applied Energy, 252, Article 113481. DOI: 10.1016/j.apenergy.2019.113481.
65. Waide, P. and Brunner, C.U. (2011) Energy-efficiency policy opportunities for electric motor-driven systems. IEA Energy Papers, No. 2011/07. Paris: OECD Publishing. DOI: 10.1787/5kgg52gb9gjd-en.
66. Xia, Y., Song, Y., Wang, W., Wang, S. and Wang, J. (2021) 'Infrared thermography-based diagnostics on power equipment: State-of-the-art', High Voltage, 6(3), pp. 387–407. DOI: 10.1049/hve2.12023.
67. Xu, J. and Wang, L. (2017) 'A feedback control method for addressing the production scheduling problem by considering energy consumption and makespan', Sustainability, 9(7), Article 1185. DOI: 10.3390/su9071185.
68. Zhang, J., Wang, P., Gao, R.X., Sun, C. and Yan, R. (2019) 'Induction motor condition monitoring for sustainable manufacturing', Procedia Manufacturing, 33, pp. 802–809. DOI: 10.1016/j.promfg.2019.04.101.
69. Zuberi, M.J.S., Tijdink, A. and Patel, M.K. (2017) 'Techno-economic analysis of energy efficiency improvement in electric motor-driven systems in Swiss industry', Applied Energy, 205, pp. 85–104. DOI: 10.1016/j.apenergy.2017.07.121.