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Evaluation of electrical substation automation operational parameters: A systematic literature review

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Abstract: The need to address inadequate power supply led to the development of automation strategies to improve the efficiency of power substation. This study conducts a systematic literature on the automation of operational parameters in electrical substation. Initially, 84 articles were retrieved from online as articles and grey literature. Upon the implementation of the inclusion criteria, 31 articles were selected and reviewed due to the fact that their focus and finding match with the aim of this study. The outcome of this study indicates that one of the recent advances in the automation of power substation is the development and implementation of the International Electro-technical Commission (IEC) 61850 standard. The standard boasts of several advantages such high compatibility, interoperability, cyber security features, efficiency, reliability, scalability and centralised control. However, some of its challenges includes time synchronisation standardisation of its testing procedure as well as integration into the communication network architecture. The study may promote the reliability of electrical protection, to reduce load-shedding incidences. It may also assist utilities and other electrical energy industries to better grasp how the automation protocol utilised affects substation efficiency.
Keywords: *Automation, IEC 61850, Power substation, Substation efficiency.*

1. Introduction

Generally, electricity is essential for any country as it is the bedrock of socio-economic wellbeing and national development [1]. Ateba [1] mentioned that electrical energy contributed to the Industrial Revolution by ensuring the deployment and operation of appropriate technology, infrastructure, and an essential resource for increasing productivity. The United Nations (UN) Sustainable Development Goals (SDGs) also feature electrical energy need. For example, SDG 7 advocates ensuring access to sustainable, affordable, reliable, and modern technology for all. On the other hand, SDG 13 calls for urgent action to combat climate change by reducing energy-related carbon dioxide emissions [2].

There is a shortage of electricity supply in South Africa, and electricity is an essential input for production in the country to attain industrial competitiveness. Recently, Eskom, which oversees about 96% of South Africa's electricity, introduced load-shedding, lasting at some point for ten hours daily. The electricity infrastructure comprises three sub-sectors: generation, transmission, and distribution [3]. Eskom is the dominant electricity producer; it generates, transmits, and distributes electricity to households, industrial, mining, commercial, and agricultural customers. Additionally, the utility purchases electricity from independent power producers (IPPs) [4].

The power generated passes through a complex network, like transformers, overhead lines, and other equipment, before it reaches the end of use. For example, transmission losses are approximately 17%, whereas distribution losses equate to 50% [5]. The substation is an essential part of the electricity distribution system. It performs switching and protection tasks and changes voltage levels from high to low and vice versa, using power transformers. Establishing a global energy market has increased the rivalry between diverse energy suppliers [1]. As a result of the introduction of new enterprises, more formally known as power players, and increasing market pressure, energy suppliers' primary focus is

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increasingly on the happiness of their customers. The presentation of accurate information to the relevant party is critical to the successful execution of a transaction. As a result, vast volumes of information are traded on the energy market [1]. The difficulty that utilities must solve is managing information and providing suitable information to users so that they may assess it and use it for the proper applications. As a result, creating a typical architecture to harness information flows is an essential requirement [1].

At the substation level, the transformer, through heat losses and the resistance of copper coils [5], primarily causes electrical energy losses. Improving efficiency at a substation is key to sustainable energy generation and distribution. This is due to the fact that substation automation helps in increasing the efficiency and reliability of electrical protection, aiding detailed electrical-fault analysis, displaying real-time substation information in a control centre, and advanced automation functions that monitor and reduce load-shedding incidences [6].

Figure 1 shows the typical overall electricity distribution in South Africa. The substations that need automation are found in generation, transmission, and distribution.

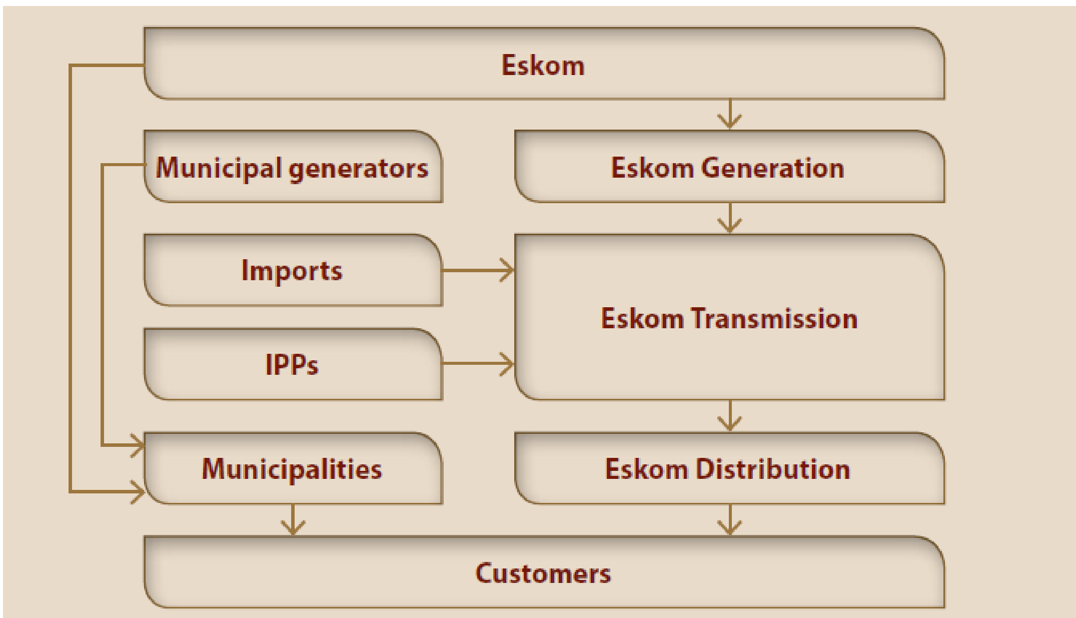

Figure 1.
Electricity generation, transmission, and distribution. Adapted from Mokoena [7].

The aim of this study is to evaluate the automation operational parameters of electrical substation in South Africa.

This study is significant in that it adds to the understanding of the substation automation in order to improve its operational efficiency. The study may also promote the reliability of electrical protection, to reduce load-shedding incidences. This research will help utilities and other electrical energy industries to better grasp how the automation protocol utilised affects substation efficiency than they were able to previously. With this additional knowledge, they will be better able to make informed decisions about the automation protocol that should be utilized for new substations; when there is an issue with the plant's machinery, excellent communication aids in quickly identifying the source of the problem. The longevity of a substation's equipment is directly proportional to the effectiveness of its automation and communication systems. Because of the isolation, the risk of equipment damage is lowered or avoided, resulting in cost savings for the company.

2. Methodology

This study uses systematic literature review approach to extracts information from articles from secondary sources. The review comprises of articles retrieved from academic database, as well as reports from grey literature. The review was conducted according to the guidelines of Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) (Figure 2). The Systematic Literature Review (SLR) selected because it can be used for a detailed synthesis of literature to address in order to draw useful insights and inferences [8]. The selection criteria include the year of publication and the relevance of the articles to the topic of discussion. Articles with conceptual, theoretical and empirical findings were also selected. Initially, 84 articles were retrieved from online comprising of articles and grey literature. Upon the implementation of the inclusion criteria, the articles were pruned down 31 articles which were selected and reviewed. To minimise bias during the screening process, a collaborative review and brainstorming sessions was conducted by the authors to screen each article and to match the relevance to the aim and focus of the study.

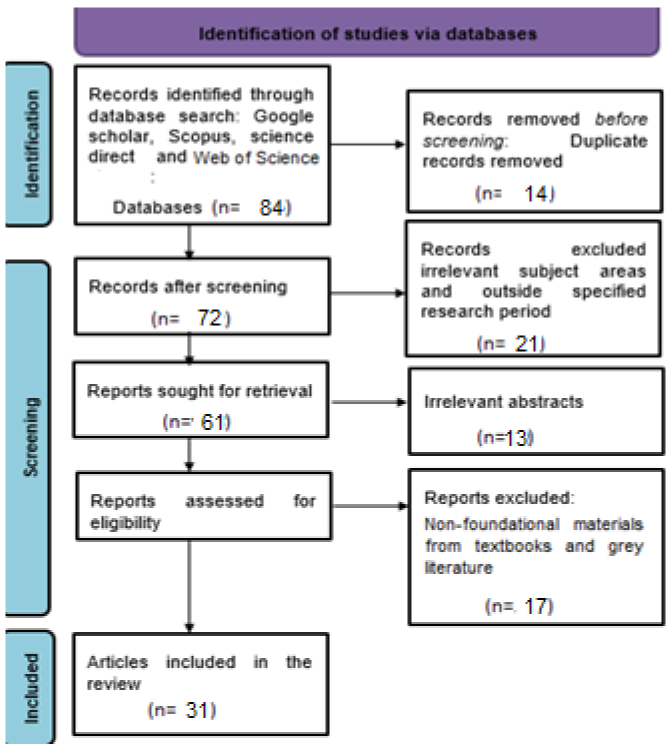

Figure 2.
The selection process using the PRISMA approach.

3. Systematic Literature Review

3.1. Digitisation of Substations

Throughout the decades, the digitisation of substations has been gaining momentum, and the IEC 61850 is the latest standard for substation communication networks (SCN) that permits peer-peer communication between substation devices, allowing faster communication platforms between intelligent electronic devices to share critical interlocking electronic devices by sharing messages. Additionally, IEC 61850 supports bay-distributed functions, which ensures reliability, because the loss of communication due to a switch failure does not render the intra-bay schemes inoperable [9].

Additionally, utilities and other electrical-energy industries will better understand the newly established communication protocols that leverage the 61850 specifications. This application can also construct digital switchgear that does not rely on hard wiring, which helps to reduce the amount of copper needed in panels and, in turn, helps to reduce the adverse environmental effects associated with

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copper manufacture. On the other hand, discovering issues is considerably easier, since Ethernet connections are utilized to facilitate communication between intelligent electronic equipment. This, in turn, makes identifying the problematic component in a network more manageable and faster. Customers will profit more from transitioning from traditional to the most recent standard since they can access the necessary guidelines and improved skill sets.

The IEDs play a crucial role in the whole operation of the substation. The overall electrical automation efficiency is linked to the accuracy and operation of the IEDs, as they link the process level and the station level. The tripping times that are recorded from the relays during periodic maintenance are crucial for testing the performance, efficiency, and reliability of protection relays. By injecting simulated fault or abnormal conditions into the secondary side of the relay, engineers can verify that the relay operates correctly and initiates protective actions as intended [9].

This testing helps ensure that the relay will respond accurately in real fault scenarios, providing necessary protection for electrical systems and equipment. It is an essential part of commissioning and periodic maintenance to guarantee the overall reliability of the protection scheme [10]. It helps ensure that the relay detects the fault, discriminates between various fault types, and operates the protective devices accurately. Ultimately, secondary injections with simulated currents enable comprehensive testing of the relay's performance under fault conditions, contributing to the overall efficiency and reliability of the electrical protection system.

Analysis of the efficiency of any protection relays can be done by comparing the tripping times from the abnormal currents injected. The amount of current injected, T nominal, T actual, and deviation, can be used as the measure of efficiency and accuracy of operation of that specific relay [9].

Figure 3 shows the typical example of a modern substation that is using IEDs with 61850 standards, with all three operational levels.

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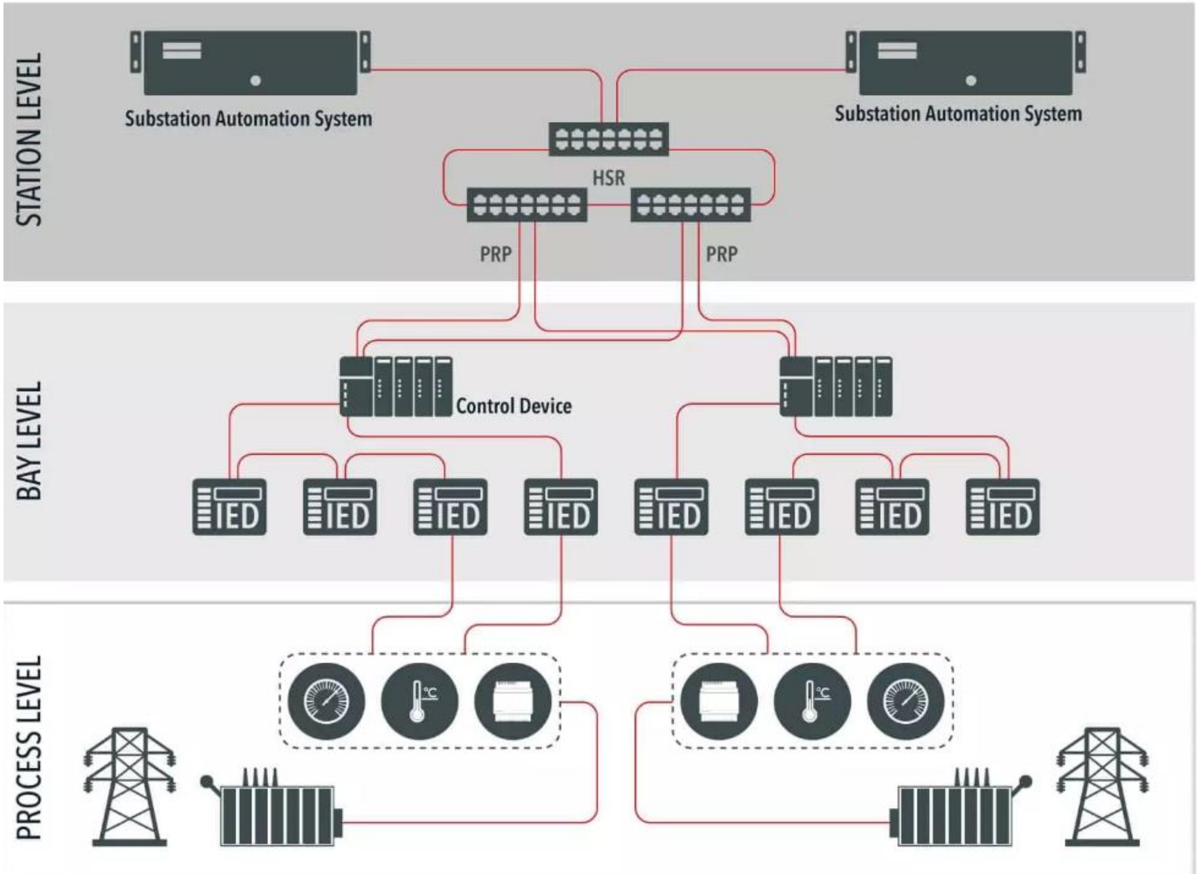

Figure 3.
Substation architecture configuration for IEDs with 61850 standards.

The substation that is using IEDs with 61850 standards has three main levels. These levels are the process control level, bay level, and station level. IEDs are the interconnecting part between the process level and the station level. The function of the station level is to control and monitor the substation at a global level, as well as communicate with remote-controlled IEDs. At this level, HMI, Ethernet switches, gateway, and firewalls are gathered in a control room. These elements are interconnected by a station LAN whose communication media is usually high-speed Ethernet cable or optical fibre [11].

The bay level is a connection level between the primary plant equipment with the station level. This level is situated between the switch yard and station and the control room. The function of each IED is to perform control, protection, and monitoring functions. All the bay IEDs are grouped into a metallic cubicle and placed in local control rooms. The process level includes analogue devices, such as current/voltage transformers (CTs/VTs), circuit breakers, and circuit switches. At this level, this is where the high voltages are stepped down for control purposes [12].

Figure 4 shows a figure of a traditional substation that uses a hardwired configuration that is used by microprocessor-based relays.

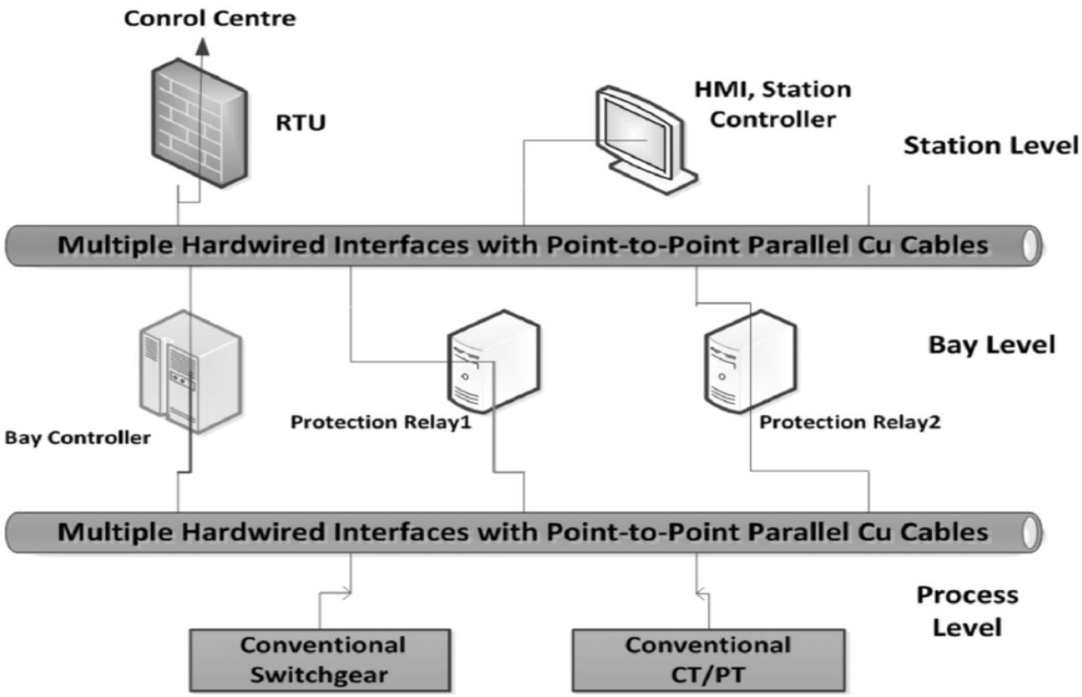

Figure 4.
Substation architecture configuration with microprocessor-based relays.

The overall substation architecture configuration of a substation with microprocessor-based relays has three main bay levels. The station level is where the overall control of a substation is achieved. Usually, there will be an HMI (human interphase) unit station controller and the RTU. The functionality of the HMI and the RTU is to execute control commands and monitoring. The second middle level is the bay-control level, which consists of the bay controller and microprocessor-based relays. This level acts as the heartbeat of the overall substation automation scheme and the operation ultimately is the link between the control level and the process level where the switching units and the main voltage intakes are situated.

The last level is the process level. At this level, there are conventional current transformers and voltage transformers. The conventional switchgear is also situated at this level. The functionality of switchgear is to control the distribution of electricity from the main high-voltage yard to the bay level of the substation.

3.2. Guidelines for Electrical Substation Automation Technology Migration

The list in the Table 1 shows the common operation checklist that exists between microprocessor-based relays with traditional protocols and IEDs with 61850 standards. The automation scheme of IEDs with 61850 standards has more operational functions compared to microprocessor-based relays with traditional automation protocols. Automation engineers who wish to migrate from substations that are using traditional protocols to substations with the latest automation standards can use the following common checklist [13].

Table 1.
Common migration checklist from traditional automation to the latest automation standards [13].

Automation scheme function	Microprocessor-based relays with traditional automation protocol	IEDs with 61850 standards	The solution offered by IEDs with 61850 standards
Basic protection	Available	Available	Currents and voltage functions are available in both schemes, but fast acting is only provided by GOOSE.
Interoperability	Not available	Available	Not vendor-specific; same language on IEDs
Flexibility	Not available	Available	Protection files can be downloaded using the Internet of Things.
Control	Not entirely available	Available	Remote-control functions are available
Large data	Not available	Available	Multiple data transfers are available, especially with the GOOSE application
Monitoring	Not available	Available	Overall substation monitoring is possible.
Remote analysis	Not available	Available	Remote analysis and downloading of data possible on IEDs with 61850 standards
Self-healing	Not available	Available	Better achieved on IEDs with 61850 standards

Table 2 shows the common merits between microprocessor-based relays with traditional automation protocols and IEDs with 61850 standards. Nine basic automation scheme functions can be compared between the two schemes when migrations are considered by automation engineers [14].

Table 2.
Common operational checklist for both schemes.

Automation scheme function	Microprocessor-based relays with traditional automation protocol	IEDs with 61850 standards
Costs	High operational costs	Low operational costs
Reliability	Not entirely reliable	High reliability
Cyber security	Not entirely secured	Cyber threats are there
Speed of operation	Slow due to a great deal of wiring	Very fast due to RJ45 cables
Selectivity	Average	Very high selectivity
Failure modes	High failure modes	Average failure modes
Flexibility	Not entirely flexibly	Very flexible
Complexity	More complex wiring	Easy operation
Maintenance and testing	Periodic maintenance required	Data is monitored and sent to operators in real-time

Figure 5 shows Model A, a migration guideline process that can be used as the guideline for system migration. The model accesses four critical stages that need to be checked if engineers want to start the migration from the legacy system to the newest system [15]. The model has four main structures that need to be thoroughly investigated before the migration takes place. The first structure is evaluation, which looks after the classification, asymmetric migration, and symmetric migration. The second phase is the approach, which deals with big bang migration, accessing the legacy system and the new system. The third phase looks at the process. This part includes all the implementation stages, from project scoping and estimation to post-migration activities. The last and fourth phases look at the benefits of the migration process [16].

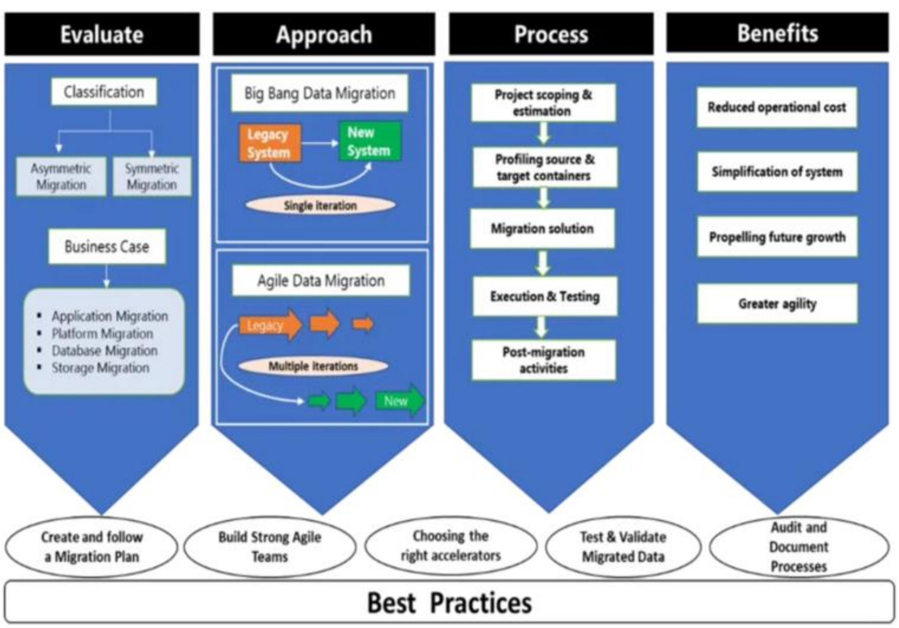

Figure 5.
Guideline for technology-migration process Model A, adapted from (Clive, 2018).

Figure 6 shows a guideline for phases to be accessed before the technology migration project is implemented [17]. Any business need that wants to migrate from the old technology to the newest technology needs to critically access all five phases. Phase one deals with the direction that the business wants to take, also accessing the customer needs. Phase 2 deals with the current state collection and baseline. In this phase, it is critical to access the current state of technology used. Phase 3 accesses the future target or state development, defines the future targets and helps customers align the desired state. Phase 4 deals with the assessments and solution options, and this phase identifies the viable solution with customers. The last phase, 5, deals with the strategy realization development, and finalization of the roadmap [17].

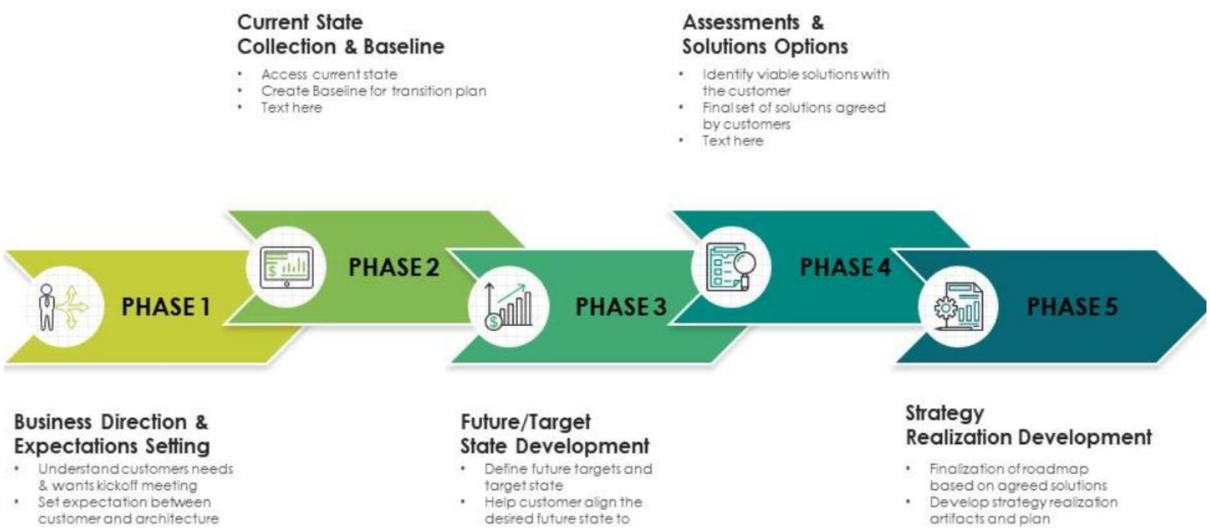

Figure 6.
Guidelines for technology-migration process (model B) [17].

3.3. Evaluating the Automation Efficiency of Substations

Yong and Zhou [18] asserted that it is prudent to understand smart substations to reach a reasonable evaluation system. Zhu and colleagues further explain that many indices can be used to evaluate the efficiency of substations. The key characteristics to be considered when evaluating a power station are [18]:

- *Applicability* – it involves qualitative and quantitative indicators of the substation. These indicators are selected premised on the special nature of the smart substation.
- *Measurable* – assessing indicators requires that they should be measurable; for example, quantitative indicators should be measurable with instruments to scale value, whereas qualitative indicators can be transformed into indirect measurable scale.
- *Association* – evaluating a substation is not a matter of the sum of quantitative indicators; however, there should be a correlation between physical and electrical characteristics.
- *Retrospective* – evaluating a substation should be a continuous process based on before the event, during the event, and after the event to check the consistency of the efficiency of the substation.
- *Comprehensive* selection of an index or construct should comprehensively reflect on the overall energy efficiency of the smart substation, considering one aspect.

Figure 7 presents the energy-efficiency evaluation hierarchy diagram. The Smart Substation evaluation system consists of two components: first, the individual energy consumption characteristics of the substation are evaluated to establish their level. Second, a comprehensive evaluation of the energy consumption and operating characteristics of another substation [18]. The second component of this research is a comprehensive analysis of the energy consumption and operating characteristics of several smart substations. These two can be implemented independently or in conjunction with static energy consumption and dynamic performance to provide a holistic evaluation. In most circumstances, the later assessment's conclusions can be more thoroughly examined [18].

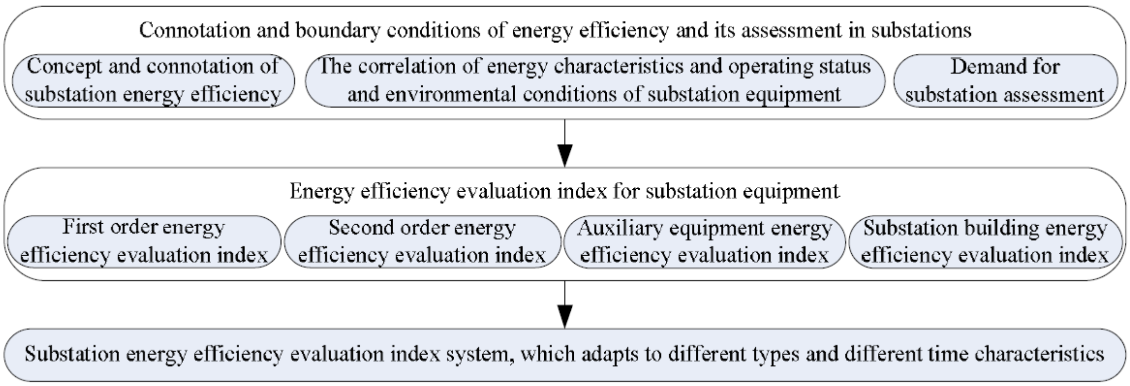

Figure 7.
Energy-efficiency evaluation diagram [15].

The first component of an intelligent substation is divided into two categories, as indicated in Figure 8: conversion equipment in the first-order system and detection and control equipment in the second-order system. Both of those objects have a degree of connection with one another, as well as a degree of dispersion. The content structure can be divided into the following categories: if the relationship between them is managed correctly during the evaluation process, the results will be accurate. It also elaborates that the second component is a complicated system that intelligently transforms and distributes power [18]. It is a collection of energy-conversion equipment and gadgets, as well as office, construction, and other supporting facilities. Smart substations have grown in popularity in recent years. Several substation factors must be considered to conduct a full and effective analysis of the smart substation. When it comes to the process of evaluating something, any aspect is an essential component of the index system. The smart substation's auxiliary index considers both the energy consumption of auxiliary equipment and the energy efficiency of buildings [18].

Figure 8 depicts the two components of evaluating a smart power station [19] Hui [20] explained that to conduct an in-depth examination of energy efficiency, all relevant variables must be considered; collectively, they comprise the I-level evaluation index of smart substations. A modern smart substation is a comprehensive synthesis of technological, economic, social, and practical factors. The utility index primarily reflects the practical application of smart substations, whereas technical indicators primarily reflect smart substation characteristics.

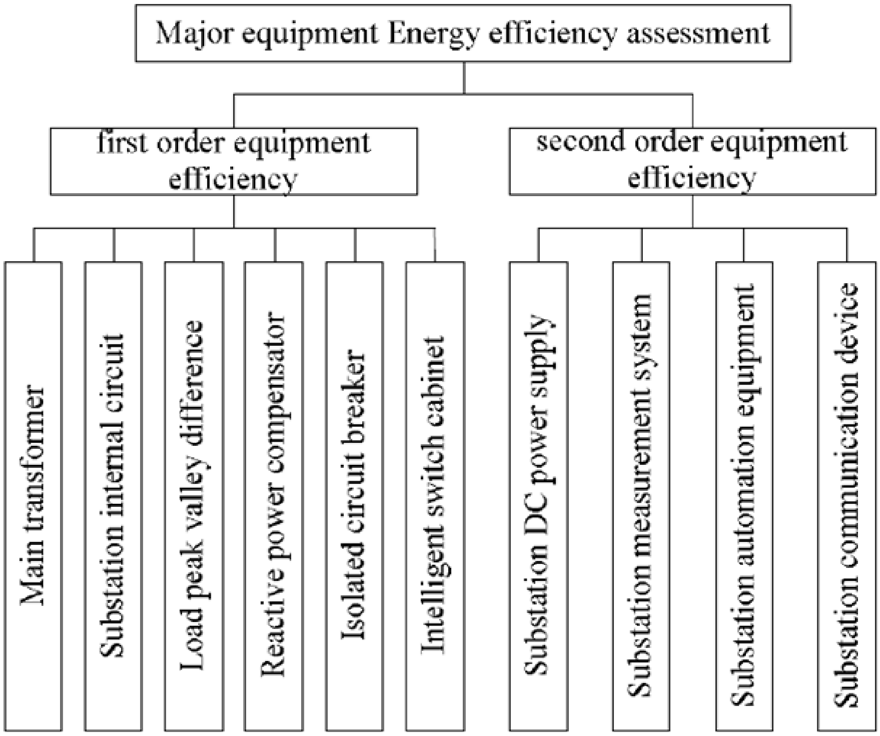

Figure 8.

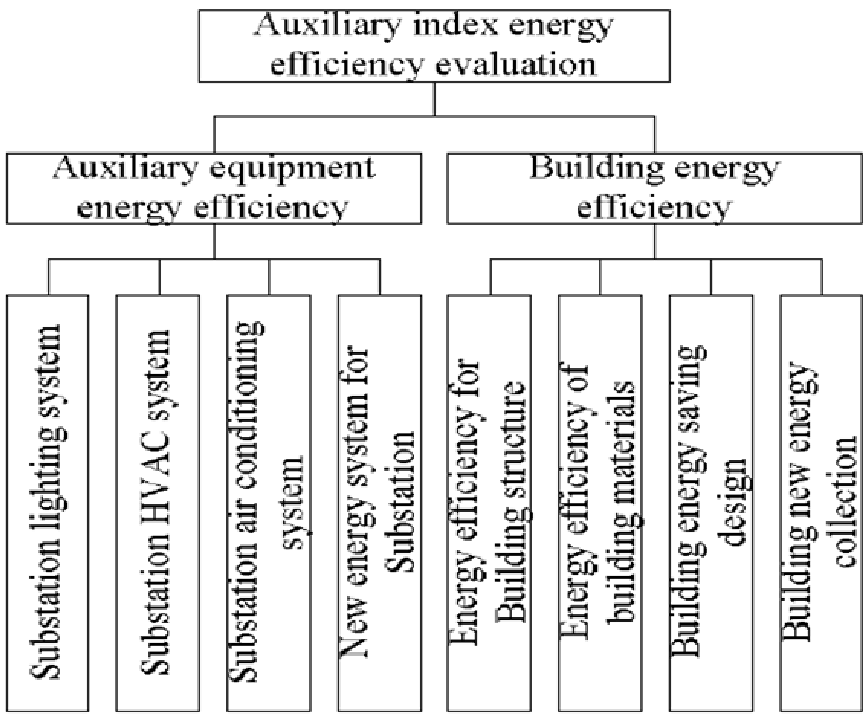

Figure 9.
The two components of evaluating a smart power station [19].

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Economic indicators primarily reflect smart substation cost-efficiency ratios. Social indicators imply social impact and technical indicators imply smart substation features [20]. Figure 10 presents the structure of characteristics that have to be considered when evaluating a substation. This study followed the social index component.

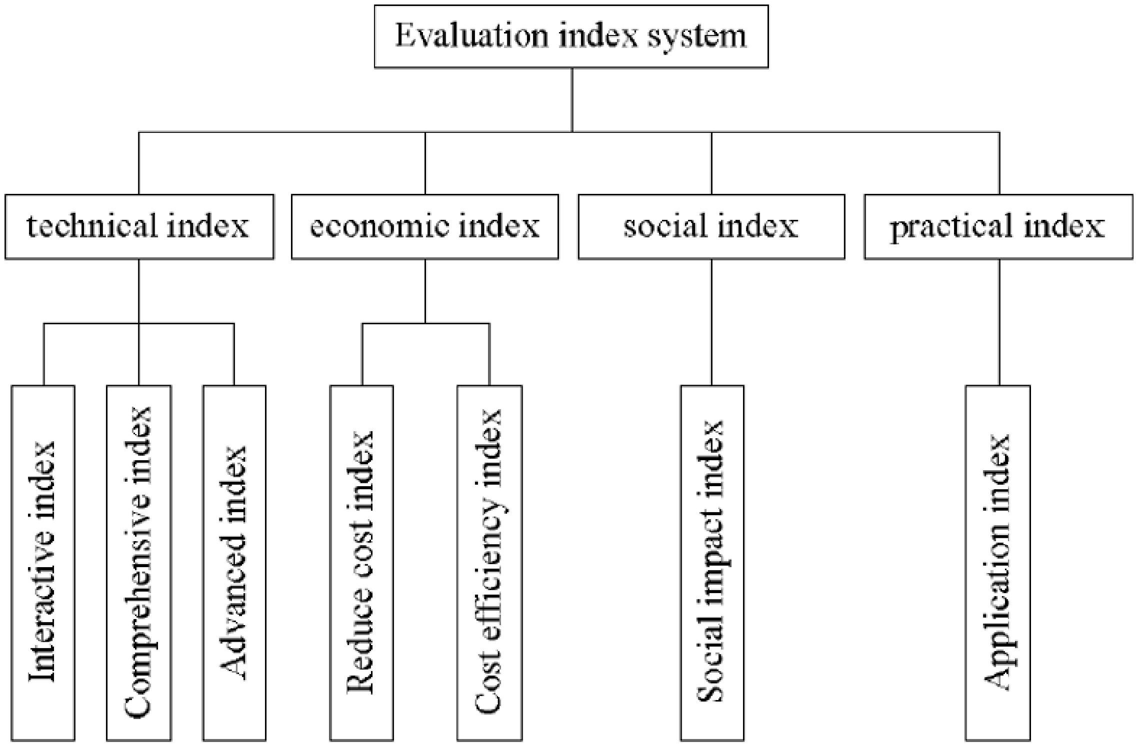

Figure 10.
The structure of the evaluative index system [20].

4. Findings and Discussion

This section presents some outcomes of the existing studies on relays and automation of operational parameters of electrical substations. Over the years, power system industries usually use the bus transfer scheme for supplying system load and to switch to alternative power supply in case of failure or maintenance. The bus transfer has been transformed from a discrete electromechanical relay to a more sophisticated micro-processor-based relay with improved communication capabilities.

Existing studies indicate that one of the recent advances in substation automation includes the development of the International Electrotechnical Commission (IEC) 61850 standard. It is an Ethernet-based communication network for automation and protection within power substation. The IEC 61850 standard promote interoperability among the intelligent electronic devices (IED) for improved performance. It has high functional hierarchy and provides high interoperability among the communication devices in a substation [21-24]. Mokari-Bolhasan. and Taghizadegan-Kalantari [22] conducted a comparative reliability analysis of substation automation architecture based on IEC 61850 standard and concluded that the IEC 61850 standard has a higher reliability compared to traditional based relays.

The IEC 61850 was developed to address some challenges affecting the performance of existing multiple protocols in substation communication. These include multiple propriety protocol, hand-wiring, cost and complexity. With the IEC 61850 system, it is possible to integrate IEDs on the Ethernet communication network thus eliminating the need for hand-wiring among multiple relays [25-27]. IEC 61850 boasts of high loading characteristics and reliability [28-29. The automation of

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substation can also be achieved using the programmable logic control (PLC), SCADA, microcontroller-based control and monitoring system, protection systems, cloud computing and intelligent electronic devices. However, there are some requirements that must be met for the implementation of IEC 61850 standard such as integration into the network and communication architecture and configuration issues amongst others [30]. For instance, there is a need for proper configuration of the IEDs with IEC 61850 which requires the electrical and network expertise.

5. Conclusion and Recommendations

The study aimed to evaluate the electrical automation efficiency between the two scheme designs for protection relays on substations. The challenges associated with the design and operational issues between the microprocessor-based relays with traditional protocols were evaluated. Additionally, the challenges associated with IEDs with 61850 standards were evaluated as well. The evaluation will help to provide an improved framework that will act as a guideline for automation engineers. The parameters associated with each scheme will be assessed and used to assess the merits of each scheme. Since the world inclines to the Fourth and Fifth Industrial Revolution, it is of the utmost importance to invest in digital solutions. Some of the utilities, such as the mining industry, where old technologies are still in use, will benefit from this study by having more knowledge of what they are missing when they are still using traditional automation protocols.

This study is limited to systematic literature review of electrical substation automation operational parameters. Future studies may consider the modelling and simulation of microprocessor-based relays in order to identify some of the challenges mitigating their full deployment electrical substation automation so as to address them.

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