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Electric Grid Modernization

Edited by Mahmoud Ghofrani

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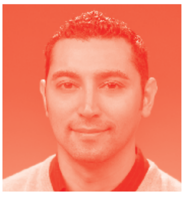
Meet the editor



Mahmoud Ghofrani received a BSc and MSc in Electrical Power Engineering from Amirkabir University of Technology, Iran, and the University of Tehran, respectively. He received his Ph.D. from the University of Nevada, Reno, in 2014. Dr. Ghofrani is currently an associate professor at the School of Science, Technology, Engineering and Mathematics, University of Washington, Bothell. His research interests include power systems operation and planning, renewable energy systems, smart and micro-grids, electric vehicles, and electricity markets. He is the author and co-author of more than fifty publications in top-tier journals and conferences. He has also edited/authored several books and chapters in the field of smart/micro-grids, pattern recognition, and its application in renewable energy forecasting, hybrid renewable energy systems, and more.

Contents

Preface

Electrical grids worldwide are experiencing major changes in terms of energy generation, transmission, delivery, and distribution in order to enhance the entire system's control, reliability, efficiency, and safety. Advanced energy systems and technologies such as renewable sources of energy, energy storage systems, and electric vehicles (EVs) as well as equipment such as sensors, smart meters, and communication devices along with innovations in computing technologies, machine learning, and data analytics are used to modernize the electric grid and the way it is planned, operated, and managed.

This book provides an overview of several aspects of grid modernization including micro-grids, smart grids, energy storage, and communication systems.

The book is organized into six chapters.

Chapter 1 is the introductory chapter that highlights the editor's perspectives on the most important features of electric grid modernization. The chapter includes three main sections regarding micro-grids, smart grids, and energy storage systems and their associated challenges that need to be addressed within the context of grid modernization.

Chapter 2 presents recent trends and applications of smart grids. A comprehensive grid modernization technique is proposed that incorporates the following characteristics:

- controlling and sensing to enhance system consciousness
- smart integration of distributed resources
- enhancing the role of renewable energy
- transportation electrification
- admittance to actionable energy information
- competent transmission and distribution administration

In addition, an integrated mechanism is introduced to resolve grid modernization complications. Future perspectives of grid modernization are also discussed in this chapter.

Chapter 3 presents a Smart Grid Architecture Model (SGAM) for grid modernization planning. It also discusses the integration of a pilot project into the SGAM reference model. The integration is achieved by identifying key performance indicators that generate the most value and impact for the pilot project in the context of smart grids.

Multi-criteria analysis (MCA) in combination with cost-benefit analysis (CBA) is used to facilitate the decision-making and evaluation of smart grid projects. In addition, a case study is presented for distribution grid planning for rural smart grids. The application of the SGAM reference model and combined MCA–CBA for the case study is demonstrated to increase local economic development and reduce CO_2 emission among other values.

Chapter 4 introduces advanced communication and control methods for smart grids. Intelligent electronic devices (IEDs) and their performances are tested and compared from the reliability perspective. This chapter explains IEC 61850 standard for communication systems and its extension to IEC 61850-7-420, which facilitates communication among various distributed energy resources (DERs) in micro-grids. A lightweight IED is developed and implemented on a microcontroller as well as on an FPGA. The performance is evaluated through Hardware-in-the-Loop (HIL) testing in terms of communication latency, processing time, and control action. The chapter concludes that FPGA performs better than other microcontrollers and, as such, is better suited as a micro-grid controller.

Chapter 5 reviews different energy storage technologies including pumped hydro, supercapacitors, flywheel, thermal, and battery storage systems, and their role in renewable integration. Applications of energy storage systems for energy and capacity, ancillary services, transmission and distribution services as well as end-use applications such as power quality, demand charge management, time-of-use, and real-time pricing are also discussed. In addition, challenges and opportunities of storage systems applications for renewable integration are presented.

Chapter 6 evaluates the capabilities of the emerging 5G cellular technologies and their integration with a xIoT application such as a smart grid to develop a xIoT-ICT infrastructure. Challenges of communication among various smart grid components are presented, which include grid communications network possession, associated standards, and interoperability. Two 5G-based business and architectural models are proposed for a converged power grid–ICT infrastructure to enable seamless end-to-end interoperability among various communication devices within the smart grid. The proposed models are concluded to facilitate the integration of DERs and enhance grid resiliency.

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Chapter 1

Introductory Chapter: Electric Grid Modernization - Challenges, Solutions, and Opportunities

Mahmoud Ghofrani

1. Introduction

Electrical grids worldwide are experiencing major changes in terms of energy generation, transmission, delivery, and distribution in order to enhance the entire system control, reliability, efficiency, and safety. Advanced energy systems and technologies such as renewable sources of energy, energy storage systems, and electric vehicles (EVs) as well as equipment such as sensors, smart meters, and communication devices along with innovations in computing technologies, machine learning, and data analytics are used to modernize the electric grid and the way it is planned, operated, and managed.

This book provides an overview of several aspects of grid modernization including micro-grids, smart grids, energy storage, and communication systems.

2. Micro-grids

Distributed energy resources (DERs) and their integration into existing electric grids call for innovations in planning and operation of such resources. Micro-grids facilitate this integration and offer flexibility by providing capability to operate in different modes including grid-connected, stand-alone, and hybrid. Microgrids also improve the system reliability and efficiency by optimizing the interaction of DERs such as battery storage, EVs, renewable generation, etc. Challenges and complications associated with operation, reliability, control, and protection need to be addressed comprehensively in the design phase for the successful implementation of micro-grids throughout the electric grid [1].

3. Smart grids

Unlike traditional electric grids with unidirectional flow of power from generators to consumers, smart grids provide bidirectional flow of both power and data to offer additional benefits including DER integration, data-driven and automated functions such as self-healing actions, and self-awareness, among others.

Smart grid development involves several challenges such as outdated technology, security vulnerabilities in its computation, communication and control subsystems, and interaction among smart grid main components including software, hardware, network, user, server, and data. In addition, high volume, high velocity, and high variety data generated by sensors, smart meters, phasor measurement units (PMUS), and automated revenue metering systems (ARMs) create big data which requires big data analytics and processing methods, and associated technologies to optimally, securely and reliably store and process such data [2].

4. Energy storage systems

Energy storage systems facilitate integration of intermittent renewable sources such as wind and solar by charging during periods of high renewable generation and discharging when renewable generation is deficient. This provides several benefits such as renewable energy arbitrage, energy, ancillary services, hedge against forecast uncertainty, etc. [3]. However, the charging/discharging of storage systems and their coordination with renewable generation must be optimized in consideration of the system operation.

EVs and their battery storage systems can also be used for renewable integration in modern electric grids [4]. However, the EVs adoption for such service is more complicated than energy storage systems due to their mobility and stochastic driving patterns. Stochastic optimization is therefore required to optimally charge and discharge EVS while providing incentives for EV drivers to participate in such services [5].

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Chapter 2

Smart Grid Modernization: Opportunities and Challenges

Saumen Dhara, Alok Kumar Shrivastav and Pradip Kumar Sadhu

Abstract

Recently, there have been significant technological approaches for the bulk power grid. The customer demand is associated with conventional grid coupled large central generating stations through a high voltage transmission to a distribution system. Urban transmission systems are consistently progressing to meet the increasing needs for power and to replace old-pattern generation with native renewable generation and power provisions from outward green energy resources. Power grid is undergoing remarkable modernization towards advanced consistency, greater efficiency, and less cost by the incorporation of renewable energy and developed control technology. Quick developing nature of grid, consumer needs, and industrial invention situates substation modernization at the leading of grid transformation. Smart grid is essential to accomplish all the fastest technological reformations occurring in generation, transmission and distribution (T&D) of electric power, with growing application of sensors, computers and communications. In this study the recent trend and application of electric power grid is briefly enunciated.

Keywords: Power grid, renewable generation, transmission and distribution system, substation, electrified transportation system, smart meters, sensors, IoT based smart grid, Big data analysis

1. Introduction

For the past 100 years, substantial revolutionary developments have been made in the mass electricity system. With new developments including easily growing and ecological cordial generation tools, higher voltage apparatus, power electronics as high voltage direct current (HVDC) systems and versatile alternating current transmission system (FACTS) products, the grid network has been constantly modernised. Also, the outcomes of an efficient grid comprise, progression in computerised controlling process, safety and protection, voltage regulation, grid administration systems for development of power network, real-time activities, upkeep strategies for load demand response and energy-effective load management. For delivering of power, generating stations are contained basically of steam power stations that pre-owned non-renewable energy sources and hydro turbines which are turned into large inertia turbines. The transmission framework developed from nearby and provincial grids into a big interlinked system that was overseen by facilitated working and arranging techniques. Maximum load demands, advanced energy utilisation at unsurprising rates, and technical innovations are executed in a comparatively distinct operative and managerial atmosphere.

The electrical grid is a dazzling illustration of human inventiveness and designing of modern power network. It spans a huge number of miles, is taken care of by a large number of manufacturing amenities, and assists hundred millions of consumers. It is the biggest machine ever assembled and one that enables each figuring scheme, system administrations, and corresponding advancement of the Internet Era.

Grid network upgradation has been catch-all expression to allude variations required in the electric grid to familiarise all the fastest innovative changes occurring in the generation, transmission and distribution of electric power. Recent Grid is fundamental to guaranteeing the energy networks that empower our human lives and support our economic aspects that are prevented from future troublesome actions. Nevertheless, beyond just enlightening by reforming the power grid additionally makes a link to achieve significant ground on moderating the future effects of environmental change. All through the nation, efficacies and energy corporations have a remarkable benefit to spend in advancements and resolutions that improve the deceivability and control that operates the electric framework. These advances empower a scope of new capacities that improve flexibility, diminish working expenses and enhancing the effectivity by successfully upgrading the nature of electric assistance. These equivalent advances can likewise strengthen fundamental capacities to producing development on environment.

Inventions for power grid technologies build opportunities to enable T&D workflows. Smart data metering technology, grid management systems (DMS/TMS), resource administration phases and geospacer application structures have also been covered by many rounds of grid engineering expenditures in developed economies. The latest solutions include networks and grids. These frameworks were broadly observed as segregated resolutions providing soloed framework necessities. Therefore, for these reasons, presently the reformation of grid is become troublesome. Service organisations have been reacted by proposing some complete grid-modernization strategies. In 2018, the requested grid modernization initiatives earned a mere $2 billion out of $15 billion. There is clearly a difference between the sort of service organisations suggest and what controls believe to be correct.

However, the grid network modernization ventures may meet a several aspirations. It is significant that the suitable protections are set up to assure benefits, which are exacerbated and consumer expenses are overseen. These incorporations, for adjusting the local arrangement destinations to extensive range distribution strategies, guaranteeing all advantage streams are run after, and checking that the aftereffects of these ventures are estimated against the normal results once they are set up. A few states are presently driving comprehensive partner cycles to guarantee these ventures and different contemplations are represented.

An efficient grid that saves reasonable energy expenses and advances monetary development is essential to our present-day civilization. Over its accomplishment, the grid ensures about the efficiency and excellence of satisfaction of people in the future by assisting with guaranteeing our energy remains consistently accessible and progressively green and maintainable. Specifically, grid modernization technique frequently suggests the growing utilisation of sensing instruments, PCs and communications, i.e., there are several techniques to keep up.

By the incorporation of the environmentally friendly energy sources making the transmission grid intensely complex to comprehend and prototype to apply a new controlling or activation techniques for advancements. This requires a quick prototyping stage for investigation and experimenting under the innovative novel broadcasting illustration. Such a structure ought to be profoundly incorporated, closed loop, and proficient for impersonating a substantive power grid for examining under new controls or algorithms. Though, conventional programming simulation packages generally perform specific errands, for example, dynamic simulation or state assessment yet come up short on the capacity of giving an incorporated closed-loop platform. To acquire practical information for investigation under the new transmission worldview for working on a genuine power grid network. Moreover, Substation development stays a basic component of state-of- the-art electric power networks. Substation improvements incorporate the utilisation of hardware tests, maintainable practices, digitization, and progressive solutions for the needs of large power network with alongside recompense of reactive power and large-distance renewable incorporation of sustainable power sources. Substations should progressively act not just in light of a legitimate concern for the large grid, yet additionally on the ground of decision making at the neighbourhood level. They are dependent on knowledge processing areas to improve potential costs due to the introduction of technological advances.

2. Necessity of grid modernization

To attaining various goals, one major question is how much should be capitalised in the grid as too much (Distributed Energy Resources) DER schemes assist loads except using the grid for prolonged intervals of time. The consistency and security of the electric power supply load will possibly be impaired when renewable power supply is not available or is not subject to renewable power loss in the transmission and distribution (T&D) grid network. It is therefore necessary to improve the capacity of the T&D structure to host and enable increasing DER penetration ranges.

The transformation of the grid and the spread of DER are certainly related, however, it is not necessary for the prior to this transformation. Benefits like Commonwealth Edison (ComEd) and Centre Point, operating in distribution areas that have evolving DER ranges, have been effectively employed with the continuation of incremental grid continuity to modernise grid networks. Resilience and network performance focus growing network prospects, customer facilities, and substitution of the old configuration. The 2600 numbers of smart on–off switches and 4,000 numbers smart sensor meters have been arranged since 2012, and the ComEd Energy Grid Restoration Act has remained capable of removing nearly 4.8 million customer disturbances. The restructured networks would make it easier to transition to a new trend requiring a deeper penetration of DERs, which has been a further benefit to grid modernisation.

States such as California and Hawaii violently endorse DER's deployment in order to accomplish the RPS objectives and shift a new delivery grid rapidly into successful service. In view of the pre-arranged achievement of grid equivalence by distributed generation in certain marketplaces, a standardised higher-range implementation of DERs is also inevitable. In order to facilitate the usual practice for present and future delivery systems, the accompaniments in grid restructuring infrastructures and schemes should be calculated with necessary savings.

3. Features of changing electric power grid networks

The fast improvement in the electricity grid network is guided by universal rules, finances and technological innovations. The improvement of the power network to ensure that green and sustainable energy supply consistent electricity. The energy grid has switched into the latest two-way power flow scheme with a very fast range and continues as shown in **Figure 1**.

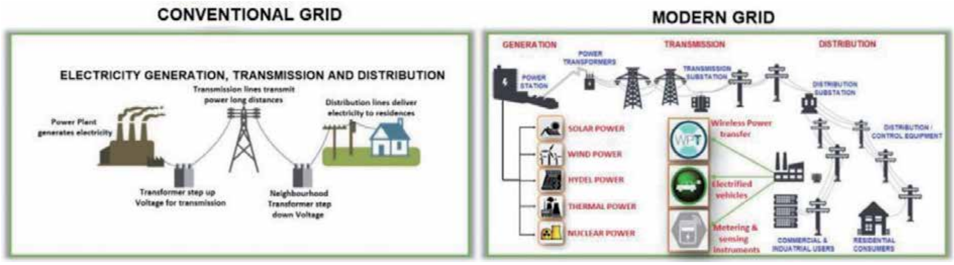

Figure 1.
Transition from traditional to new electrical grid with two-way power flow [1].

The deregulation of electricity utilities in the United Kingdom and elsewhere was a significant cause of electrical markets. Battle eliminated the risk from the stockholders' rate spenders, lowered customer prices and enhanced rapid modernisation. The initiations of the markets and environmental policies have enabled large variations in the mixing of fuel, producing plants that produce coal and nuclear power as a resourceful natural gas-fired connective cycle unit. The current competition among the large electricity markets and universal plans which support or promote other traditions to use energy efficient renewable sources and to respond to huge demands. In terms of financing, such technical advances have steadily benefitted, leading to lower consumer prices, improved ecological management and deployment. The governing reform continues to lead to reforms in the utility company to address the problems of electricity supply system management. The ruling revolution promotes tremendous economic growth. The IoT simplifies additional choices that can be taken at geographic, remote or mechanical levels by customers to promote customer differences and preferences. The distribution system was engineered and developed essentially to meet full demand for load and transmit power initially over radial substructures. Today, however, more customers are increasingly using the grid to offset their own generation and load demand, as well as to be a holdup supply when their regional generation of energy is insufficient.

4. A comprehensive grid modernization technique

Electric grid upgradation is vital to confirming the energy saving schemes that empower our lives and support our budget which prevents from forthcoming troublesome actions. But far basically the grid upgradation also makes a situation to make significant development on modifying the forthcoming influences of environmental alteration.

All over the country, efficacies and energy corporations have an unparalleled benefit to capitalise in machineries and resolutions that improve the perceptibility and monitoring that controls the power network. So, technological innovations empower a series of novel abilities that progress resiliency, decrease working expenses and rise effectiveness. Hence, similar knowledges can also authorise introductory competences to creating development on environment.

However, savings for grid upgradation may synchronise a lot of ideas. It is significant that the proper precautions are in event to confirm the assistances are exploited and consumer expenses are controlled. These comprises line up provincial plan objectives with long-term deployment strategies, guaranteeing all helping streams are followed, and authenticating that the outcomes of these savings are surveyed in contradiction of the predictable results once they are in event.

Numerous countries are now foremost comprehensive and shareholder procedures to confirm these and other contemplations are taken by consideration. Therefore, an efficient grid that retains reasonable energy expenses and supports financial growth is emergent to our existing civilization. Numerous characteristics of Grid modernization are discussed as follows as indicated on **Figure 2**.

4.1 Controlling and sensing for improving system consciousness

With the invention of miscellaneous cost-effective Controlling and Sensing instruments, the efficiency of electric grid in the power network has enhanced intensely. Numerous explanations have been found more specifically throughout the grid network on HV substations or main transmission lines. Nowadays, alike resolutions are discovering their technique down into the distribution system. System operators are capable to sensing how apparatus throughout the network is performing, the disorder for outages, the situation of power delivery and more altogether in nearby actual time.

Although, these innovative skills can reinforce the electrical grid efficiency and progress physical framework competence. The information could assist to improve workplaces service and lesser expenses for customers as well. A foundational expertise of controlling and sensing substructure is developed for smart metering technique. In US from 2010 to 2016 the utilisation of smart meters become gradually increasing in the ratio of 8.7% to 42.8% [3]. Over these numerically coupled meters, grid workers are not only capable to protect on operational expenses, but may also get extra precise understandings, well consciousness of disorder for outages and other assistances that come from more power and energy usage information. Nowadays, Grid utilizations are discovering opportunities through an innovative generating skill for resolutions of power system network. Comprehensibly, these are often highlighted on troublesome set-up to avoid disastrous collapse and disturbances like natural disasters. Grid mechanics must work with

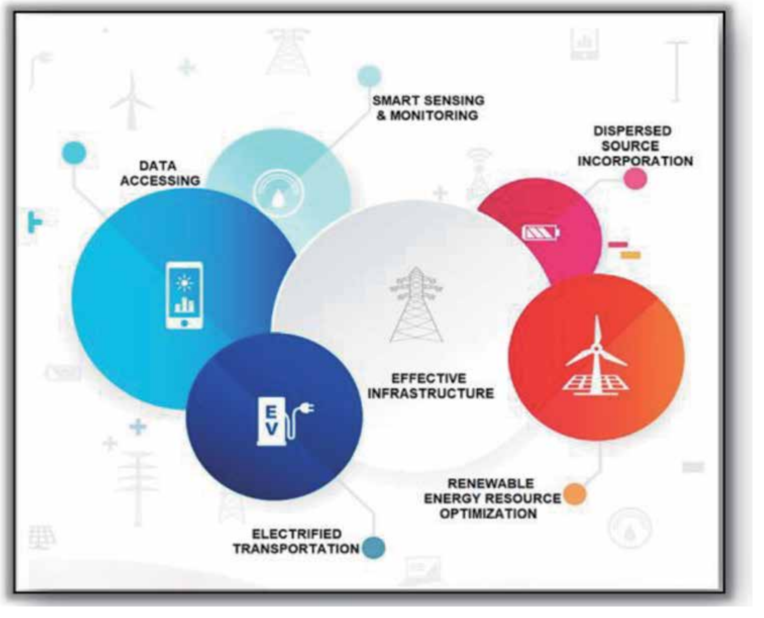

Figure 2.
Schematic diagram of grid modernization aspects [2].

stakeholders to analyse system requirements, contemplate accessible resolutions and describe the commercial event to move elsewhere for demos and keep attention for mounted distributions. For instance, sensing devices at substations can control the health of properties and recognise when pro-active upkeep is essential.

Moving frontward, controlling results will correspondingly comprise sophisticated analytics competences to originate valuable, actionable information from the data streams coming from the propagation of smart meters and sensors monitoring. This system of controlling functions could principally work as a grids nervous system.

Analytical explanations are progressively accessible to solve the 'big data' task of making suitable choices based on massive quantities of data. Information on energy saving schemes can be vary based on ranging from more energy requirements and adequate facility of various grid substructure properties. These explanations frequently run as a grid network cloud.

4.2 Smart incorporation of several dispersed resources

In view of grid modernization, the multiplicity of low-range supply sources and progressively affianced energy subscribers for adding up to a sturdier green energy resource. These sources gradually have the potential to gratify a substantial amount of our forthcoming grid energy needs and while incorporated at the allowable range. These systems can similarly play a greater role in affording other facilities to meet our energy scheme requirements.

Dispersed energy resources cover behind power generation properties, such as roof solar arrangements, to include an increasing set of generating and efficacy opportunities. The associated heat and power systems, micro-turbines turned by airstream or water, energy storing over the usage of batteries, demand side administration resolutions and microgrids where miscellaneous dispersed resources are combined to power the requirements of resident amenities.

Demand side administration, in specific, remains to develop to assist the requirements of energy subscribers and energy system workers alike. Interconnections and controls explanations are making it probable to schedule and regulate refrigeration, heating and additional energy usages in households and industries and minor consumption throughout intervals of highest demand. Logically to handling the energy usage takes suppleness to the network and supports for inspiring the enhanced utilisation of energy throughout time intervals where it is less expensive and/or when the supply has very small carbon strength.

Services, controllers and shareholders are also commencing to assess and arranging the role of 'non-wires alternatives' which could play in acceding or eradicating the necessity to increase transmission, distribution and generation capability. These substitute grid infrastructure possibilities may contain demand side programs, system effectiveness, storing and other smart-grid resolutions that may gratify anticipated demand and necessities of the grid throughout other difficult circumstances of the power system.

When presenting new machineries into the energy network, it's significant to embrace the wide use of standards and reconstruct paths to inspire inter portability once the standards are executed. These steps will support to avert the problems for individuals and industries wanting to link their dispersed assets efficiently into the grid, and will also help prevent grid workers from having stranded resources in the form of solutions to assimilate various dispersed sources. **Figure 3** shows after attaining 1 million solar powers setting up in 2016, the U.S. is composed to reach 2 million in 2018 and 4 million by 2022, which is linked with the new grid set up techniques [5].

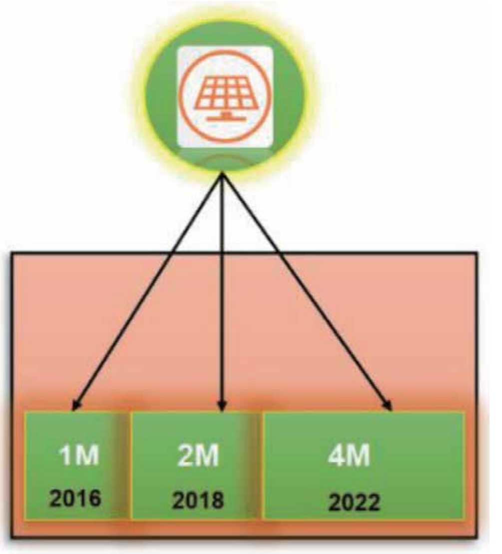

Figure 3.
Graphical diagram of solar power installations related to grid modernization aspects [4].

4.3 Enhancing the role of renewable energy

Renewable energy assets have become a principal generating source of power in the United States. 15% of electricity produce from renewable energy assets in 2016 [6]. Mostly from large upsurges in wind and solar energy, this up about 50% throughout the past five years. The green energy flourishment has become guided by dropping the cost of green energy sources, dynamic awareness from peoples and industries. The loyal (mostly sub- nationwide) policies are decided how to reduce forthcoming low carbon energy emission for green environment. Covering this tendency, those renewable sources make up important portion of the energy mixing, necessitates grid upgradation savings and resolutions at particular range.

For upgradation of electrical grid, the green energy investors are making a path to make it stronger, mainly at the regional level. In few areas, the required driving force make an influence on weather and carbon management, which also marks in clean air across societies. In other aspects it may be career making for financial activity or the reduction in electricity expenses that is capable for renewable energy generation.

Many societies (such as Hawaii and recently St. Louis) throughout the nation have a green energy (solar or wind) prerequisite or aim, contingent in big part on their source and variety of techniques. In particular areas similarly utilise geothermal, hydro and renewable biofuels, while others may advance in marine/ocean energy generation. Consistent asset management will persist centrally to the dependability of energy schemes with important stages of green energy.

An energy scheme with important levels of renewable resources will require flexible grid reconstruction resolutions to enhance the consumption of green energy. Emerging this suppleness will likely comprise transmission arrangement shape outs and it will contain progress of other important zones. For example, particular grid upgrading implications can result in well predicting and system modelling. Grid workers can plan for the requirements of the system, in consideration of environment and atmospheric conditions. Apparatuses used into resource scheduling and effective grid controlling schemes, grid workers will be capable to maximise the efficiency of green energy resources.

Bringing a mix of green energy to unfledged zones where it could be used an extra transmission and distribution arrangement, though, all principal resourceful savings would be considered. A miscellaneous set of grid administration solutions will allow societies and wider areas of the system to run on important levels of green energy sources.

4.4 Electrified transportation systems

Zero emissions vehicles drive new beginnings for conveniences while meaningfully decarbonizing transport systems. The electric power subdivision carbon emissions have dropped for the first time since the late 1970s, under those of the transportation division [7]. To drive carbon and other emissions even lower, the U. S. might strengthen its emphasis on electrified vehicles and guaranteeing they are power-driven with green energy. Additionally, to making noteworthy development on environment, electric cars can generate new marketplaces for products and services that catalyse financial progress and careers.

In the United States approximately 0.2% cars are electrified among more than 260 million recorded travelling cars [8]. However recently the quantity is rapidly rising states. Bloomberg Novel Energy Economics guesstimates that electrified transportation systems will make up 54% of all new low-duty cycle vehicles in the U.S. by 2040 and add as much as 5% of worldwide power consumption [9].

This quick electrified transportation development can reinforce grid worker corporate models as a result of the improved revenues that come from millions of electric cars. Furthermore, empowering the infrastructure to charge and operate electric cars presents an important commercial prospect for grid workers and other service benefactors.

4.5 Admittance to actionable energy information

Serving customers make smart conclusions that assist themselves and the imparted electric grid. Most consumers obtain data on their energy usage once a month in a usefulness bill, and this comes to them some time after they have used up it. Given the postponement and absence of detail intricate with information provided at this stage, this procedure does not authorise consumers to accomplish their energy usage. Evolving information accessing standards allowed by grid reconstruction completely alter this dynamic by providing consumers with expressive, existing and illegal information to take control of their energy usage.

With the advent of new energy opportunities and services including roof mounted solar power, smart thermostats, and building computerization schemes, few customers and industries aren't eager to just take [10] an inactive role when it comes to their energy usage. Rendering to the Smart Energy Customer Cooperative, customers are extremely attentive to take part in real-time reporting of electricity outages (66%), energy usage information (65%) and contribution for certain rating programs (59%).

Massive quantities of information from grid upgrading savings can be composed from smart meters, connected thermostats and other sources. New applications then turn that data into actionable data for energy users in an easy-to-recognise and easy-to-engage format. This data provided by efficacies or other third parties equips people and industries with the tools they need to dispose how to accomplish their energy and power their lives in the ways to maximum gratifying them.

Efficacies and several third-party benefactors have the prospect to strike the right stability of getting deep information to those that demand it, and providing easier options to others who prefer less-involved energy implications. Henceforth their level of engagement, energy customers want more than just lesser expenses. Their welfares can comprise:

- Improved interconnections for outages and refurbishment;
- Possibilities for retrieving green energy;
- Signing up for demand administration programs;
- Additional resiliency explanations to keep the power on;
- Serving sustenance community-based projects;
- Seeing where their energy arises from; and
- Relating their usage to neighbours or others in alike living circumstances.

These grid competences assist to come back to all energy subscribers in the form of the minor rates.

4.6 Competent transmission and distribution administration

With the variety of available technical solutions, services are capable to not only reconstruct the old substructure and meet future needs, but also proactively capitalise in analytics and controls that upsurge the operation of available apparatuses. These explanations may increase energy scheme competences, profitability, and dependability, while enlightening the excellence of electrical grid facility in a maintainable way.

The power grid has become planned with substantial dismissals in the sequence to confirm that through several active situations, from blackouts to overloading condition, consistent electrical facility might be afforded to all consumers. For example, the electric grid is constructed to maintain the uppermost level of power needs. A cost-efficient modern grid may work as a platform that allows numerous sources to meet requirements of electrical load demand. These principal effective savings in energy substructure help confirm that consumers save currency and net profit for an additional suitable level for the schemes and solutions that consistently tie them into the power grid.

For illustration, permitting dispatch when specific transmission paths are limited for transmits a signal to power workers regarding transmission measurements. This request for changes in power generation stages may be more cost-efficient than supplementary transmission build-outs, and supports to rise the utilisation of present substructure [11]. Other proficiencies empowered by grid reconstruction savings can recover the total quality of electric service. Voltage enhancement, for example, uses sensors for better perceptibility into grid maintenance to allow workers to match network voltage more accurately with the electricity demands of consumers. This cost-efficient, proven implantation can progress service, save consumers currency and accept the need for new generation, transmission and distribution.

Well-organised substructure administration does not completely substitute the need for novel substructure. EEI reports that its investor-owned utility associates increased transmission arrangement savings from around $10B a year in 2010 to around $20B in 2015, a level which likely only upsurges [12]. The country's energy arrangement and planning are ageing, and making investments in transmission sources to progress dependability, resiliency and to integrate renewable energy. In doing so, however, controllers, customer advocates and others must assess all theoretically reliable solutions to lodge system demands, and incentives should be in place for grid workers to select source active options that align with state and provincial goals.

5. An integrated mechanism to resolve the grid modernization complications

The combined, step-by-step upgrading plan represented in **Figure 4** can be developed with efficiencies first; corporations need to define the performance results that the modernization programs will perform, using the key performance indicator (KPI) and metrics. The first aims to regulate the basic abilities and key investments necessary for achieving the vision. The second aims at furthering business cases for localised grid investments. This can be done in particularly specific uses and are not related to investments. It is crucial to avoid investing in streamlined assets to meet proven needs. Many shareholders – like consumer teams, supply chain players, regulators, and IT firms – do not regularly participate in investment programme development in a soloed investment programme. Investment in grid systems and other business areas is substantially co-related; if this interdependency is not documented and considered, poor implementation plans may arise. The development and implementation of grid modernization plans are assigned insufficient resources. Investments contributing to the objectives of

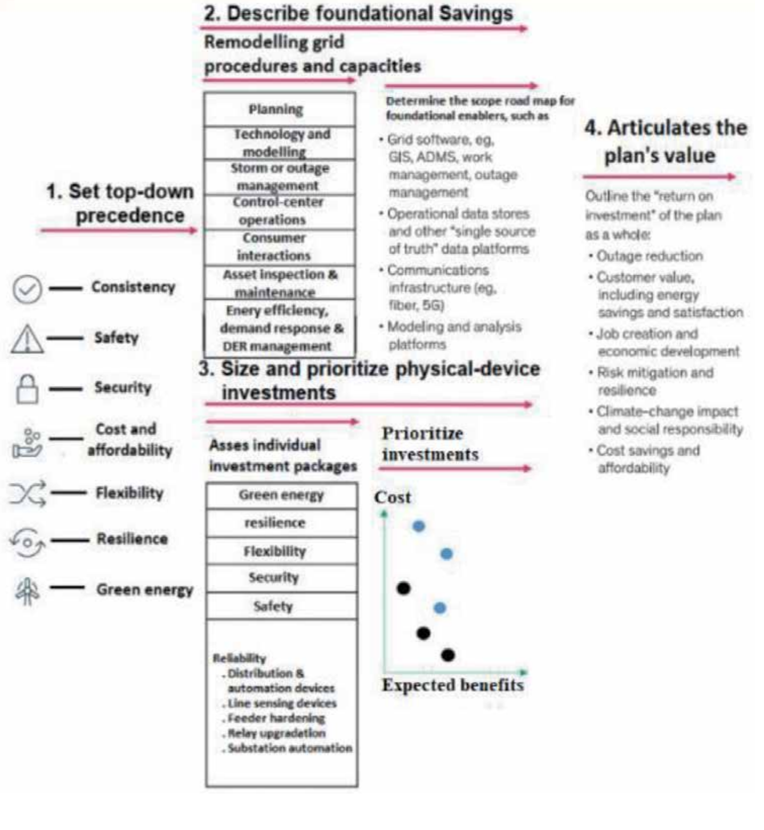

Figure 4.
Grid modernization planning steps [13].

strategic capacity must be given priority, while the immaterial ones should be removed from the capital plan.

T&D personnel who advance a recovery policy to offer maximum client service and persuade controllers of its effectiveness should provide an invented full description of the return of assets to the taxpayer.

5.1 Set top-down precedence's

Utilities used clear and well-known arrangements traditionally for the purpose of justifying their grid projects, namely to endorse their proposals in a dialogue regarding the creation of a consistent electric grid. Utilities have precise metrics (e.g., Consuming Periodic Interruption Index, occupational health and security records) to monitor reliability and safety, and shareholder potential is adversely affected by continuous growth. Otherwise, more capital meant greater market and civilisation reliability. The first step against regulators and consumers is to describe precisely what effectiveness means "modernisation" as seen in **Figure 5**. "Grid modernization" can mean multiple things to different shareholders.

5.2 Define initial savings

Skills are not binary. Some can grow mature and widespread over time across the grid. For example, tracking and control are usually important. Most conveniences therefore have simple monitoring and control skills, though many strive to improve their sophistication over time, as stated in **Figure 6**.

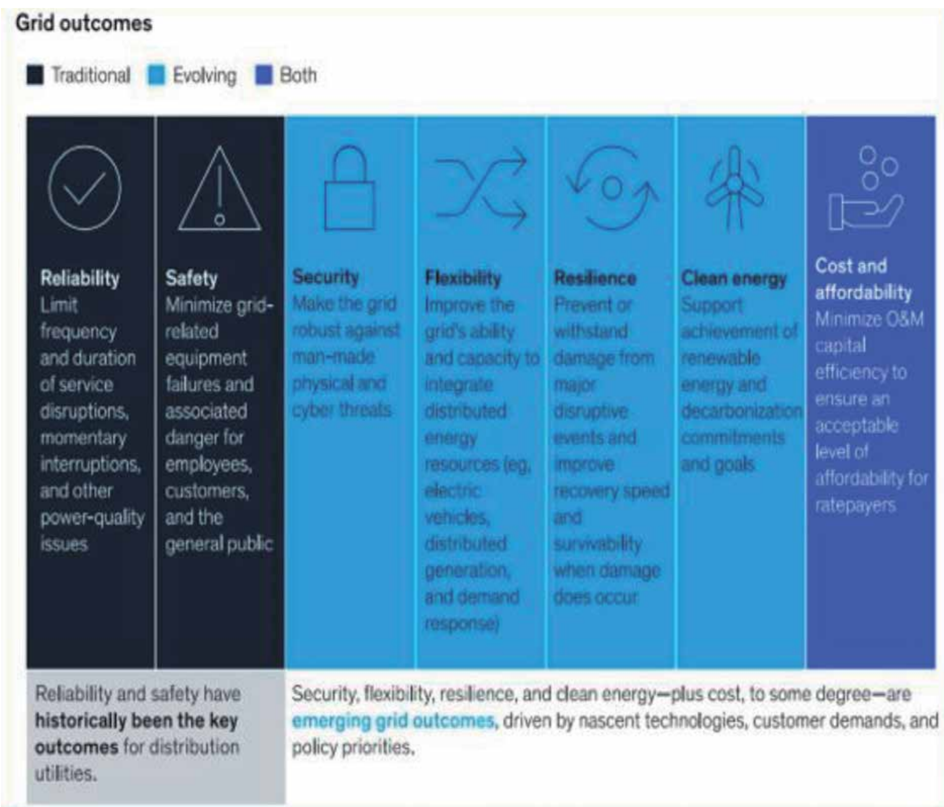

Figure 5.
Steps of grid modernization set top-down priorities [13].

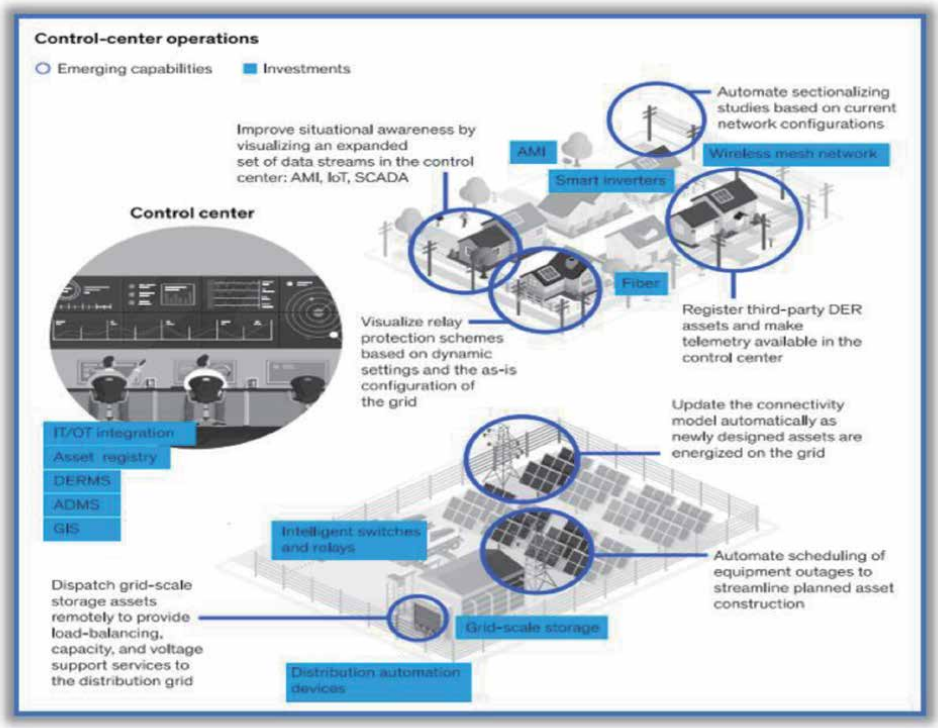

Figure 6.
Step of investments for grid modernization [13].

The basic savings required can be difficult since they are not usually linked to a certain grid or asset. Corporations should concentrate their efforts on the shortcomings in current basic workflows such as network infrastructure, asset design, control and duty systems, with topic, line and line leaders.

5.3 Size and prioritise investment in physical equipment

Media stories on grid-modernisation agendas aim to span millions of policy expansions. Smart automated substations, smart metres for future generation and distribution computerization instruments contain these tracking and control policies (recloses or sectionalizes). However, what is not mentioned is that others programmes depend on the update of out-of-date designs, including transforming substation and feeder into higher voltage. The packaging for savings can then be sized according to the target awareness level of the device and then prioritised on the basis of calculable customer outcomes compared with each box price.

5.4 Manifesting the plan's value

Most initiative refusals in the country are embedded in insufficient reporting of the incentives for taxpayers, and is related to cost savings. This pattern will continue—except for efficiencies that speak of the importance of the consequence of the payer and pledge themselves, if mandatory, to goals that their plans permit. The methods for grid modernisation frequently surpass the number of their elements. The painting of the whole image will make controllers and owners alike more productive and also accountable.

6. Numerous features of grid modernization technique

- Substation developments – The heart and brain of the grid are imaginative substations. The improvement achieved by the substation includes infrastructure testing, durable procedures, digitalisation, and advanced technologies for a range of device requirements, as well as reactive energy compensation and long-term clean energy incorporation of renewable energies. Substitutions must increasingly function, both for the benefit of the wider grid and to help local decision-making. They should act as data collection positions that will boost potential investments in emerging technology. Substations can be fully usable, invisible or enticing to the public in particular in very crowded environments, in an effort to achieve their convenience. Sustainability is a further component of creativity in substations such as the replacement of SF6 methane, greenhouse gas, for sulphur hexafluoride for other gases used in lightweight insulated gas substations (GISs).

- The growth and problems of the Urban Power Grid - The urbanisation of the world is growing demand for electricity in big and mega cities. Land expense and shortage find it impossible to obtain modern transmission rights for traditional routes. Advanced transport technology will effectively enhance current system power, reliability, and usage and increase grid stability in extreme contingencies or disastrous circumstances. These innovations for the enhancement and transformation of urban grid have been taken into account and adopted by electric utilities.

Urban grids have grown over decades with population and inflation and now face multiple extension and technical problems to accommodate more demand growth and related (stringent) criteria in terms of reliability. The exponential growth in demand has pushed power grids closer to their capacity limits. In conditions without sufficient voltage and local reactive energy source, where the infrastructure encounters very severe occurrences, the municipal power grid could be vulnerable to voltage collapse or blackouts.

- The Network extension infrastructure options—Electrical providers have the option to add the following to deal with network expansion issues:

    - new circuits to reduce overloads of circuits or to boost current circuits

    - new transformers or advancement of present ones to mitigate substation overloads

    - new or current transformers to reduce sub-station overloads

    - Phase-shifting transformers for the regulation of active power transfer in mesh networks (PST) also called phase-angle regulators (PARS), sen transformers (TS) as well as VFS (Variable Frequency Transformers).

    - Reactive power compensators for voltage balance and energy shift, for example shunting reactor or condenser banks and Static Var (SVcs), or static sync compensators for energy change (Statcoms).

Figures 7 and **8** is the general metropolitan electricity grid structure. It consists of the major transmission networks extra high-voltage (EHV), the sub-high-voltage

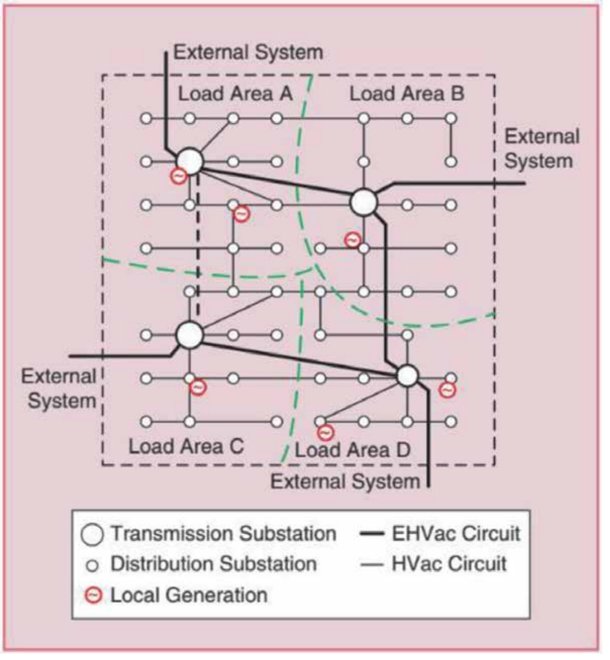

Figure 7.
The urban power grids are typically divided into multiple load areas by electric utilities for convenience in planning and operating of the system [14].

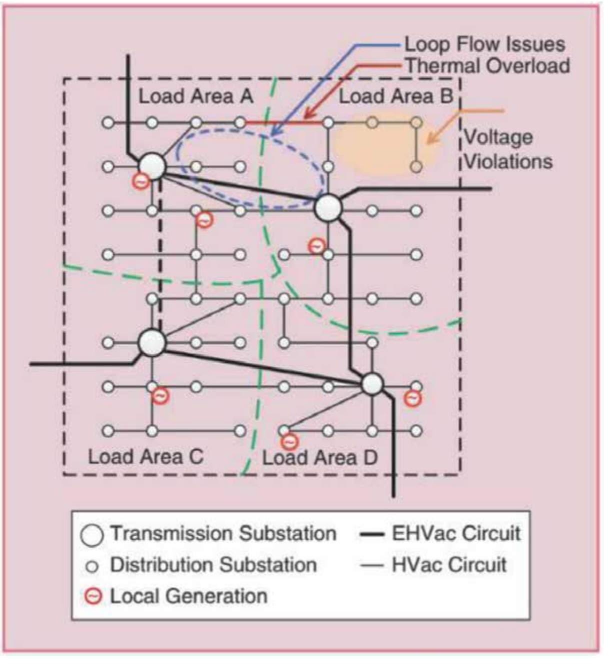

Figure 8.
The optimised network explanations solutions are needed to address for increasing multiple network [14].

transmission networks, transmission substations, primary generation substations and municipal power generation systems. The city grid is normally split into load areas or load areas that determine the portions of the grid allotted to facilitate system planning and electricity operations. The charging areas which have different

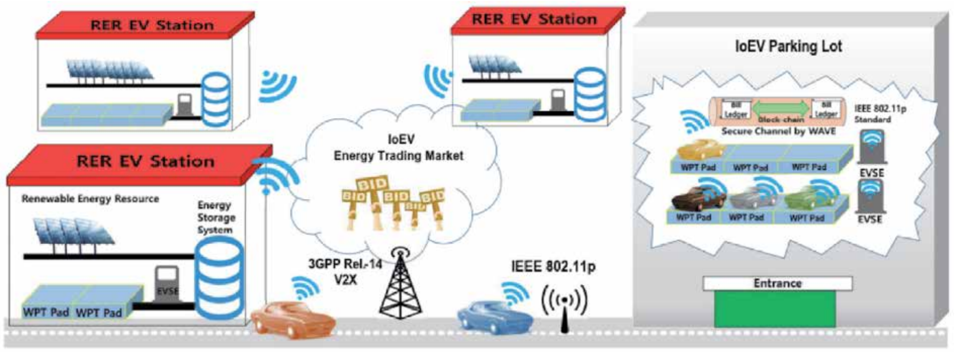

Figure 9.
The architecture of the relaxed framework suggested. (IoEV charges the electricity automatically via WPT in the proposed system. The billing is securely paid via WAVE technology and block chain) [15].

requirement features, service efficiency and specifications for power quality. Usually in the range of voltage from 345 to 500 kV, the eHV main transmission networks transfer bulk electricity from and from external sources. In certain metropolitan power grids municipal power also forms a large proportion of the overall energy supply. Many of these units are old, less effective and dispatched to provide operational reserves and voltage-support functions as consistencies must-run units. Many of these ageing thermal units will possibly be phased out in the near future due to economic reasons and environmental restrictions.

New problems of hybrid electric car wireless power transfer and safe Internet billing Intelligent grid modernisation and Internet incorporation of electric cars (IoEVs) have gained significant interest because of the power and speed they provide as represented in **Figure 9**. Furthermore, growth of magnetic resonance or wireless inductive transmission (WPT) technologies can increase performance and convenience in power transmission. However, there are many issues that need to be overcome to incorporate such a convenient method. Moreover, it is especially difficult to develop an effective and stable accounting method when IoEVs are loaded automatically in the anticipated convenient system.

7. Internet of things based smart grid modernization approach: technological aspects, designs, implementations, architypes, and future investigation guidelines

In the face of the one-way data source, the power loss, increased electricity requirements, the depth of confidence and protection of traditional electric grids are transformed into smart grids (SGs). The Smart Grid offers two-way energy streams between sources and consumers in conjunction with electricity generation, transmission, distribution and operating systems. A bulk quantity of SGs are utilise to different equipment's for observation, examination and control of the grid network, positioned at generating stations, delivery stations and in customers' premises. Thus, a Smart Grid needs interlinking, mechanisation and the tracing of such equipment's. The Internet of Things helps to do this (IoT). In addition to connecting, mechanising and tracking of these facilities, IoT provides the means to support Smart grid frameworks for diverse network purposes during generation, transmission, delivery and power uses through the integration of IoT devices (such as sensor devices, actuators and smart metres).

A conventional electric grid comprises bulk quantity of broadly interlinked synchronous Alternating Current (AC) grids. It conducts three major roles: generation, transmission and distribution of electrical energy [16], where unidirectional electric power flows from supplier to the customers. Initially, in power production, a huge amount of power generating stations produce electrical energy, generally from burning of coal and nuclear power stations. Then the electricity is distributed from power generation plants by high tension transmission lines from a remote load terminal. Next, the delivery network assigns electrical power at lower voltage levels to the load centres. Any network of grids is centrally managed and tested to ensure that the generation stations deliver electricity in line with consumer specifications under the power system network limitations. About any electricity generation, transmission and distribution is possessed by utility companies that supply consumers with electricity and charge them adequately to recover costs and to generate income.

From its beginning in 1870 to 1970 the traditional grid worked admirably [16]. Despite the drastic rise in energy consumption by the consumers, it was also somewhat shocking. But since 1970 the concept of using electricity has been modified considerably, due to the burden of electronic devices, new sources for high-strom use, such as electric vehicles, have risen to be the fastest growing portion of full power requirements (EVs). Such influences as excess machinery and insufficient smart innovation for clients, inconsistent management, electrical privileges and untrustworthy communication and observing – particularly the absence of components in the stockpiling of generated electrical power [17–19] – make grid networks an essential factor in consuming electricity. Furthermore, electricity grids are confronted with other problems as well, including the development of energy interests, coherence, security and the development of eco-friendly energy supplies and maturing basic problems.

The basic Smart Grid concept was a challenge with a range of data and correspondence developments to resolve these difficulties. The adequacy, efficiency, reliability, protection, longevity, consistency and extensibility of the traditional network can be improved by such developments [20]. SG differs in numerous angles from traditional grid networks. SG, for instance, gives vendors and purchasers a two-way correspondence stream while a traditional electricity grid only provides single way connections from providers to consumers. SG has gradual measurement Setup, intelligent metering technology, adjusting for vital clearance of defects, find of unsubscribed use and load change [21–24], and self-rescue [25].

SG transmits various types of equipment for grid network observation, analysis and control. This test facilities were installed at power generation facilities, electricity transmission lines, power transmission centres, delivery areas and consumer locations. One of the main concerns of SG is the interconnection, computerization and detection of such a vast amount of gadgets, where swift, universal and bilingual advanced digital correspondences need scattered observation, investigation and activity. For these gadgets or "material," it calls for dispersed SG mechanisation. In fact, this is now recognised by invention in the Internet of Things (IoT). The IoT is described as a device that can connect any object on the Internet based on a data trading convention and correspondences between various intelligent gadgets in order to achieve recognisable purposes for observing, detecting, managing and area [26]. Over the past years, IoT engineering has taken on a number of dimensions and took into account internet intercommunication to various network-based devices used in daily life.

The Internet Technology initially supported individuals and people as a network. While the volume of Internet-related items surpassed universal levels in 2008, the impact of IoT creativity continues to increase. The results are also increasing. IoT is a system of actual Internet technology products or things. These products are equipped with implanted innovation to interact indoors and outdoors. These items detect, test, run and jointly select individually or with different items through a broader tempo, self-governing and pervasive bi-directional device correspondence. This is what the Smart Grid really needs. Through the integration of IoT gadgets (such as sensor devices, actuators, and smart metres), the Io T-innovation will support smart grids with various device capacity, during power production, storage, transmission, delivery, and consumption.

The only big use of the IoT is the automation of the intelligent grid [27]. Today, while many home-grown devices that use energy are linked to the Internet, there are also many home-grown devices, which do not come with the web. For example, in the world there is a significantly less amount of microwave ovens and washing machines connected with the Internet than of units not linked to the Internet. Basically, all power uses by connecting to the Internet are more beneficial (for example, microwaves and clothes washers, that are associated with the Internet can be worked distantly and at off-busy times, consequently saving expense, just as give solace to human beings through robotization). Therefore, we will later forecast that the IoT-coordinated intelligent grid will be greater than the intelligent grid, and that the existing intelligent grid will not be feasible save for the IoT breakthrough. New entrances will be exposed to enhance future growth possibilities by addressing IoT engineering as a worldwide standard for intercommunications and the justification for smart grid. Since the IoT and the smart grid must be incorporated, a new session on SG and IoT has begun, as is an exceptional question on the Smart Grid Internet of Things. The need and importance of the combination of IoT and SG is also shown.

8. An outline and integration of internet of things based smart grid

A. **Internet of Things**- The IoT is a system that can interface any person with the Internet that is reliant on a data exchanging convention and on communications with various smart devices for observation, tracing, management and region recognition purposes [16]. The IoT focuses on the recognition of three major concepts, in particular stuff, the internet and the semantic. The theory involves intelligent gadgets such as RFID stickers, sensor units, actuators, photographic sensors, optical scanners, GPS, and near-Field Communication. Smart gadgets are the basis of this approach (NFC). The Internet-based concept facilitates connectivity between smart devices and connects them via the Internet through various advances in correspondence, such as ZigBee, WIFI, Bluetooth or smartphone connection. The semantic concept comprises a number of applications with the help of intelligent devices. The IoT breakthrough has gained a great deal of attention over recent years in various implementations, taking into account the Internet's interconnection with different network-implanted gadgets used for daily life [28]. The activities of various frameworks have been robotized: for example: medical care, transport, defence, home automation, security, monitoring, agro-industry and electric grids. IoT devices, including the external objects (e.g. people) enable the recognition of fully mechanised systems that make it a basic part of the Internet, include the most common objects equipped with routers, micro-controllers and traditional stacks.

B. **Smart Grid**- The SG is being promoted to be a demanding response for reducing electricity spending and for tackling the problems of traditional grid system, making future progress in terms of expertise, adequacy, reliability, protection, constantans and increasing electrical energy needs. The main features of the smart grid are self-mending, improving power efficiency, scattered generation of and load consumption output, joint business and customer participation and effective management of the source. As implemented in **Figure 10**, in four sub-frameworks SG completely reforms energy generation, transmission, delivery and consumption. It includes three systems: a home zone network (HAN), an area network for neighbourhoods (NAN) and a network for wide areas (WAN). HAN is the main layer; it addresses the demand power requirements of customers

This includes intelligent devices, home appliances (counting clothing laundries, TVs, air conditioning, fridges and stoves), electric vehicles and renewable energy sources (like solar cells). HAN is arranged within housing, factories and corporate systems, and integrates with smart metres for electrical devices. The NAN is the second stage of the CS which consists of smart metres with a large number of HANs which is otherwise called the Field Area Network (FAN). NAN underpins correspondence for power delivery frameworks between dispersion substations and field electrical gadgets. It collects the data from several HANs and passes it on to the information authorities the interface NANs to a WAN. The WAN is the SG's third level which encourages the correspondence of doors or complete centres as a backbone. It promotes the interplay of mechanisms on power delivery, large power generating schemes, renewable sources of power and zones control [30].

C. **Significance of SG in Smart Metropolises**- Smart urban areas are contained of various factors, like administration, structures, safety, medical services, economy, transport and energy demand. Between them, energy is the most vital segment for moving towards a more bearable metropolitan life, also for incorporating different shareholders and complex network. As such, smart urban communities are firmly combined with the upgradation of customary electric grid, i.e., SG due to if the power is inaccessible for a specific timeframe, any remaining activities of smart urban areas will be paused. SG gives three fundamental capacities which are extremely needed by a smart city. The traditional grid is first and foremost transformed into SG by robotics, remote control and checks. In addition, SG enables consumers to know about their electricity use, costs and thus allows customers to adjust their quality of energy. Finally, the SG is empowered to coordinate renewable and distributed

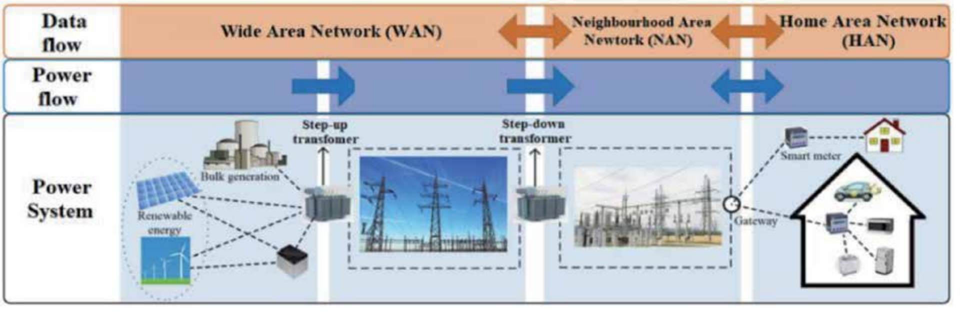

Figure 10.
Architecture for smart grid (SG) presenting power grids, power flow and flow of knowledge. The SG consists of five major subsystems (power generation, storage, delivery and usage) and three network groups (WAN), community area (NAN) and home area networks (HAN). Power passes through the subsystems, while knowledge passes via the networks. [29].

energy reserves. Thus we may conclude that smart urban societies cannot fully survive apart from such practises [31, 32].

D. **Combination of the IoT and SG**- In data detection, transmission and handling, the SG has effectively carried out large selection, and IoT creativity now plays an important part in the grid growth. The key driver of SG's operation is the advancement of the organisation, maintenance and functioning of each section of the power grid by ensuring that it is able to "hear" and "speak" and to empower robotic systems in SG [33]. For instance, in conventional power grid, the service organisation possibly thinks about the disturbance of service when a consumer advises other partners of the grid network. In SG, the service organisation will mechanically contemplate about the interruption of service in light of the fact that specific parts of SG (like smart meters in the fondness area) will stop distribution of the gathered sensor information. Here, the IoT assumes the major part in empowering this situation since every segments of the grid framework (indicated in **Figure 11**) should have IP addresses and ought to be equipped for bi-directional correspondence. This is empowered by the IoT. IoT innovation gives collaborative real-time system linking with the customers and gadgets through different correspondence advances, power hardware through different IoT smart gadgets, and the collaboration needed to acknowledge continuous, bi-directional and very fastest information allocation across different applications, improving the general effectiveness of a SG [32]. The IoT can be divided into three types of Smart grids, depending on tri-step IoT engineering [31, 34]. IoT is primarily used to arrange various IoT smart equipment for testing the conditions of equipment (i.e., at insight layer of IoT). IoT is also applied to include data on devices by means of their correspondence developments with the help of their associated IoT Smart Gadgets (i.e., at network level of IoT). Finally, for the regulation of the SG across application borders, IoT is introduced (i.e., at application level of IoT).

IoT gadget detectors are commonly radio sensor systems, RFIDs, M2M gadgets, camera systems, infrasound sensors, laser detectors, and GPS gadgets. IoT creativity will extraordinarily boost and support the data detection in an SG. In addition, IoT Invention also plays a key role in the substructure positioning and dissemination of

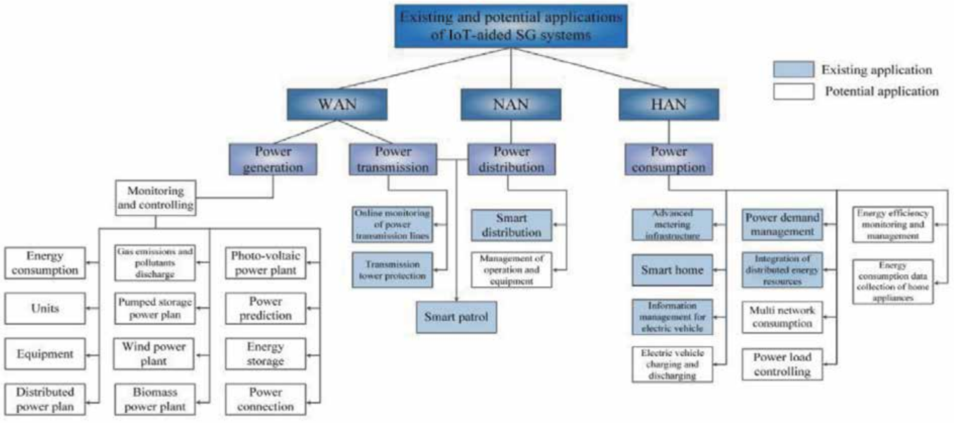

Figure 11.
Existing and future implementations of the WAN, NAN and HAN IoT-aided SG networks. These structures are often known as subsystems, i.e. power generation, storage, delivery and use. The blue boxes represent the implementations that exist, and the white boxes (empty) represent future uses [29].

SG information, supporting the creation of the network, operations, management welfare, maintenance, security surveillance, data collection, evaluation, customer cooperation and so forth. In addition, the IoT enables data streaming, power flow and distribution to be combined in an SG [34, 35]. Furthermore, present SG structures principally highlight around the necessities of power suppliers to deal with the total grid system [35]. The consumers are getting in touch with a smart metering system by methods for General Packet Radio Service (GPRS) or other cellular networks. The modern realism in which consumers will now have other intelligent home frameworks (such as Wi-Fi) has not yet been introduced into existing SG's network correspondence. While some mechanisms grant current smart home frameworks, the adaptability of large investments is not expected. These conventions, which are explicitly applicable to IoT and SG framework, cannot be extended directly in the IoT-supported SG frameworks because they only take into account the specific features of either IoT or SG frameworks which are insufficient for an integrated IoT-supported SG framework.

9. Sum-up and understandings of IoT based smart grid

The complete investigation of the present applications of IoT-based smart grid to make the total system more comprehensive. Though there might be several applications of IoT-based SG schemes, as illustrated in **Figure 12**. Few IoT-based SG systems implementations have been already deployed but much more needs to be done as all the instantaneous information capacity and large data processing are taken advantage of. Current applications threaten a number of focus areas, for example:

- Observation of buildings or of power apparatus establishments (towers and electrical transmission networks);
- Regulating home utilisation by active energy scheduling, which exploits changeable estimating;

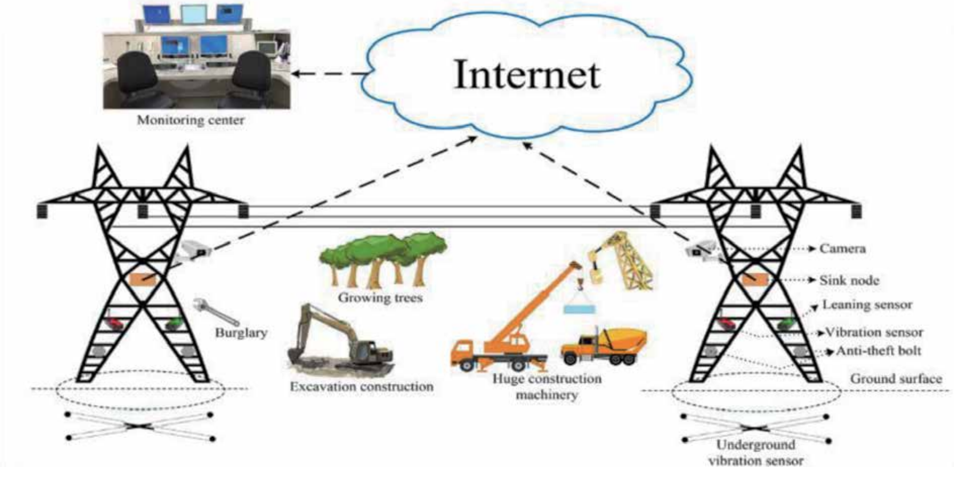

Figure 12.
IoT assisted transmission tower safety towers security system against buggy attacks, natural hazards, barbarians and the growth of trees. Transmission tower protection systems this device includes a sink node and numerous sensors to provide the monitoring centres with early warnings of threats to high-voltage transmission towers [36].

- Meter perusing and utilisation checking, private and business sector;
- Electrified cars charging and parking;
- Power requirements and source administration, including incorporated environmentally friendly power sources; and.
- Caring of power supply frameworks, by identifying line faults and breakdowns.

This analysis found that little work is being done on the use of IoT-based SG frameworks for nearby stations, transmission and power consumption. For example, IoT-based forecasts of the climate conditions that will guide energy stream between many areas and the effectiveness of the connecting equipment can be dependent on the capacity of environmentally-friendly sources (solar cells, wind turbines etc.).

10. Smart grid architecture model (SGAM)

The SGAM is a reference architecture intended to show the cases of SG architecturally. This was the result of an EU Mandate M/490 reference working group [37, 38]. SGAM primarily consists of five component layers: business, functionality, content, communication and layers. These are referred to as interoperability layers. Each interoperability layer contains a smart grid plane covering electrical space and knowledge processing areas. The main aim of this model is to show which areas of data management communicate with each other.

Three-layered Architecture- The three-layer IoT-assisted SG architectures have been used extensively in [39], focusing on the IoT-assisted method's characteristics. As seen in **Figure 13**, the architecture consists of three layers, a vision layer, a network and an application layer.

1. **Perception Layer**- The aim of this layer is to detect and gather information using different IoT-assisted SG devices. They have various types of IoT system for the collection of data in an SG system, such as RFID tags, sensors, WSN, GPS and M2M. It consists of two substrates, a vision control sub-layer and a connectivity extension sub-layer. The vision of a sub-layer controlling knows how to physically handle IoT equipment, obtain, monitor and manage information, while a communications module connecting IoT to network levels exists in the sub-layer extension communication.

2. **Network Layer**- The network layer consists of the converged telecommunication and internet networks [40]. Owing to its advanced architectures, the network layer has been generally embraced. The aim of the protocol is to map data from IoT systems on the perception layer of the telecom protocol [41]. The mapped data is then transferred to the application layer through the corresponding telecommunications network. The central network, i.e. the Internet, is responsible for the routing, transmission and control. Other telecommunications networks are the basis for the network of access. The IoT and Knowledge Centres are also part of the network. The network layer may be based on public communication networks, as well as industries.

3. **Application Layer**- The implementation layer consists of integrating IoT technologies into a wide range of IoT-aided SG applications as well as market experience. Its purpose is to process and monitor IoT devices and the SG

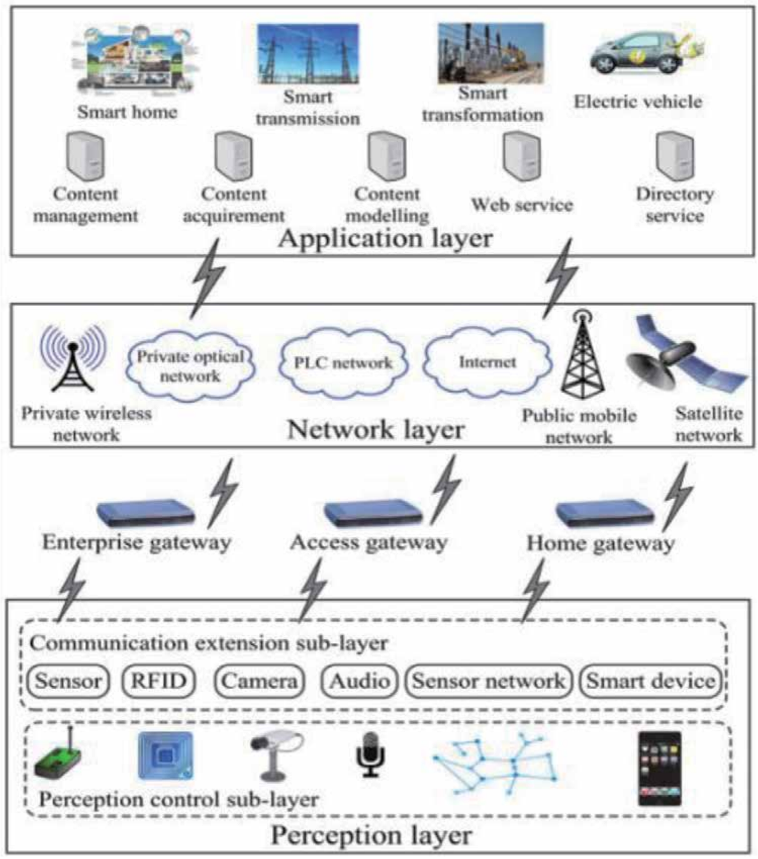

Figure 13.
IoT-aided SG structures, with a vision layer, network layer and device layer, have a three-cover architecture.. The layer consists of two sub-layers, a sub-layer for contact expansion, and a perception [36].

ecosystem in real time based on the information obtained by the network layer. There are several aspects of the IoT-assisted SG systems presented in **Figure 3**. It comprises an infrastructure/middleware frame and various types of records, web and directory resources servers. IoT technology computing, delivery and services are offered through the application/middleware infrastructure. The key components of the application layer are information sharing and secrecy. The deployment layer would particularly increase for SGs who can provide far richer data sets.

4. **Four-layered Architecture** – A characteristic feature of the SG Information and Communication Systems was proposed in a four-layer IoT-assisted SG interface architecture. As seen in **Figure 14**, this architecture consists of a terminal layer, a layer of the field network, a distance layer and a layer of devices. The terminal and field networks are consistent with the design with the IoT knowledge layer, the IoT network-level remote communication layer and the IoT application-level MATS interface layer with the IoT three-layer hierarchical model.

5. **Cloud-based Architecture** An essential component of SG, needed for global sustainable growth, is improving the energy efficiency of a building. Smart energy is also an important area of IoT science. Buildings account for about 71 per cent of the total energy usage of green buildings in the US. However, green buildings like this have not been as strong as expected to date. This can be

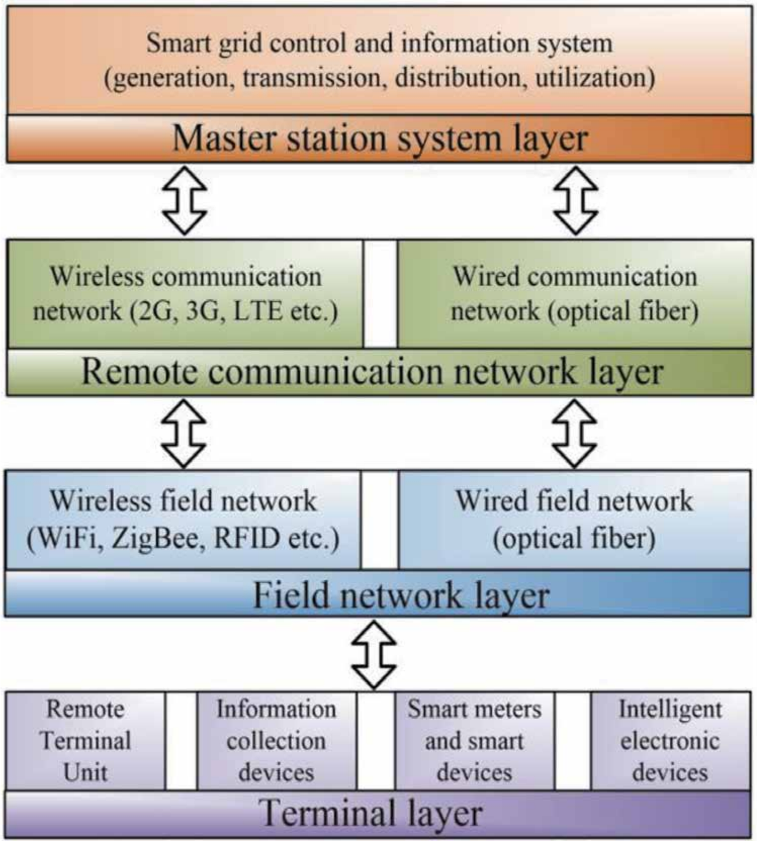

Figure 14.
IoT-aided SG systems' four-layered architecture built on the SG features. It consists of a terminal layer, a field network layer, a remote connection and a system layer for the main station [36].

because fixed and stagnant schedules do not fit in with consumer lifestyles or because there are volatile business dynamics. Users are now using their smartphones or PCs to change energy conditions using IoT technology. This allows users to comply with their own schedules by adjusting policy as and where necessary to easily respond to accidents. The IoT interface has been proposed in 2015 for the effective control of smartphones and cloud computing services. This new framework transforms the existing statically energy management system and central control modes, which generally consists of different buildings, to complex and dispersed energy control on the user side of SG. This frame is seen in **Figure 7**, which includes four key elements, (i) energy conservation policy for multiple sources, (ii) telephone tracking and monitoring, (iii) automated access position-based control and (iv) data storage and computing cloud network. The premise of an enterprise consists of a variety of separate sections, including campuses, houses, offices, laboratories and offices, each with different energy needs and regulations, which are essential in terms of energy use management. Each family member often has a preference for energy usage in a single home, which has to be taken into account. As seen in **Figure 15**, there are several layers in different stages in this scheme of energy saving techniques. This management strategy framework (e.g., building, department, lab and room).

6. **Web-enabled SG Architecture**- In [43], for IoT-assisted SG frameworks, Web architectures have been proposed (**Figure 16**). A number of IoT

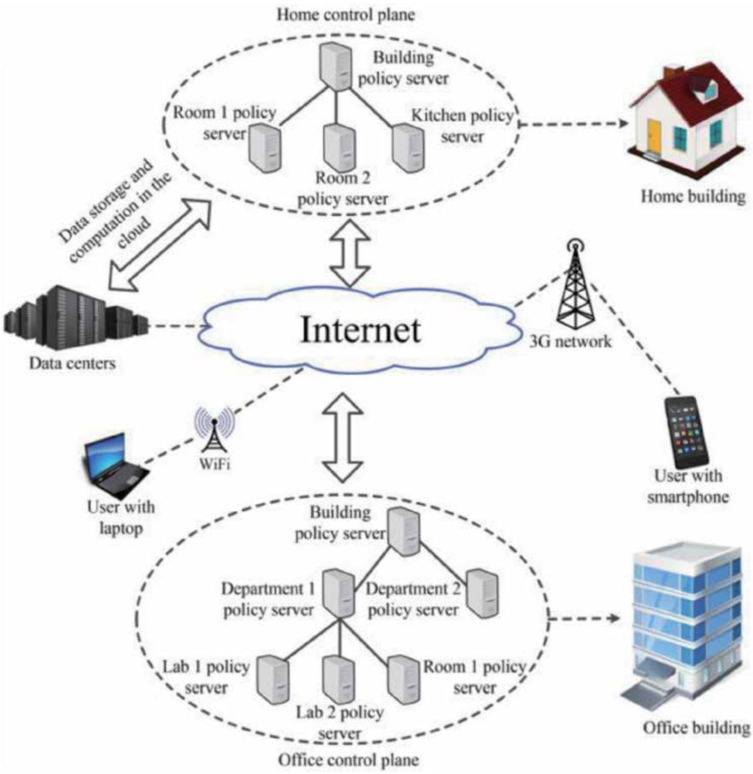

Figure 15.
Network-enabled SG architecture with IoT-advanced web services [42]. There are two different categories of renewable and non-renewable energy sources, all linked to modern energy metres [36].

computers provide access to online services, which are the guidance of the web browser to these web services. There are several online sites in the Internet. Two forms of energy exist: non-renewable and renewable energy. Non-renewable energy sources are thermal energy stations like coal and oil fires, which release carbon dioxide into the air and the nuclear power stations. Renewable energy is an environmentally friendly alternative which comprises hydropower, wind turbines, solar, biogas and biological fuel as well as geothermal, tidal/wave fuels.

It consists of three key components, the network of a sensor and drive, the simulator and IoT server. The sensor and actuator network comprises sensor and actuator nodes and IP gates. The IoT system has an IoT message sending computer, an SG database, a data processing server, a software setup, a settings unit, a device log and a safe Access manager. User interfaces are a visualisation interface, a gui settings, and an API Web Server.

11. BIG data analytics in multiple cloud for IoT-based smart grid architecture

A. **Need of Big Data Management in IoT-aided SG Systems-** IoT technology is combined with SG at an expense that requires vast quantities of data to be managed routinely and saved. This information covers market load demand, electricity usage, status of network components, power lines failures,

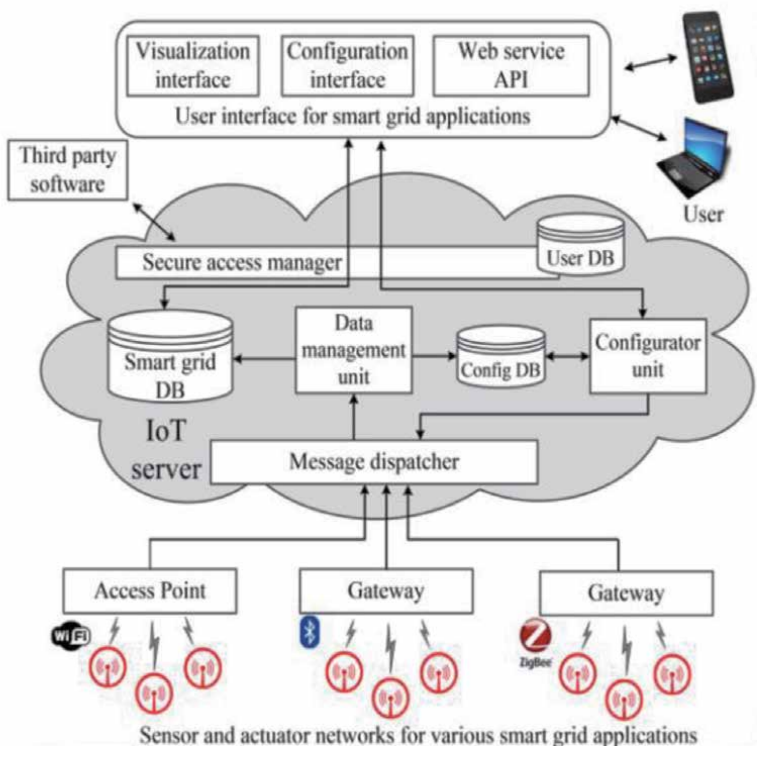

Figure 16.
Fixed metre IoT embedded SG architecture. The components, sensor and power supply networks, IoT server and user interfaces. The sensor and actuator networks are made up of sensor and actuator nodes as well as IP passages. The IoT server has a message dispatcher, an IoT client, a data processing unit, a settings database, a user database and a safe access manager. The user interfaces include the visualisation interface, the web service API and the configuration interface [36].

advanced metering reports, failure control records and requirements for forecasting. In other words, the service companies must be able to store, handle, and process information obtained from IoT devices safely and easily using hardware and software [44]. From application to application, the rate of data processing and stored for IoT-aided SG systems varies. Some programmes, for instance, execute their functions at a certain day time, including weather forecasts, which can be done every day at night. Another programme performs its functions at any point, such as online real-time tracking of transmission power lines, which means that the management and analysis of its data needs attention. Big data analytics can help handle tremendous knowledge in real time.

The key decision-making feature in SG is the Supervisory Control and Data Acquisition (SCADA) scheme. It gathers data from IoT sensors spread around the grid and provides online surveillance and control in real time. It also helps control network power flow to achieve consistency of use and stability of power supply. It is typically situated at separate locations of services on local machines. As the SGs increase in complexity, utilities are facing a challenge to update and expand SCADA networks. Cloud storage is a good option for hosting SCADA systems in order to solve this problem.

On-demand cloud infrastructure provides access to a common pool of computing resources, including storage, computing, networking, device, server and operation.

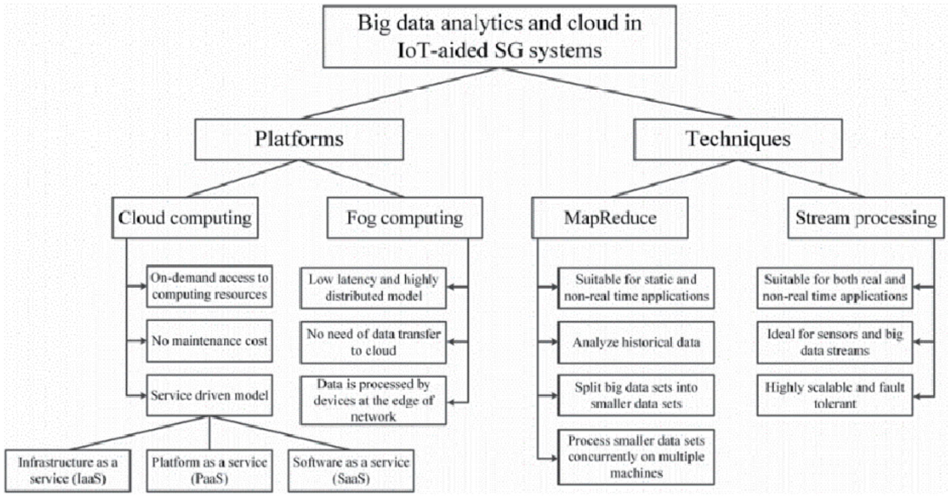

Figure 17.
Big data processing classification into platforms and methods of IoT-assisted SG programmes. Cloud and fog processing are on the platforms, while MapReduction and stream processing are the techniques [36].

A. **Platforms**- A business model can be divided into three kinds in the cloud computing environment, namely, service infrastructure (IaaS), service platform (PaaS) and service software (SaaS). IaaS offers IT infrastructure, mostly through VM, including Amazon EC2, Flexiscale, GoGrid, and Joyent as a service. PaaS assists developers in building operating systems and smartphones by using their cloud-based applications, such as Microsoft Windows Azure, Force.com and the Google software engines. SaaS is an on-demand Internet service-on-demand multipurpose network. It is a ready-to-use technology for IBM, Microsoft, Oracle, SAP and others. The services migrate their SCADA programmes in their entirety into the cloud and use the provision of storage, computing and other cloud related tools. Which allows the utilities to take advantage of many advantages, including no costs overhead and repairs, increased communication, payment for usage and reduced power costs (**Figure 17**).

B. **Techniques**- MapReduce and stream processing consist of two principal processes. Map Reduction can be used for IoT aided SG systems (e.g., weather forecasts) for static and non-re-time applications, whereas for online monitoring, auto healing and fraud detection and non-real-time applications. The MapReduce technology is a tool for analysing and using extensive historical information. It splits big data sets into smaller data sets and processes smaller data sets with the same code on several machines simultaneously. Sensor streaming and massive data streams are considered to be adequate for transmission. The architecture has been developed to handle massive data in real-time with high scalability and defect tolerance. There is also enormous scope for big data management in streaming of the IoT supported SG systems.

12. Future perspectives of the grid modernization

The change in the delivery stage of the electrical power system depends on several factors. The vision might be brief as follows:

- With continued developments in energy efficiency, the need for electricity will increase.
- The population will continue to rise and the need for affordable electric power
- Electrical transport proliferates by electric trains and electric vehicles Electric transport (cars, buses, and trucks).
- Green energy supplies are the gateway to fuel revolution.
- Consumers need a stronger, cleaner more secure and more efficient grid that requires system and process upgrades.

13. Conclusions

In future urban grids, powerful, reliable, versatile, protected, robust and inexpensive electrical supply will be needed. The most versatile advancement strategy choice for accessing different planning problems related to urban grid enhancement and transformation, suggested by submission resolutions sponsored by the VSC-HVDC. The organisational versatility and stability of urban grids can be greatly improved by launching direct input of electricity into load centres and improving intercity power generation capacities and dramatically decreasing the need for the regional generation and spinning supplies. The technology of VSC-HCDC is evolving and developing continuously. New architecture concepts rely on modular products and lightweight systems which will have the ability to incorporate urban power grids.

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Chapter 3

Smart Grid Project Planning and Cost/Benefit Evaluation

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Abstract

The smart grid involves a set of interconnected ecosystems applications (electrical, electronic, computer and communications), so the modernization is needed of information, security and infrastructure systems that monitor, control and manage them are increasingly evident. The upgrading smart grid process is a complex interaction between different alternatives and adequate selection of assessment criteria, where tangible and intangible items must be chosen with little information or with uncertain data. This work presents a framework within the context of the Smart Grid, to provide electric energy companies with a tool for planning the modernization of their generation, transmission, distribution and marketing systems. The planning of the modernization networks under the smart grid concepts is represented based on Smart Grid Architecture Model (SGAM) reference model. Furthermore, it presents how to integrate a pilot project (Smart Grid information source) into the SGAM reference model, through the identification of key performance indicators defining it. Multi-criteria analysis (MCA) combined with cost/benefit analysis (CBA) concept is explored, providing a novel insight into the approaches used in smart grid research applied at a case study: a distribution grid for rural smart grids.

Keywords: Smart-Grid, Project Planning, Cost/Benefit Evaluation, Analytic Hierarchy Process, Distribution Grid

1. Introduction

Smart Grids (SG)refer to advanced energy networks that incorporate the advances, trends and needs of the 21st century.

The current electric power transmission, distribution and commercialization infrastructure allows SG to add the technological potential of electronics, communication and computing, achieving a bidirectional flow between the equipment installed in the user's network area and the service providers. Therefore, SG seek to support a more efficient and reliable electric grid, which improves the security and quality of supply, according to the advances of the digital era [1]. Additionally, SG have been conceived in such a way that they can generate a positive environmental impact in the reduction of the "carbon footprint" due to their implementation through global policies and regulations.

SG emerge in their first generation to solve issues related to building more grids, installing automatic meters, developing a workforce oriented towards new communication technologies, and reducing losses and increasing system reliability. The second generation includes the concepts of stability, market design issues and the setting of hourly tariffs.

The third and fourth generations point towards a smart energy grid, addressing the new needs of the world's sustainable energy system by making full use of new methods for optimization, the penetration of electric mobility with electric vehicles, renewable energies, storage, distributed generation, and distributed, interoperable and secure information systems. These opportunities, which are important for society and new fundamental research challenges, demand a breakthrough in the modernization of SG [2, 3].

The wide range impacts not only monetary aspects are of interest, clearly identify the impact allocation is difficult because indirect/side effects by intangible impacts and quantify all impacts is not possible. Data availability and reliability are necessary for strategic decision-making. One of the main aspects of decision making in planning is identifying the best options. The best option involves the assessment the option performance on several conflicting criteria, making trade-offs, considering the stakeholder perspective and typically achieves a comfortable level of performances by minimizing the related cost. The Smart grid planning calls for effective tools for complex decision- making problems.

Most Smart grid assessment frameworks descend from EPRI approach. Some methods are devised on the specific case study, while others are devised as general frameworks where only qualitative or quantitative criteria are considered [4].

For the majority of the methods for analytical frameworks, large amount of input data and high analyst know-how are main requirements. These make those methods have low replicability due to different context or different assets. Therefore, low comparability of results from different frameworks limited feedbacks from real smart grid projects. The gap between users' requirements and methods for smart grid assessment is great and the lack of unprofitable projects reassessment grows a gap in how to deal with uncertainty and regulation [4].

The proposed methodology is based on the latency model [5]. In this model, every pilot project is considered a Smart Grid information source, where its data can be analyzed in different layers according to latency and storage. After the modeling of the pilot project, Key Performance Indicators (KPI) are defined for each of the layers described in the reference model used. Once the KPIs have been defined with the characteristics of effectiveness, efficiency, quality and economy, the Analytic Hierarchy Process (AHP) is applied for the multi-criteria evaluation including the cost/benefit analysis to obtain the weights relating the indicators to the criteria. This last phase allows the comparison between the different alternatives for prioritization.

2. Good practices in smart grid project assessment

Several factors at the global level, as well as the emerging technologies needed to establish the criteria and vision of a smart grid, lead electric energy companies to exchange information to ensure the reliability of the operation of interconnected electricity systems [6].

Advances in the integration of SG can be observed in the most important countries and economic groups in the world, among which we can mention:

- European Union: problems related to climate change, a need to generate clean and renewable energy, show greater competitiveness from energy efficiency, interest in issues related to national security viewed from energy independence and automatic demand management and cover the new needs of today's society (electric vehicles, digital society).

- United States: national security issues viewed from energy independence, economic recovery, modernization of transmission and distribution (T&D) infrastructure, creation of new jobs, reliability, security and the growing need for renewable and distributed generation, treaties on climate change where direct actions are required to address this issue and automatic demand management as an inherent need for SG.

- Japan: treaties and issues associated with climate change, increasing integration of intermittent distributed generation (Distributed Photovoltaic), aging T&D infrastructure, (these factors affect competitiveness given the nation's high levels of economic growth).

- China: accelerated growth of the electrical infrastructure and the large extension of land which requires long distance transmission (so efficiency in the energy sector is an urgency for this nation).

- India: accelerated growth of electricity infrastructure and the quest to reduce non-technical losses, which are around 40%, are factors that encourage their vision of the implementation of a smart grid as a basis for their development.

However, the infrastructure of electric grids is generally heterogeneous, i.e., there are different formats, technologies and management and storage systems with proprietary and closed formats that hinder interoperability between companies and even internally. The problem of having a large number of data interfaces, multiple processes for exporting and importing information, as well as diverse requirements for transforming the exchanged data, has become exponential. Likewise, several typical problems arise, such as duplicity of information and functions that occur when two or more systems contain the same data or perform the same function; data inconsistency is evident when two systems have different values for the same data; and incompatibility that occurs when information from two or more systems cannot be combined for technological, political, syntactic or semantic causes [7].

In 2011, the IEEE P2030 [8] international standard proposal for Smart Grid Interoperability was published with the objective of providing common understanding, terminology and definitions for the design and implementation of Smart Grid components and applications. P2030 offers three key viewpoints: the energy systems perspective, the communication technology perspective, and the information technology perspective. In addition, each perspective is composed of seven domains: generation, transmission, distribution, service, markets, control/operations and customers. Each domain is composed of a few entities that are logically connected with interfaces. P2030 is promising reference architecture for the standardization of interfaces. However, there is no evidence to determine whether smart grid concepts are appropriate in this approach and the links between the different perspectives are not presented. Therefore, it is not clear whether this approach is feasible for a rigorous analysis with respect to the functionalities envisioned for the smart grid, and their manifestation within the system. In the following subsections, reference models widely used in smart grid representation are presented.

2.1 Smart grid architecture model

The Smart Grid Architecture Model (SGAM) is a reference model for analyzing and visualizing the use of SG in a neutral way [9]. In addition, it supports the comparison between different approaches to smart grid solutions so that differences and similarities between different paradigms, roadmaps, and viewpoints can be identified.

The SGAM provides a systematic approach to deal with the complexity of SG, allowing the representation of the current state of implementations in the power grid, as well as the evolution of future scenarios of SG by supporting the principles of universality, localization, consistency, flexibility and interoperability. The current trends take as a reference model the one proposed by the European community called SGAM, which is shown in **Figure 1**.

The ease of representation in this architecture allows the SG structure to be extended in one dimension of the complete electrical energy conversion chain, divided into 5 domains: generation, transmission, distribution, distributed energy resources (DER) and local customers and in the other dimension of the hierarchical levels of the power management system, divided into 6 zones: process, field, station, operation, enterprise and market. Interoperability as a key factor for SG is intrinsically addressed in SGAM by the overlapping of the 5 layers: components, communication, information, functions and business. The SGAM layers allow modeling the different business views, which are described below:

In the **business layer**, economic and political regulatory structures are mapped onto the models related to enterprises, business possibilities and the market players involved. Business processes can also be represented in this layer. Thus, the management group is supported in making decisions related to (new) business models and specific business projects (business case) as well as regulatory agents in defining new market models. The SGAM technical views are modeled in the four lower layers.

The **function layer** describes the functions and services that the business needs. The functions are represented independently of their physical implementation (represented by elements in the component layer).

The **information layer** contains the objects and information data models, their usage and the exchange mechanism between functions.

The emphasis of the **communication layer** is to describe the mechanisms and protocols for the interoperable exchange of information between functions.

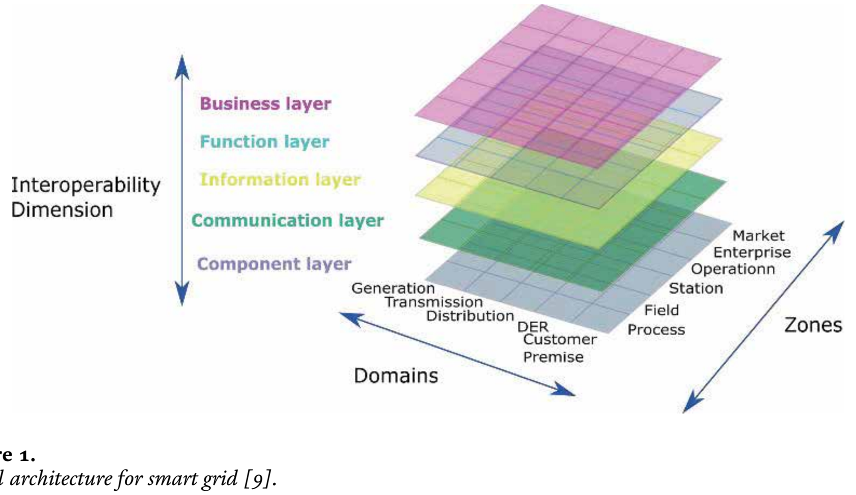

Figure 1.
Model architecture for smart grid [9].

The **component layer** describes all the elements involved. This includes the power system equipment (typically found in process and in the field), the teleoperation protection and control devices, the network infrastructure (wired/wireless communication connections, routers, switches) and any computers. For a specific use case implementation of the identified functions, they can be mapped to components that complement the relationships between all layers [9].

2.2 GridWise architecture council

The GridWise Architecture Council (GWAC) emerges as a conceptual reference model for the identification of standards and protocols needed to ensure interoperability, IT security and define architectures for systems and subsystems in a Smart Grid [10].

Technical interoperability: it covers physical connections and communications between devices or systems (electrical contacts, USB ports).

Informational interoperability: it covers the content, semantics and format of data or instruction streams (such as the accepted meaning of human and programming languages). It focuses on what kind of information is exchanged and its meaning.

Organizational interoperability: it covers the relationships between organizations and individuals and their parts of the system, including business relationships (contracts, properties, and market structures) and legal relationships (regulations, requirements, protection of physical and intellectual property). It emphasizes pragmatic aspects (context, regulations, laws), especially management and the electricity market.

2.3 Smart grid compass

The central objective of the Smart Grid Compass is to redefine the approach to Smart Grid planning that ensures successful technology deployment and maximizes operational resource efficiency. The framework created by the compass is based on an assessment of the key challenges of Smart Grid planning and the associated causes of failure in implementation [11]. Due to the complexity of the environment and market change, utilities face a myriad of business planning challenges. The approach to building and expanding a smart grid provides a 360o view across the entire core service domains:

- Smart grid operation.
- Intelligent customer service.
- Intelligent asset and human talent management.
- Smart energy.
- Intelligent organization, which acts as a driver and "controller" of the changes needed in the other domains. The use of these smart grid domains ensures consistency in language and collaboration across the organization.

2.4 Smart grid maturity model

The Smart Grid Maturity Model (SGMM) proposed by the Software Engineering Institute of Carnegie Mellon University [12], is a management tool that allows planning functions, a quantifiable measurement of evolution and a prioritization of strategies on the way to the implementation of SG.

The SGMM has the following characteristics: it provides a framework for analyzing and addressing modernization needs with a systemic and integrative approach, and with a balance between domains involving processes, people and technology.

This model uses domains and levels to assess and set aspirations for achieving smart grid maturity. The 8 domains of the SGMM represent logical groups of smart grid capabilities and characteristics:

- Strategy, Management and Regulation.
- Organizational Structure.
- Grid operation.
- Personnel and asset management.
- Technological Infrastructure.
- Customer.
- Business Value Chain.
- Society and environment.

In the SGMM there are 5 levels, which represent the stages that evaluate the maturity in each domain (see, **Table 1**).

2.5 Methodology for the representation of a smart grid project on a SGAM reference model

Given the diversity and complexity of SG, each project must be described in detail to be represented on the SGAM reference model.

Maturity level	Name	Maturity features
5	Leading	The organization drives new business models and moves towards the latest trends.
4	Optimizing	Smart grid implementations are defined to increase organizational performance.
3	Integrating	In the organization, the theme of Intelligent Networks is being integrated into its organizational structure..
2	Setting up	The organization is making progress in the implementation of functionalities, which will allow it to achieve and maintain modernization.
1	Getting started	The organization is in the process of implementation.
0	Basic	Level defined by default at the start of the study.

Table 1.
Maturity levels and features.

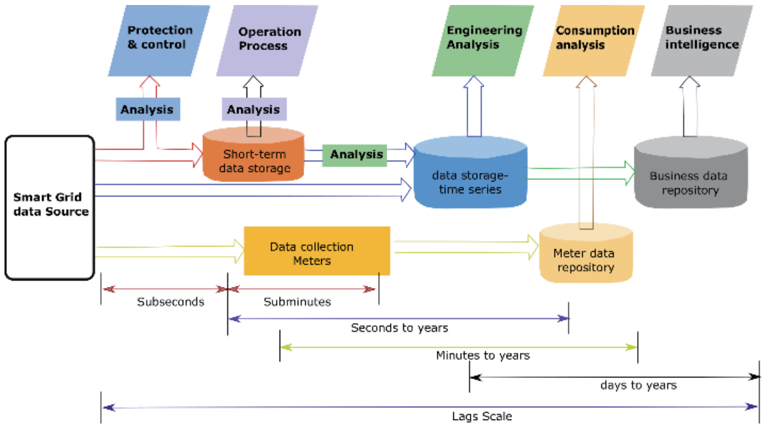

Figure 2.
Roles, data storage framework [5].

Figure 2 shows the roles and latencies for storage in the databases for each zone such that they model a smart grid source [5]. The roles of each zone or storage outlet are described as follows:

- Protection and control: this group stores and delivers indicators related to the protection and control systems of the smart grid system. The indicators of this block are related to the component layer of the SGAM reference model.

- Operation: the indicators obtained in this layer allow to evaluate the correct operation of the network. The indicators in this block are represented in the components layer of the SGAM reference model.

- Engineering analysis: in this block are the network design specifications (emissions reduction, installation size) and the indicators to define maintenance and/or network expansion actions. The indicators enable the evaluation of the communications layer in terms of the protocols used and cybersecurity issues. This block also evaluates the information layer. Since data integrity can be analyzed in the business model and the goods and services offered by the system.

- Consumption analysis: in this group the important indicators from the user's perspective are related. The functions layer is evaluated with the indicators of this block.

- Business intelligence analysis: the indicators are focused on the management of physical resources, new business and human talent. Regulatory policies and business objectives are related to the business layer of the SGAM reference model and are evaluated with the indicators generated in this block.

2.5.1 Procedure for the representation of a Smart Grid source in the proposed model

The representation of a Smart Grid source requires following a basic procedure for modeling in the SGAM architecture. The procedure consists of four steps and can be repeated iteratively to refine the result. Each iteration can cover a different aspect of the class of systems:

Step 1. **Smart Grid source selection**, this step involves the analysis of available sources and the acquisition of design documentation. This step is crucial for obtaining the model and applying it to the reference architecture. The result of this step is a set of design data and specifications.

Step 2. **Identification**, **creation or adoption of indicators for each stage defined in the reference model**, the purpose of this step is to find through different key performance indicators those with the lowest level of abstraction in the representation in the reference model. The use of existing terms (derived, for example, from standardized glossaries) enables generalization in the implementation. The result of this step is a set of reference indicators.

Step 3. **Modeling the reference level,** in this step each KPI is projected onto the layer level and its respective latency. This translation of the KPIs to the layer level allows a better comparison of the individual KPIs, as well as accessibility to the relevant information of each layer. The result of this step is the relation of the KPIs with the layer level and their latency.

Step 4. **Validation of the reference architecture**, the creation of reference indicators and their assignment to the layers of the model may not be valid. Therefore, the task in this step is to present the resulting model to Smart Grid system experts, operations, commercial, financial and engineering managers from the power sector, and Smart Grid users to validate whether the Smart Grid source is represented correctly. The result of this step is a validated reference architecture.

3. Multi-criteria analysis for planning assessments

Decision making can be considered as a cognitive process resulting from the selection of a belief or a course of action among several possible options. Every day, all people are faced with different alternatives from which they must select and identify the one that seems to be the best alternative or the one that satisfies the greatest number of intended needs. It is common to find circumstances that lead to make decisions that are relevant in a specific context and the fact of facing the choice of one alternative over another, generates several sensations to the decision maker [13]. It is, therefore, an emotional reasoning or process that can be rational or irrational.

A decision can be considered good or safe, if it comes from an appropriate methodology, considering all related aspects. On the other hand, it is not possible to consider a decision as good if it has not provided an optimal result, or the source and the procedure in its adoption are unknown. The process used to decide becomes important now of choosing the best alternative, since in this way it is possible to support that the solution was the best possible within the options and resources available. The three main characteristics for making a good decision can be found in [14]:

- The objective to be achieved has been outlined.
- All relevant information has been gathered.
- The preferences of the decision maker have been considered.

In engineering projects, decision making is a daily activity. Therefore, the project leader must be clear about what will be the best decision so that the project can thrive and have the least number of inconveniences. It is common that during the development of engineering projects, complex decisions are made and that these have direct consequences on the stakeholders and affected by the decision-making process. Therefore, before making any decision, knowledge, facts, and experience must be gathered and evaluated in the context of the problem. The decision-making process usually relies on the experience of the decision maker or on the similarity to decisions previously made that led to good results.

3.1 Multi-criteria analysis

Multi-criteria analysis (MCA) is a type of decision analysis tool that is applicable to cases where mutually conflicting criteria must be assessed, tangible and intangible impacts must be evaluated simultaneously and allows qualitative assessments such as environmental and social impacts to which quantifiable values cannot be assigned [15]. Multicriteria analysis can help individuals to make decisions in complex situations, where the problem can be addressed from different points of view and the interests can be social, political, environmental, technical and financial. This methodology provides support for decision making as it helps to focus on what is most important, it is logical and consistent and easy to use. At its core, multi-criteria decision-making analysis is useful for:

Breaking the decision into smaller, more understandable parts.

Analyze each part of the problem.

Integrate the parts to generate a comprehensive solution.

The above, supported by mathematical, analytical, research and experimental foundations of management sciences [16]. The application of this type of techniques has been developed since the 50's of the last century, where the main objective has been to help managers and leaders to make complex decisions. There are several techniques for multi-criteria decision making, among which the Scoring method, the multi-attribute utility, the Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), among others, stand out. The most widely used for solving problems related to the choice of technologies is the AHP. The AHP method is widely used to choose among certain technological options which would be the best, considering the characteristics of certain areas with their respective particularities.

In [17, 18] the method is used for the prioritization of microgrid generation plans considering resource uncertainties and efficient energy dispatch in smart microgrids. Finally, in [19, 20] AHP is used to obtain the best data information process of an energy metering system and the selection of a smart metering infrastructure according to the needs of an energy meter developer company.

3.1.1 Analytical hierarchical process

The Analytical Hierarchical Process (AHP) is a theory of measurement through pairwise comparison and subsequently organized by expert judgments to obtain priority scales. Developed by Thomas L. Saaty between 1971 and 1975 [21], it has been extensively studied and refined since then. This technique is applied in a wide variety of situations associated with the fields of public administration, industry, business, health, and education. To perform an AHP analysis, those who are involved require a thorough knowledge of the issue to be solved because the construction of the hierarchical structure must include enough relevant details to fully describe the problem. After being clear about the main objective of the problem, the first thing to do is to decompose it in a top-down hierarchy, position it at the top vertex and from there, place the criteria first, to make the selection of alternatives, the constituent parts of the problem, the sub-criteria and their fundamental relationships, as shown in **Figure 3**.

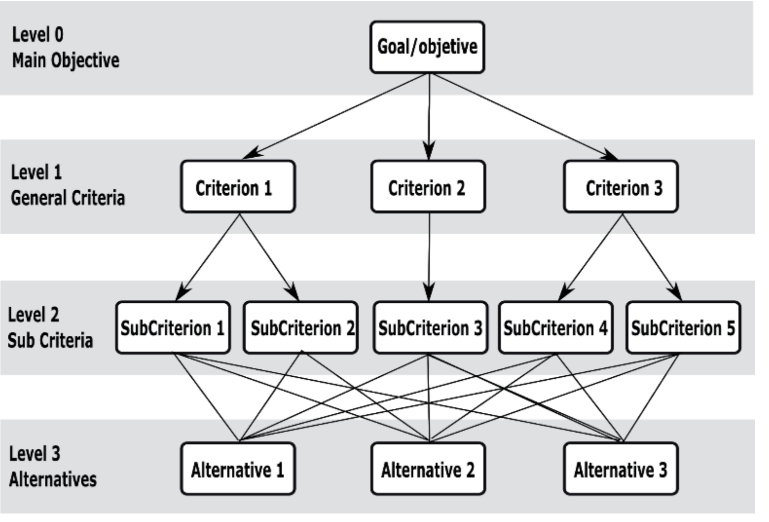

Figure 3.
AHP hierarchy. Goal, criteria and alternatives.

When the hierarchy is established, the decision-makers (panel of experts) methodically evaluate each of the elements to compare them with each other; these comparisons are made at each hierarchical level in pairs, as they seek to determine the importance of each of them to the higher-level element to which it is related. When making the comparisons, the experts can use concrete (quantifiable) data on the elements that are necessary, or they can use their own judgments according to their level of relevance. It is fundamental to the AHP method that judgments are used to make the assessments [22]. The comparisons assessments made by means of pairs are evaluated by preference indices if alternatives are compared, or importance indices if criteria are compared, which are subsequently evaluated according to a numerical scale proposed by Saaty, the scales for direct assignment are given in **Table 2**.

The intermediate integer values (2, 4, 6, 8) can be used to express a preference between two adjacent judgments. Humans could establish relationships between objects or ideas so that they are consistent. For this reason, it is important to review the logical consistency of the resulting matrix, to verify whether a contradiction is generated between the values stipulated to the criteria, as a result of the pairwise

Verbal judgment	Saaty's ratio scale (w_j/w_k)
Absolute preference for element w_k	1/9
Demonstrate preference for element w_k	1/7
Strong preference for element w_k	1/5
Weak preference for element w_k	1/3
Equal preference	1
Weak preference for element w_j	3
Strong preference for element w_j	5
Demonstrate preference for element w_j	7
Absolute preference for element w_j	9

Table 2.
Saaty's score judgment.

comparisons. The number of required pairwise comparisons for AHP increases as the number of the criteria and/or of the alternatives increase by performing the process of paired comparison between criteria and alternatives, this leads to a relative scale of measurement of the priorities given to the problem. The AHP converts these evaluations into numerical values that must add up to the unit, giving them a respective weight, in order to be able to compare them with each other in a rational and consistent way. This is how the AHP distinguishes itself from other decision-making techniques. In the final part of the evaluation, numerical priorities are calculated for each of the decision alternatives. The numerical values obtained (see **Table 3**) represent which of the alternatives has a higher weight to achieve all the criteria of the main objective of the problem [23].

3.2 Multicriteria analysis & cost/benefit analysis for smart grid project

Strengths of a combined evaluation approach in smart grid project is to select profit each one. The cba is reliable tool for an economical/financial evaluation of tangible impacts, shows some fundamental shortcomings when a large share of intangible impacts is involved. The AHP allows for considering multiple heterogenous, even conflicting criteria, soft effects are directly evaluable and monetization for all impact is not required.

The transformation of traditional power grids to SG demands significant investment in technological infrastructure, certainly, the ability to effectively monitor and manage these technologies will determine the performance of SG and will be critical to the success of those involved in the energy sector. Specifically, in the United States and Europe, regulatory and governmental bodies have for some years defined tools to measure how "smart" current power infrastructures are [24, 25]. In the rest of the world, utilities and government agencies are beginning to work on quantifying and implementing them in the context of each region. These tools help to make important decisions at the organizational level, by allowing to have a clear vision of an implementation towards the future through the results obtained, and to execute in a reliable way, in order to increase the satisfaction of the company itself and its users.

SG are considered as a model that seeks to optimize energy supply, helping to improve efficiency, reliability factors and availability and security from its generation to its delivery to consumers [26].

Some authors are working into integrate MCA and CBA in the evaluation smart grit project, Celli et al. 2017, present a sequential MCA-CBA funded by the Italian Regulator to define the condition for remunerating DSOs which own and operates storage for network issues. Many plans involving storage devices are devised by using a multi-objective optimization approach. Then, the economic sustainability of the alternatives pertaining to the Pareto frons is assessed by a CBA [27].

Alternatives	KPI_1	.	.	.	KPI_n	**Weighting**
A_1	w(1,1)	.			w(1,n)	w_1
.	.		.		.	.
.	.			.	.	.
.	.				.	.
A_m	w(m,1)				w(m,n)	w_m
	$\sum_{k=0}^{m} w_{(k,1)} = b_1$				$\sum_{k=0}^{m} w_{(k,n)} = b_n$	$\sum_{k=0}^{m} w_k = 1$

Table 3.
Decision matrix.

Another job presented in 2016 for Marnay et al. [4], an MCA is used for evaluation the TEC smart grid demonstration project which is divided in three subprojects: distributed automation, microgrid, and smart substation. Four different evaluation domains are considered: technological, economic, social, and practical. An index is assigned to each subproject according to the performances on each domain, an overall score is computed by using the proposed SG-MCA method which combines AHP and fuzzy evaluation method [4].

The upgrading plan of the Italian smart metering infrastructure is evaluated by means of MC-CBA approach. Three different areas of interest are investigated: economic, enhanced smartness of the grid, and externalities. Three different MCA techniques to investigate the effects on the provided result [28].

It will show the construction of the approach in smart grid project assessment based on MCA and CBA methods.

3.2.1 Key performance indicators

Key performance indicators (KPI) are tools that provides information on the measurement (management or results) in the delivery of products (goods or services) generated by an institution, covering quantitative or qualitative aspects [29, 30]. Indicators are measurable factors that facilitate decision making.

KPIs are the final phase of strategic planning, which implies an adequate evaluation, selection and definition in the context of SG. In the construction of the KPIs for SG projects, a review was made of the most widely used indicators and those that generate value and impact for the pilot projects evaluated were included [24].

Table 4 describes a KPI which is related to the impact of the alternatives on the quality of the electrical power supply service. The electrical power supply service.

3.2.2 Normalization for quantitative KPI

The normalization of the KPIs is used to obtain the weights when they are quantitative, since for qualitative KPIs the weights are obtained by means of paired comparison. The objective of normalization is to ensure that the sum of the KPIs for each alternative is 1. The ideal value for each KPI can be for its maximum or minimum value, taking into account this characteristic, it is necessary to select between Eq. (1) or (2).

$$KPI_{Maximization} = \frac{KPI_i - min}{max - min} \tag{1}$$

KPI- Duration interruptions per customer, including climate related disruptions	
Description	This criterion assesses the extent to which the project option contributes to reducing the duration of the interruptions. The system can improve the fault location and restoration procedures.
Index	System Average Interruption Duration index [occ/yr] (SAIDI)
Quantitative appraisal	The quantitative appraisal of the KPI is possible by comparing the values of the SAIDI before and after the project development. $\mathbf{KPI}=\frac{\sum_{i=1}^{n} U_i NC_i}{\sum_{i=1}^{n} NC_i}$
Qualitative appraisal	A qualitative appraisal can be indirectly made by estimation the level of the monitoring that can be achieved based on the monitored system features.

Table 4.
KPI description table.

$$KPI_{Minimization} = \frac{max\ - KPI_i}{max\ - \ min} \tag{2}$$

where min and max are the lowest and the highest values of the KPI for each criterion, respectively.

3.2.3 Cost/benefit analysis

Cost/benefit analysis (CBA) is one the most acknowledged tool for assessing the financial viability of industrial projects. It aims to an optimal resource allocation in which the monetary benefic outclass cost, and for the most profitable investment alternative. It also provides an incremental analysis regarding a particular scenario and produces easy to read economic indicators. The economic performance indicators are the indexes obtained from a CBA:

- the Net present value (NPV) criterion measures the project profitability in terms of the net benefit. In general, an investment option is economically viable if NPV is positive. The profitability of the investment increases as the related NPV grows. It is a quantitative criterion measured in terms of currency.
- The Internal rate of return (IRR) criterion measures the quality of the investment option. An alternative is positively evaluated if its IRR is higher than the reference social discount rate. It is a quantitative criterion measured in percentage terms.
- The Cost Benefit ratio (CBR) criterion measures the efficiency of the investment option. An alternative is positively evaluated if its CBR is greater than one. It is a quantitative dimensionless criterion.
- Investment payback period (Pt) is the period of balancing net profits and all construction expenses. It is a significant index for reflecting the project's investment return capacity. Payback period can be broken down into dynamic and static. To simplify the calculation, the static investment payback period is adopted for the calculations for the smart grid project. Those criteria are fulfilled according to the increasing values of the related indices (see **Table 5**).

Electric utilities invest large sums in dedicated utility equipment to review compliance with their regulatory or statutory obligations. For example, the benefits of extending service to new regions and planning for continued growth are generally accepted and implicit in mandatory regulations. These companies routinely meet these non-discretionary obligations and minimize their execution costs. Moreover, they are often well prepared to defend their decisions within this cost-minimization framework. Smart Grid projects, on the other hand, may not fit into this time-tested paradigm of cost minimization because they may be discretionary. For example, the decision to invest in a Smart Grid project to improve reliability beyond currently acceptable levels depends on how much to invest to obtain the improvement, and whether the improvement gained justifies the amount of money to be invested. This goes far beyond mere regulation, maintaining the stringent nature imposed by the regulation itself.

Many Smart Grid investments require going beyond cost minimization. In addition to their novelty, Smart Grid applications offer new benefits beyond basic or least-cost service. They can improve reliability and quality of service beyond

Index	Calculation method	Evaluation Standard
NPV	$NPV = \sum_{t=1}^{n}(CI - CO)_t(1 + i_c)^{-t}$ CI: cash inflow; CO: cash outflow; n: calculation period; Ic: Specified discount rate (benchmark yield)	if NPV is ≥0, the project achieves its expected benefits.
IRR	$IRR = \sum_{t=1}^{n}(CI - CO)_t(1 + IRR)^{-t} = 0$ CI: cash inflow; CO: cash outflow; n: (CI-CO)t; net cash flow of the t-th year; n: calculation period; IRR: internal rate of return.	if IRR is > benchmark yield, the project achieves its expected benefits.
Pt	**Pt** = (The year in which the accumulated net cash flow becomes a positive value −1) + |accumulated net cash flow previous year/the net cash flow of the current year|	if Pt is > benchmark yield, the project achieves its expected benefits.
BCR	**BCR** = The proposed total cash benefit/the proposed total cash cost. Prior to dividing the numbers, the NPV of the respective cash flows over the proposed lifetime of the project – considering the terminal values, including salvage/remediation costs – are calculated.	if a project has a BCR >1.0, the project is expected to deliver a positive NPV to a firm and its investors. if a project's BCR ≤ 1.0, the project's costs outweigh the benefits, and it should not be considered.

Table 5.
Evaluation economics KPI [4].

currently accepted levels, in addition to providing customers with options and services never before experienced. Consequently, they are discretionary for the utility, and a feasible/positive scenario is needed to incorporate such innovations into the regulated business. Eventually, Smart Grid technologies are the only realistic alternatives to address technical issues that may arise when services such as distributed generation or electric vehicle charging become commonplace on distribution systems. However, these technical issues are mostly in the future, so today it remains the responsibility to devise a business and economically positive scenario, showing sufficient benefits to offset the costs [31].

The CBA is a methodology proposed by the Electric Power Research Institute [31], it aims to determine whether the benefits of a project or decision outweigh its costs. However, CBA analyzes costs and benefits from a particular point of view, which can range from the broad and societally impactful (public perspective) to the particular and focused (private perspective). General economic analyses adopt a social perspective, determining whether a project is a good allocation of social resources, without considering the distribution of benefits. This contrasts with financial analysis, as performed in private companies, which generally focuses on investment returns. This tool allows for a mid-point analysis, as the focus is on the costs incurred by the company, which are borne by the customers. The planning analysis of regulated companies minimizes the cost of reliable service while assuming the return on investment. When minimizing the cost of service is inconsistent with public policy goals, legislators and regulators can impose conditions designed to address those goals, in the hope of stimulating decisions that benefit society.

The methodological approach of the EPRI-generated guidance sets out a CBA methodology that is compatible with either the societal or customer approaches to weighing costs and benefits. This concept is more comfortably suited to fully integrated companies, as costs and benefits are easily aligned, and all are contained within a corporate environment (except for externalities that fall outside the electricity sector). Costs in one part of an enterprise can be offset by savings in another part of the same enterprise, minimizing or even eliminating the need for additional cost recovery. In addition, users are recognized as a variety of utility entity types, many of which participate in some of the functions of a generation, operation, transmission and/or distribution utility. Costs incurred within one entity may produce offsetting savings in a separate corporate entity. Although consumers may be indifferent to where costs and savings occur, the various corporate entities involved face varying levels of cost recovery risk depending on their regulatory situations and their position in the cost and savings chain. The latter is important from a private enterprise perspective. **Figure 4** shows the steps to its implementation [32].

3.2.4 Sensitivity analysis

Factors of high uncertainty among costs and benefits are analyzed, the impact on the benefits of the project is analyzed quantitatively, and sensitive factors are identified to enable control and avoidance of risks. Multi-factor sensitivity analysis is carried out as required. The risks of not realizing the project's benefits are determined according to the sensitivity analysis.

The AHP sensitivity analysis for each KPI(1..n) or sub-criterion is obtained from the decision matrix. Each alternative for the sensitivity analysis is calculated with the values of the lines obtained from the relative weights of each KPI and the overall score of the decision matrix, Eqs (3)–(5) is used for calculus. The values to calculate the KPI line are:

$$(x_2, y_2) = \left(100\%, \frac{w(i,j)}{b_j}\right) \tag{3}$$

$$(x_1, y_1) = (b_j, w_i) \tag{4}$$

$$S_i(X) = w_i + \frac{(X - b_j)\left(\frac{w(i,j)}{b_j - w_i}\right)}{w_i - b_j} \tag{5}$$

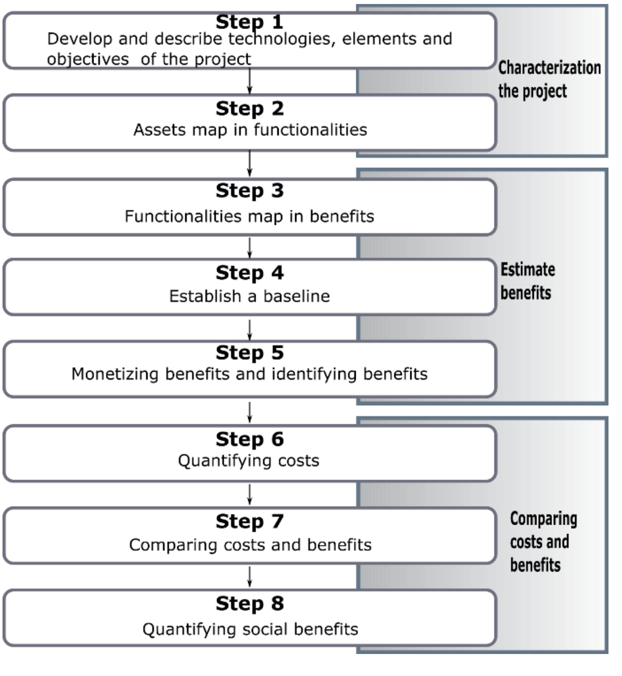

Figure 4.
Steps in describing the technology.

KPI_i	A_i	.	.	.	A_m	**Sensitivity**
0%	$S_i(0\%)$	.			S_m (0%)	b_j
.			.			.
.				.		.
.						.
100%	w(i,j)/b_j				w(m,j)/b_j	b_j
b_j	w_i	.	.	.	w_m	b_j

Table 6.
Sensitivity matrix for $\boldsymbol{KPI_i}$.

where b_j is sum of the relative weigh of j-th KPI, $w(i,j)$ is weight of j-th KPI and i-th alternative, and w_i is overall score for i-th alternative, S_i is value for i-th alternative, X is percentage for KPI value (see **Table 6**).

4. Case study: distribution grid planning of a median voltage rural grid

The case study consists in distribution grid planning of the medium voltage rural grid with five possible alternatives (see **Figure 5**).

4.1 Smart grid deployment reference model for a rural distribution grid

Table 7 presents the KPIs for a rural distribution grid project. It uses the reference model based on roles, which has 5 layers that are associated with the interoperability layers of the SGAM model.

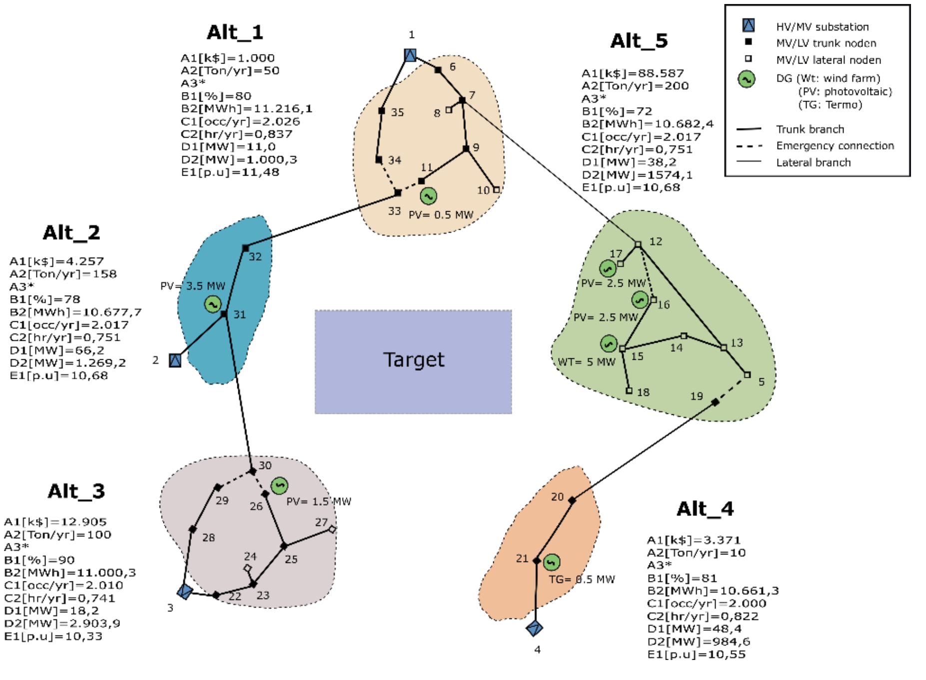

Figure 5.
*Distribution grid in rural area. * Increased local economic development.*

Criteria	Description
Protection and control	It fulfills the function of storing and delivering indicators related to the protection and control systems of the smart grid system. The KPIs of this block are related to the component layer of the SGAM reference model.
Subcriteria	**Description**
E1 [p.u] Min	Voltage variation index [p.u.] $=\sum_{l=1}^{n}\sum_{h=1}^{Nh}\left\lvert V_{max,l}^{(h)} - V_{min,l}^{(h)}\right\rvert$
Criteria	**Description**
Operation Process	The indicators obtained with this block make it possible to evaluate the correct functioning of the network. The indicators of this block are represented in the component layer of the SGAM reference model.
Sub Criteria	**Description**
D1 [MW] Max	Active power available for black start $=\sum_{j=1}^{NDES}\sum_{k=1}^{Nh} min\,(SoCn, l * ndis, l * ph, l)$
D2 [MW] Max	Maximum use in power of dispatchable resources $=\sum_{l=1}^{NDES}\frac{P_{DES,l}^{(out)}+\left\lvert p_{DES,l}^{(h)}\right\rvert}{2}$
Criteria	**Description**
Engineering Analysis	This block is fed by the network design specifications (reduction of the carbon footprint or environmental impact) and its own indicators to define maintenance and/or network expansion actions. The indicators make it possible to evaluate the communications layer in terms of the protocols used and cybersecurity-related issues. This block also evaluates the information layer since data integrity can be used to analyze the business model and the goods and services offered by the system.
Sub Criteria	**Description**
C1 [occ/yr] Min	System Average Interruption Duration Index –SAIDI = $\frac{\sum_{i=1}^{n} U_i NC_i}{\sum_{i=1}^{n} NC_i}$
C2 [hr/yr] Min	System Average Interruption Frequency Index -SAIFI=$\frac{\sum_{i=1}^{n} \lambda_i NC_i}{\sum_{i=1}^{n} NC_i}$
Criteria	**Description**
Consumption analysis	The important indicators from the user's perspective are listed in this block. The function layer is evaluated with the indicators in this block.
Sub Criteria	**Description**
B1 [%] Max	Reliability $=\frac{\#annual\ operating\ hours}{8760}$
B2 [MWh] Min	Expected network energy losses [Mwh] $=\sum_{j=1}^{Ne}\sum_{k=1}^{Nh} E_{l\,j,k}$
Criteria	**Description**
Business intelligence	The indicators are focused on the management of physical resources, new business and human talent. Issues related to regulatory policies and business objectives are related to the business layer of the SGAM reference model and are evaluated with the indicators generated in this block.
Sub Criteria	**Description**
A1 [K$] Min	Investments and reactive power exchange net value – NPV = Cost (transmission investment) + Cost (DES investment) + Q (power exchange net value)
A2 [Ton/yr] Max	CO_2 reduction = $EG * EFG$
A3	Increased local economic development

n: number of busses; Nb: number of time intervals; Ndes: number of Des, Ne: number of network elements; EG: Total energy generated by PVs [kWh]; EFG: Emissions Factor by Generation.

Table 7.
Evaluation criteria for a rural distribution grid.

The A3 sub-criterion is properly a qualitative KPI, because it is an aspect associated with the increase of the local economy, the other KPIs can be calculated from the operation records and projections of the five alternatives to be considered.

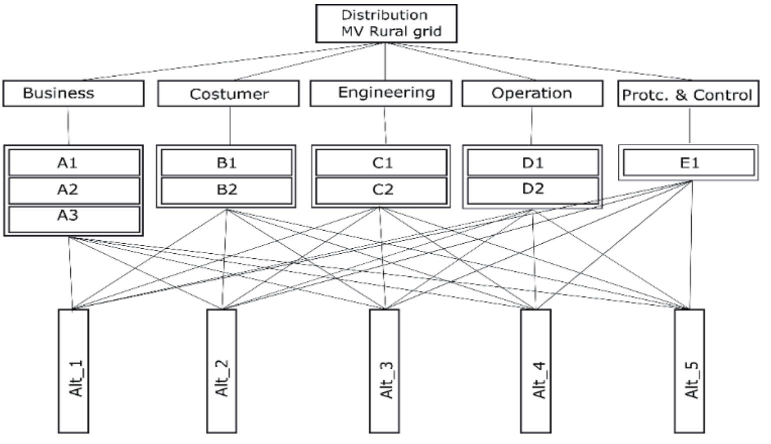

Figure 6.
AHP methodology. Goal, criteria, subcriteria and alternatives for rural distribution grid projects.

Criteria	Sub-criteria	Weights
Business intelligence (56.1%)	A1	73.6%
	A2	5.3%
	A3	21.1%
Consumption analysis (18.3%)	B1	20.0%
	B2	80.0%
Engineering Analysis (12.9%)	C1	25.0%
	C2	75.0%
Operation Process (7.5%)	D1	33.3%
	D2	66.7%
Protection and control (5.2%)	E1	100.0%

Table 8.
Corresponding weights for each layer and KPIs.

C2	Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Weighting
Alt_1	1	1/5	1/7	1/3	1/3	0,057
Alt_2	5	1	3	1	1	0,299
Alt_3	7	1/3	1	1	1	0,217
Alt_4	3	1	1	1	1	0,213
Alt_5	3	1	1	1	1	0,213

Table 9.
Performance matrix for increase local economic development.

Alternatives.	Business intelligence			Consumption analysis		Engineering analysis		Operation process		Protection & control	Rank
	A1	**A2**	**A3**	**B1**	**B2**	**C1**	**C2**	**D1**	**D2**	**E2**	
Alt_1	0.109	0.003	0.007	0.004	0.000	0.005	0.000	0.000	0.000	0.000	0.128
Alt_2	0.104	0.009	0.035	0.021	0.045	0.000	0.029	0.011	0.005	0.011	**0.272**
Alt_3	0.094	0.000	0.026	0.000	0.010	0.008	0.033	0.001	0.034	0.016	0.222
Alt_4	0.105	0.006	0.025	0.012	0.047	0.014	0.005	0.007	0.000	0.013	0.234
Alt_5	0.000	0.012	0.025	0.000	0.045	0.005	0.029	0.005	0.010	0.011	0.144

Table 10.
Decision matrix.

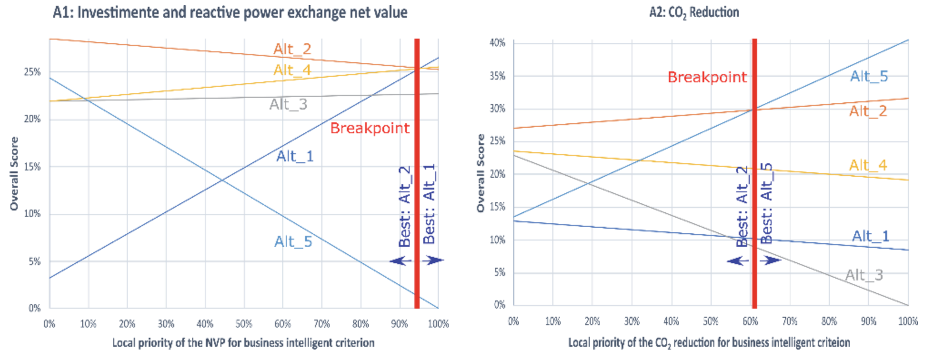

Figure 7.
Sensitivity analysis: a) NPV criterion; b) CO_2 reduction criterion.

4.2 Multicriteria analysis for rural distribution grid projects

The multi-criteria analysis for rural distribution grid used is AHP where qualitative and quantitative data can combine. In the case of quantitative data is required to maximize or minimize the KPI and calculate the corresponding weighting. For qualitative data is need a paired comparison using the Saaty's scale. **Figure 6** shows AHP's structure for rural distribution grid planning.

Table 8 presents the performance matrix of each KPI in relation to the alternatives.

4.2.1 Increased local economic development

The A3 is the sub-criteria associated to Local development that significantly contributes to national economic performance and has become more critical with increased global competition, population mobility, technological advances, and consequential spatial differences and imbalances. Effective local development can reduce disparities between poor and rich places, add to the stock of locally generated jobs and firms, increase overall private sector investment, improve the information flows with investors and developers, and increase the coherence and confidence with which local economic strategy is pursued [33]. This can also give rise to better diagnostic assessment of local economic assets and distinctive advantages, and lead to more robust strategy assessment. This indicator is evaluated using Saaty's scale through pairwise comparison as shown in **Table 9**.

The AHP requires that the weightings of the criteria, sub-criteria and alternatives be calculated. After making these assessments, the decision matrix is obtained, providing the result of prioritization among the alternatives, as shown in **Table 10**.

Figure 7 shows the sensitivity for A1(41%) and A2(3%) subcriteria, these are investment and reactive power exchange net value and CO_2 reduction, the sensitivity analysis is calculated with decision matrix.

5. Conclusions

The proposed tool aims to simplify decision making processes, so a pilot project into SGAM reference model is represented. This tool adds one more step for identifying weaknesses and opportunities, realizing for sensitivity analysis to decision-making stability assessment. This implementation includes the tangibles and intangibles impacts and data collection and allows planning smart grid based on applications of an assessment framework.

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Chapter 4

Advanced Communication and Control Methods for Future Smart Grid

Mike Mekkanen

Abstract

The reliability of intelligent electronic device (IED) function that ensures a particular disturbance will disconnect as fast enough from the healthy network to mitigate the effect of the fault is directly related to the reliability of the electrical system. This work aims to test the performance and comparison between the developed Light weight IED and different commercial IEDs from different vendor. The developed light weight IEDs are implemented on a microcontroller as well as on an FPGA. The test set-up is implemented by the Hardware-In-the-Loop platform. The simulation platform is OPAL-RT's eMEGASIM. The results shows the performance of the FPGA to be better than microcontroller and other commercial IEDs when comparing results.

Keywords: IEC 61850, light weight IED, smart grid, communication system, real-time simulation, hardware-in-the-loop

1. Introduction

The electrical grid systems have grown rapidly and rise complicity. This growing mainly based on the increasing of the decentralized renewable energy sources connection and communication between their different components. Numerous studies have been conducted to identify how these components are communicate to support power grid monitoring control and protection functions, based on its real-time operation [1]. In this context, some studies focus on the standardization of the power grid communication systems based on the IEC 61850 standard and its communication protocols implementation.

The latter brings new challenges in determining the reliability and the performance of the IEDs when having to consider both power system and communication phenomena within the multivendor environment [2]. The reliability of IED protection function that ensures a particular disturbance will disconnect as fast enough from the healthy network to mitigate the effect of the fault is directly related to the reliability of the power grid. Thus due to the vital role IED play to achieve assigned requirements and reduce the financial losses, the risk for malfunctioning should be minimized. It is therefore, performance testing, verifying and validating for the monitoring, control and protection functions settings within the assigned requirements is important. Since IEC 61850 standard has been distributed the protection, functions in different logical node (LN) that may located in different logical devices

(LD) or even in different IED. The assigned LNs need to communicate and operate successfully in order to execute the relay protection functions reliably. Traditionally, manufacturer engineers make use of standalone relay performance testing. While also it is always necessary to certify its proper functioning during commissioning, and after a certain time of service. These testing make the relay to interface to different voltages and currents sources subjected to different electrical system circumstances.

During normal electrical network operation, protection relays are naturally inactive. Relays malfunction can only detected when the electrical network in faulted condition. With the advent of digital simulators the productivity of the expert engineers are increased and can save more time. Allowing them to execute the electrical system model in real time with different circumstances and faulted conditions, meanwhile protection relay interfaced to the digital simulator as hardware-in-the-loop (HIL) to evaluate their performance. In addition, GOOSE possibilities for transmission of different kind of data offers new opportunities for upgrading relay protection functions themselves and their testing. However utilization of the IEC 61850 protocols (GOOSE, SV, MMS) add more challenges and extra requirements for protection relay confirmation about the IEC 61850 capabilities.

IEC 61850 is the enabler for the SAS automation that offers different popular SAS protocols, GOOSE, SV for intra-substation within the first version and R-GOOSE, R-SV for inter-substations within the second version over the communication medium. SAS monitoring control and protection parameters parameter can be modelled, configured and automated using the IEC 61850 Logical nodes LNs that might located in to different logical devices LDs within different IEDs. On the other hand, In [3–8] recent works raise the concept that although IEC 61850 offer many benefits for the SAS but the configuration and implementation of the IEC 61850 standard is the major challenges facing the configuration and implementation engineers according to the existing configuration tools (IED, System) within a multivendor environment.

Moreover, manufacturers support is always needed along with the commission of the multivendor IEDs project based on system support knowledge and tools. At this point, working in such multivendor project can be consider as much costly and time-consuming. However, in terms of accelerating and relaxing the standard configuration and implementations along with the rapidly IEC 61850 standard developments, a Light-Weight version can be used. These IEC 61850 Light-Weight version according to different open source libraries offer various solutions based C and Java etc. The offered solutions are worked based on low-level machine code required for the IEC 61850 implementation are automatically generated. The solutions can be implemented within different operating systems environments such as Linux, Windows, and macOS. Doing so will accelerate the development of the industrial instrument product line. Since the IEC standards are developed rapidly and usually the new/updated standards will cover/support new aspects related to the smart digital systems operation based monitoring control and protection functions. In this regard, developments industrial product lines usually took long time to support the developed new features defined based on the new/updated standards. Whereas, the Light-weight defined solution defined here helping to reduce the overhead standard complex information, limit ambiguity and accelerates the developments and testing tasks by supporting the new/updated aspects that defined based on the new/updated versions of the IEC standards. In [9–11] development and implementation of the new IEC 61850–90-5 R-GOOSE and R-SV protocols and their security standards IEC 62351 had been analyzed by using different developed source codes and tools. On other hand, the development of the smart grid controller

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based a commercial controller e.g. CompactRIO systems. However it provides a high-performance processing capabilities, sensor-specific conditioned I/O, and a closely integrated software toolchain that make them ideal for Industrial, monitoring, and control applications, but the user will be limited with the predefined control blocks afford with the initiated library, and with the supported interfaces/protocols by the controller. Whereas, the designed Light-Weight controller is more flexible and expandable in a way that able to support any state-of-the-art protocols/technologies and new/update monitoring, control and protection functions that might be defined along with the new/updating IEC standards. In [12–14] Controller development based on the Light-Weight designed controller for monitoring and managing of the reactive power flow between DSO and TSO networks was analyzed and tested, comprising between different controller that had been utilized in different boards was made.

In this work, embedded (Linux) environment is used based on microcontroller and SoC FPGA kit, since they are considering as a cost effective and flexible configuration.

In this work, different protection IEDs based Light-weight IEC 61850 are designed and demonstrated applying FPGA and microcontroller through the available of different open source software libraries. Performance testing for the designed Light-weight IEDs and the different conventional protection IEDs such as (Vamp52, ABB REF615) are validated by the RT-HIL laboratory setup as illustrated in **Figure 1**. Round-trip IEC 61850 GOOSE message latency measurements are made for those different IEDs. For RT-HIL testing, the test case study is modeled in MATLAB/Simulink and executed in real-time using Opal-RT's eMEGAsim software and running in to the Opal real-time simulator. Finally, the performance of both Light-weight and different protection IEDs based GOOSE round tripping latencies are compared and evaluated.

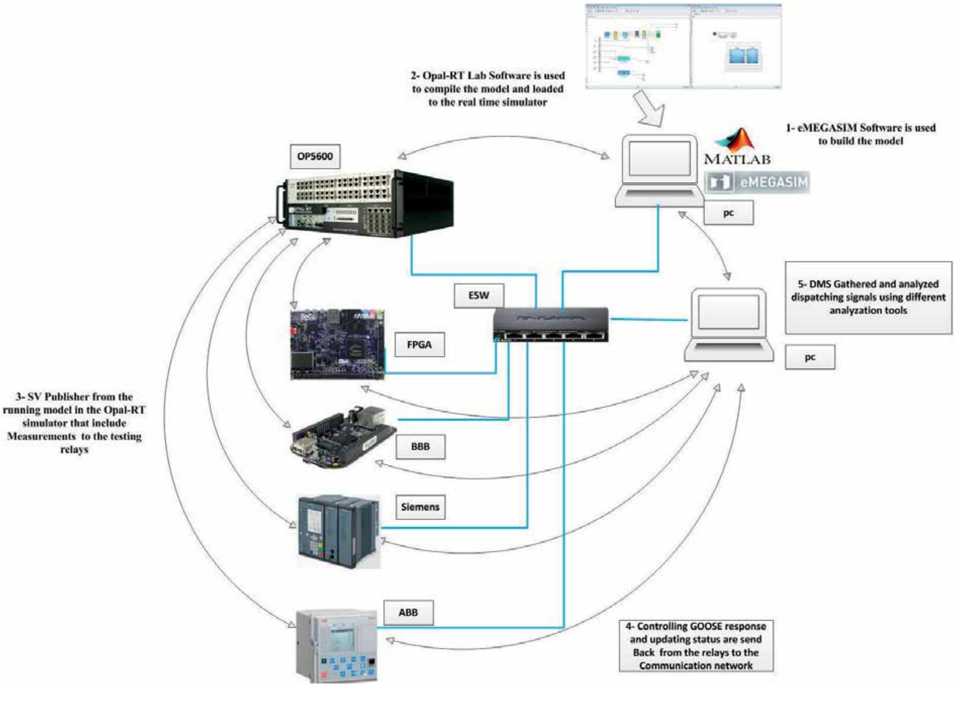

Figure 1.
Block diagram for the HIL relay testing based on IEC 61850 round trip GOSSE.

2. Standardization of the communication system brought by IEC 61850

IEC 61850 standard was published in 2003 to cover the inter-substation communication and since that the standard has expanded and evolved. Nowadays it consist of around 35 parts covering many area of power system protection an automation. The later development has expanded its use intr-substations covering wider area in the grid including distributed generation and reaching up to the control center. IEC61850 cover all various aspects, which are common and related to the substation site e.g. SCD files that specify communication protocols, SAS configuration and conformity over the channel. While, grouping and organizing SAS parameters in applications level by means of syntax and semantics in IEDs they left for the software design engineers.

IEC 61850 developed based on the associated architectural construct "abstracting" data object definition and its services. The data structures (data objects along with the associated services) are abstracted in a way that severely independent from communication links. The data structure support all the aspect of the SAS based on the monitoring, controlling and protection functions along with their associated services in order to execute and facilitate the energy system operation. Therefore, data object can be mapping over any IEC 61850 defined protocol that can meet the best requirements need.

At this point, the major focusing of the IEC 61850 specification can be organized into three main issues;

Firstly, (data object model), SAS data object that associated with the available measurements, SAS functions (functional model) and IEDs name should be standardized in a way that provides to the IEDs a shared vocabulary that support the intended semantic meaning.

Secondly, abstract communication services interface (ACSI), accessing scheme to the available data can be defined as a services that specified in different standardizing ways over the assigned communication protocols.

Lastly, eXtendable Markup Language (XML) is selected to describe all the SAS data (data object models, configuration information and communication protocol) and organized in different SAS IEC 61850 extensions files. These files can be shared among all the SAS IEDs, networks and power system.

The scope of the first version of the IEC 61850 standard is composed of 10 major parts that together define the various aspects and the entire requirement that has to be fulfilled by SAS. The main drive is to achieve interoperability among the IEDs within the SAS. Where, the positive impact of the IEC 61850 standard in SAS operation cost it is clearly known in terms of increasing the power quality and reducing the outage response [12]. However, this goal requires paying attentions on how to implement the IEC 61850 standard in order to build, integrate and operate the SAS. While, rapidly transforming of the energy systems from analog to digital environment, which need huge amounts of real-time data to be shared based on their efficient operation. Therefore, IEC 61850 standard along with its uniqueness properties, that originated in hierarchy principle from the bottom to up which are dependent from the underlying operating technology. This will allow the Standard to operate over the stat-of-the-art technologies. The standard will cover all the electrical system aspects as well as the standard will provide a novel set of functionalities, which are not, exists within the legacy SAS operation. At this point and from the IEC 61850 implementation point view, the standard will be an enabler to upgrade and utilize the fullest functionality, where their operation and implementation are depend on sharing information among different LNs located on the same LD within an IED or different LDs located on different IEDs. Therefore, numerous of benefits will be achieved that included but not limited [13].

1. Open system based standard representation for whole energy system aspects and the underlying communication protocols for monitoring protection and control to eliminate the procurement ambiguity.

2. The standard will allow different IEDs from divergent vendor within the energy system to operate smoothly (Interoperability) based on the standardization of the whole energy system objects. This standardization will provide the ability to exchange the predefined system configuration files with the available system configuration tools independently from the on-site manufacturer support.

3. Different secure techniques that dependable from the overall system by means of separating the accessing to system into different levels depend on the user privilege that allows flexible information transfers.

4. Standardization will allow to decrease the overall operation system costs and maintenance.

5. Flexibility and scalability on functions design, by means of self-description in a standardized manner, as well as led to easy adaptation.

3. DERs LNs standardizations brought by IEC 61850-7-420

The global incoming booming of the DERs that need to be integrate to the energy grid, and the concept of bidirectional power flow raising challenges. Growing need for intra-substation to limit, overcome these challenges and integrate various DER in smart grid network. As a result, an extension for the IEC 61850 standard had been announced in 2009 as IEC 61850–7-420 to address these issues. IEC 61850–7-420 define and specify different LNs that support different aspect required and applicable for various DERs. The defined LNs are used to facilitate sharing the information signals among all participant nodes in the smart grid. This sharing information based utilizing the IEC 61850–7-420 in smart grid provide a great benefits in terms of reliability and availability.

From the above mentioned the consideration has been raised that the recently newer IEC 91850–7-420 standard will address the aspect that cover the modelling for different energy system DERs, since, within the first version IEC 61850 whole energy system aspects such as the services modeling, assigned system configuration language (SCL) and the mapping schemes are defined. These DERs information modeling defined by IEC 61850–7-420 standard involve not only for the local communication among the local DERs and the local management service systems, however, they may support the sharing information with the main grids operators or aggregators who manage the electrical grid operation. The defined DERs LNs based on IEC 61850–7-420 have been grouped into four groups upon their operation characteristic (node classes and common data classes (CDC)). These DERs LNs groups are logical nodes for DER management systems, logical nodes for DER generation systems, logical nodes for specific types of DER and logical nodes for auxiliary systems. These defined DERs LNs represents all the DERs operation aspects parameters such as for instance, connecting status, availability status, economic dispatch parameters, start/stop time, operating mode etc. however, in this paper based on the defined Islanding detection scenario, number of the IEC 61850–7-420 DER LNs have been selected in which are the DPST and the DRCS LNs. The real-time ECPs status and measurements is presented by DPST LN (the ECPs are usually associated with each DER, load, lines Buses etc. that need to connect to the local power system, group of DERs that need to interconnect to the Utility energy system etc.). While, single DER or number of the same type of the DERs that may controlled within the same controller able to be presented by DRCS LN.

4. IEC 61850–90-x

IEC 61850 is extended for inter-substations and has been accepted wildly from the both point views vendors and Utilities. Wide area application in smart grid based on state-of-the-art communication technologies are highly integrated in to the Automation systems. Therefore, IEC 61850 standard had been extended to cover these issues in series of IEC/TR 61850–90-x standard.

IEC/TR 61850–90-1:2010 specifies the inter-SASs communication that allows sharing real-time data among various power system nodes over different communication protocols and networks. While using all the previous comprehensive issues that covered within the first version of the IEC 61850 standard. Moreover, IEC/TR 61850–90-1 defines interfaces (IF2, IF11) to exchange data between substations upon protection, automation and control distributed functions.

IEC 61850–90-2 report considering the communication between the substations and the control centers which is under preparation.

IEC 61850–90-3:2013 communication networks and systems for power utility automation is considered by means of IEC 61850 for condition monitoring diagnosis and analysis.

IEC/TR 61850–90-4:2013 considering the local area network based SAS as well as provides the engineering guide line for communication and the limited requirements of IEC 61850.

IEC/TR 61850–90-5:2012 considering the wide area network based monitoring protection and control (WAMPAC), as well as provides the ability to sharing digital data (digital status, synchronous phasor measurements) among different energy system nodes. IEEE C37.118 is defined the synchronous phasor measurements data packet and its content, while the exchanging concept is complaint with the IEC 61850 definitions.

IEC 61850–90-5 supports the synchro-phasors real-time exchange of measurements technical requirements that had been defined within the IEEE C37.118 standard by implementing the previously defined IEC 61850 protocols (GOOSE, SV). While, IEC 61850–90-5, R-GOOSE routable GOOSE and R-SV routable SV, new routable mechanism through the new routable control block for the GOOSE and SV is defined. These R-GOOSE and R-SV data are mapped along with the control blocks that encapsulated in a session protocol data unit (SPDU). This SPDU might include number of data sets that contain deferent information other than just the synchro-phasors measurements. At this point since the data is routed among power system unites that my located in to deferent communication networks, multicast UDP/IP protocols are used. Differential Service Control Protocol (DSCP) also used to improve the delivery priority The DSCP limits the probability of delivery packets lost upon the router congestion, by adding the priority tagging to the delivered packets. Consequently, ac-cording to the IEC 61850–90-5 specifications, Internet Group Management Protocol Version 3 (IGMPv3) provides the "source filtering" option by means of enabling the subscriber hosts to register on a router and assign which group they want to receive multicast traffic from. As a result, the router does not need to copy the stream and assigned it to all the available paths. However, based on the subscriber's defined table within the router it determines the appropriate dedicated paths in which that relax the communication network and improve the multicast delivery mechanism. Whereas, security aspects within IEC/TR 61850–90-5 is considered based on the "perfect forward" by means of exchanging the predefined encrypted key between the publisher and the subscriber. The publisher host will announced beforehand about the next key to the subscriber host as well as the subscriber needs to detect the synchronization status with the current key.

IEC 61850–90-12 2015, considers the inter substation communications upon the existing standards and protocols for the WAN communication [11], as well as the definitions, guidelines and recommendations. It, defined the inter substations and the substation-to-control center, as well as specified different issues related to these links such as energy system topology, redundancy, jitter and QoS, in order to facilitates understanding the state-of-the-art technologies, and integrating of different selected components through the conduct testing.

5. Light-weight IEC 61850 implementation of the developed control algorithm based hardware-in-the-loop

In order to test the developed light-weight IEDs based on the HIL simulations, the Substation Configuration Description (SCD) file was developed and further adapted into two different hardware, namely to the BeagleBone Black (BBB) and the Field Programmable Gate Array (FPGA). The flow steps of the developed C code start with the designed IEC 61850 IEDs based on the defined data attributes, data objects, LNs, LDs as well as it includes the operating functions, and the underlying communication protocols.

A "lightweight" IED need to implement the IEC 61850–8-1 (mapping the IED data to GOOSE) for the horizontal communication by using the open source library "libiec61850". Furthermore, the designed IEDs generated by this process will compliance with the IEC 61850 detention and agree the interoperability concept that offered by the IEC 61850 standard. As well as the IED is flexible, scalable and can be updated based on the valid SCD file. Within the open source library "libiec61850" the overall C code project files can be generated automatically based on define internal data model. This approach will reduce the research and development runtime and maximize the performance and facilitates the use of relatively low-cost embedded devices and FPGA.

Figure 2 depicts the instruction designing procedure for the "lightweight" IEDs that presented in this study. Within the first step SCD (.icd) file need to be designed based on the defined energy system aspects that includes the data attributes (DA) types, data object (DO), logical node (LN), logical devices LDs as well as communication instances of the model.

At the second step, and from the predesigned SCD file that include all the IEC 61850 data, a C code is automatically generated by the "libiec61850 model generator". This generated code is the representation of the model and their communication instances that tailored to the designed model. At this point the "model generator" attempts to convert and mapped each type of IEC 61850 data model into a C data structure. From this process a hierarchy C data structure file will achieved and collected into the project folder.

The third step was to define the parameters that are needed to be subscribed. Then to compile the design project file (or application file) to generate the execution file for running the project in the hardware under test.

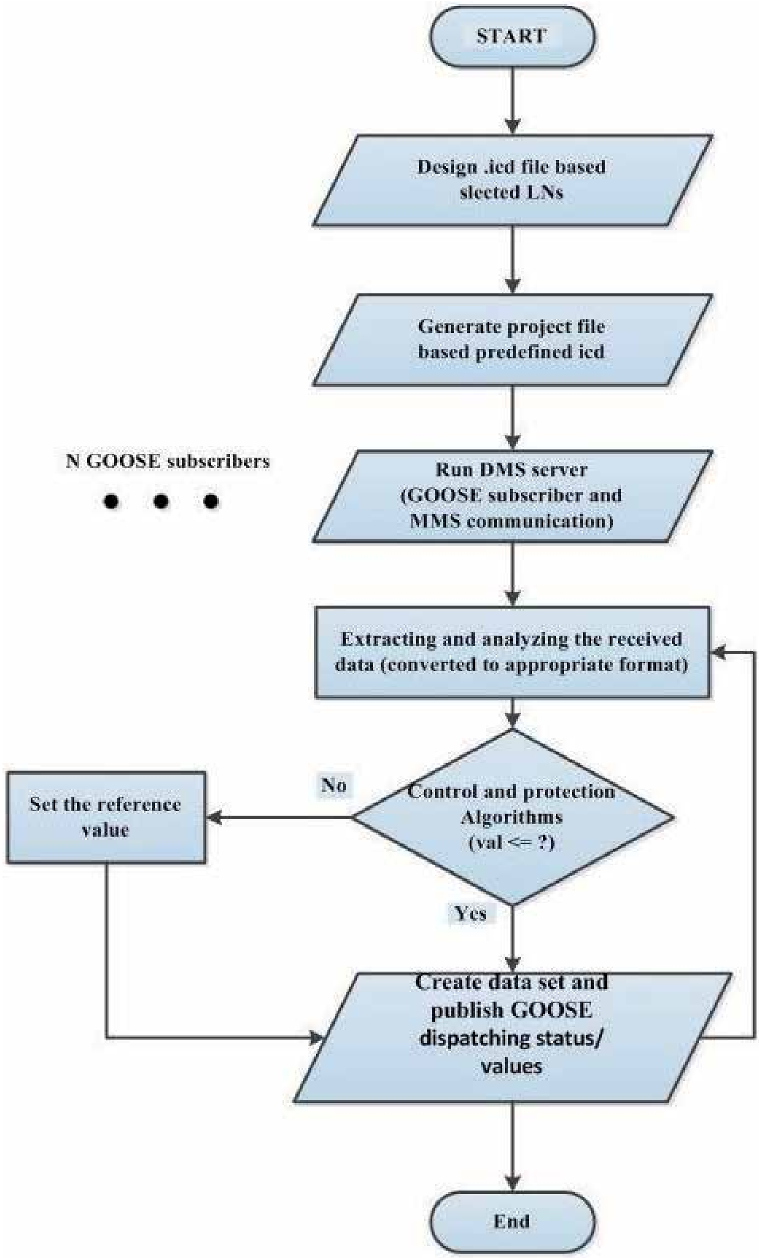

Figure 2.
The developed DMS internal processing.

The fourth step was about extracting the defined parameters (in this case the status of the main supply) from the subscribing GOOSE message from the model. Next step describes the execution of the control algorithm in the hardware and based on the result, the new status value need to be send over the communication network from the controller via IEC 61850 GOOSE protocol. On the other side the target were the simulation model is running is able to subscribe to the GOOSE message and extract the useful data to be used within the running model in real-time.

Lastly the designed project need to be tested. For cost reduction and simplicity advanced reduced instruction set computer (RISC) Machines (ARM) processor-based microcontroller BeagleBoneBlack (BBB) as well as by the ARM processor-based SoC FPGA are used. Both are compatible with C and C++ compilers.

6. Data object modeling based on IEC 61850–7-420 LNs

Data object modeling based IEC 61850–7-420 LNs need to be virtualized. **Figure 1** illustrate the round trip GOOSE messages between the publisher-subscriber-publisher which are modeled and need to be tested in real-time running in Opal-rt simulator. The round trip test setup consists from different IEDs. IEDs are configured to subscribe to the Opal real-time GOOSE messages and published back to the real-time simulator another GOOSE messages. Distributed IEDs are scattered over the communication system network through different distributed data points. These distributed IEDs are used for monitoring, control and protection function purposes.

LNs DPST and DRCS are selected to present the ECPs status and the DERs operation status respectively. LoM protection function based on its operation need to gather the information signals from the deined above LNs. LNs data structure is illustrated in **Figure 3** in which that listed and structured in tree manner down to data objects.

LoM protection function based on its operation, data object DPST.ECPConn included in to the DPST LN hierarchy is modeled for reflecting and indicating the ECP connection status. If the status of the data object DPST.ECPConn is "True" it indicates that DER is connected to the electrical grid through the ECP, and if it is "False" it indicate that the DER is not connected to the electrical grid through the ECP.

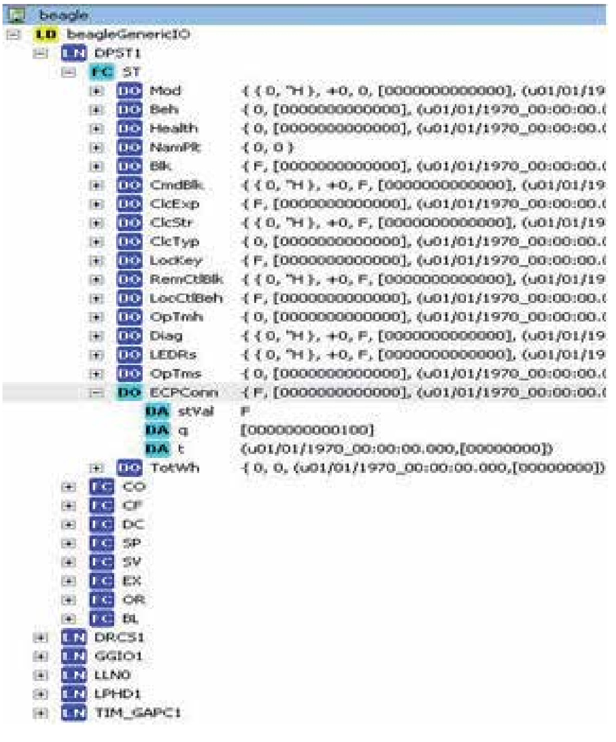

Figure 3.
Native IEC 61850 IED including the DPST and DRCS IEC 61850–7-420 LNs.

DRCS LN is include the DRCS.ECPConn and DRCS.ModOnConn data objects from the list of data objects defined in to the standard. DRCS.ECPConn data object present the electrically connected status of the ECP of the DER. Therefore, if the status of this data object is "True" the DER is connected to the electrical grid through a specific ECP, and vice versa. DRCS.ModOnConn data object present the status of the DER. If it is "True" it indicate that the DER is in operation mode "ON" and electrically connected. Whereas if it set "False" it indicate that the DER is electrically connected and not in the operation mode.

Opal real-time simulator is configured as un IED that include LNs DPST and DRCS LNs data objects in its ICD file. According to this ICD file Opal real-time simulator has the ability to publish GOOSE message over the communication system network. Different IEDs are configured to subscribe to the Opal real-time simulator GOOSE message based LoM protection function. Control decision status can be extracted from subscribing to the Opal real-time simulator GOOSE message.

7. IEC 61850 GOOSE Based HIL testing

IEC 61850 GOOSE is one of the enabling communication protocol of the standard. Its concept to replace the legacy interlocking hard-wired signal. According to GOOSE implementation, it publishes number of fast GOOSE messages from the original message in case of event occur to increase the reliability that one copy of these messages reach its destination. GOOSE assigned with the high priority (4). On the other hand, IEDs within the SAS need to be configured based on the publisher GOOSE messages parameters in order to successfully subscriber to the GOOSE messages.

GOOSE supports wide range of possible common data that can be integrated within the GOOSE dataset (binary and analog measured values). IEC 61850–7-1 part defines the GOOSE protocol where several parameters control the publishing process as follows;

DataSet: Contains ObjectReferences that the values of the members shall be transmitted by GOOSE Control Block (GoCB).

GoEna: To remotely enable/disable the publishing of the GOOSE messages.

AppID: Associated in the GOOSE messages to be used as identifier of the LOGICAL-DEVICE and a handler for subscription to different GOOSE messages from different IEDs in the same time.

ConRev: Contains the configuration revision indicate the changing updating in the data set within the GoCB.

T (time stamp): Contains the time when the attribute StNum was incremented.

StNum: State number containing a counter that is incremented each time when data set member value change is detected and the GOOSE message has been published.

SqNum: Sequence number contains counter that each time increments when GOOSE message has been published.

GoRef: The reference for the GOOSE control block.

Test: Indicates the implementing of the values of the message based on TRUE (testing purpose) or FALSE (operation purpose).

NdsCom: Needs commissioning, indicates that the GoCB requires further configuration [15].

As the GOOSE protocol is flexible and reliable based on serving different parameters that support different applications in which that compatible with the different application requirements and different data types [16]. At this point, and based on the IEC 61850 GOOSE high reliability and flexibility it is common natural to pursue smart energy system application based on IEC 61850 communication protocols e.g. LoM smart application. Therefore, along with testing steps for the proposed LoM smart protection application based GOOSE, different IEC 61850 IEDs need to be designed and configured for implementing the publishing and subscription role. At the IED GOOSE different subscribers the execution of the final smart LoM protection decision making functions are done and the new status need to be publish with other GOOSE message back to the real time simulator. More details about the smart LoM protection distributed decision making algorithm was published in our previous work.

8. The round trip GOOSE latency

The flexible GOOSE model is used by all of the state-of-the-art IEC 61850 IEDs and systems. From the GOOSE implementation point view, the publisher write the GOOSE parameter value in the local buffer, while the subscriber read the value from the local buffer. The subscriber local buffer is continuously updated via the communication system, were within the publisher side in order to control the procedure the GSE control class is used.

GOOSE round trip latency is calculated for different designed IEDs in different tests. One of the main objective of this test is to verify the GOOSE performance that the messages was compliant with the IEC 61850 requirement (not exceed 4 ms), as well as, to verify and ensuring the interoperability that the designed IEDs had the ability to operate within the multi-vendor environment.

In order to compare the GOOSE round trip latency for different designed IEDs, as well as for the commercial IEDs instantaneous GOOSE round trip latency is measured. From (1) GOOSE overall round trip latency time includes seven individual times that may affect the connection channel performance. The first individual time is the real-time model running in the target that publish GOOSE messages to the communication network, next is the communication network latency which is the needed time to deliver the message to the DUTs. Then every DUT that subscribe to the GOOSE message need to extract and computes the new status and then periodically publishes a GOOSE message to the communication network back to the real time simulator. This process was monitored by using a network protocol analyzer, Wireshark.

$$\overline{t}_{RTT} = \overline{t}_{\substack{out,\\ Target}} + \overline{t}_{net} + \overline{t}_{\substack{in,\\ DUT}} + \overline{t}_{app} + \overline{t}_{\substack{out,\\ DUT}} + \overline{t}_{net} + \overline{t}_{\substack{in,\\ Target}} \tag{1}$$

where

$\overline{t}_{RTT}$: round trip time average,

$\overline{t}_{out,Target}$: out from the target time average,

$\overline{t}_{net}$: communication network time average,

$\overline{t}_{in,DUT}$: DUT time average,

$\overline{t}_{app}$: DUT internal application average time,

$\overline{t}_{out,DUT}$: DUT, out time average,

$\overline{t}_{out,Target}$: target out time average.

In our proposed LoM case study GOOSE round-trip time between Opal-rt simulator as a publisher and different IEDs as a subscribers and publishers had been recorded by IEDScout GOOSE recording feature as illustrated in **Figure 4**. Recording file is opened by the Siemens SIGRA fault analyzer tool as illustrated in **Figure 5**. From **Figure 5** GOOSE round trip time can be measured based on the difference between IED1 GOOSE and IED2 and IED3 responses. This GOOSE round-trip time includes all the seven individual times included in the equations above.

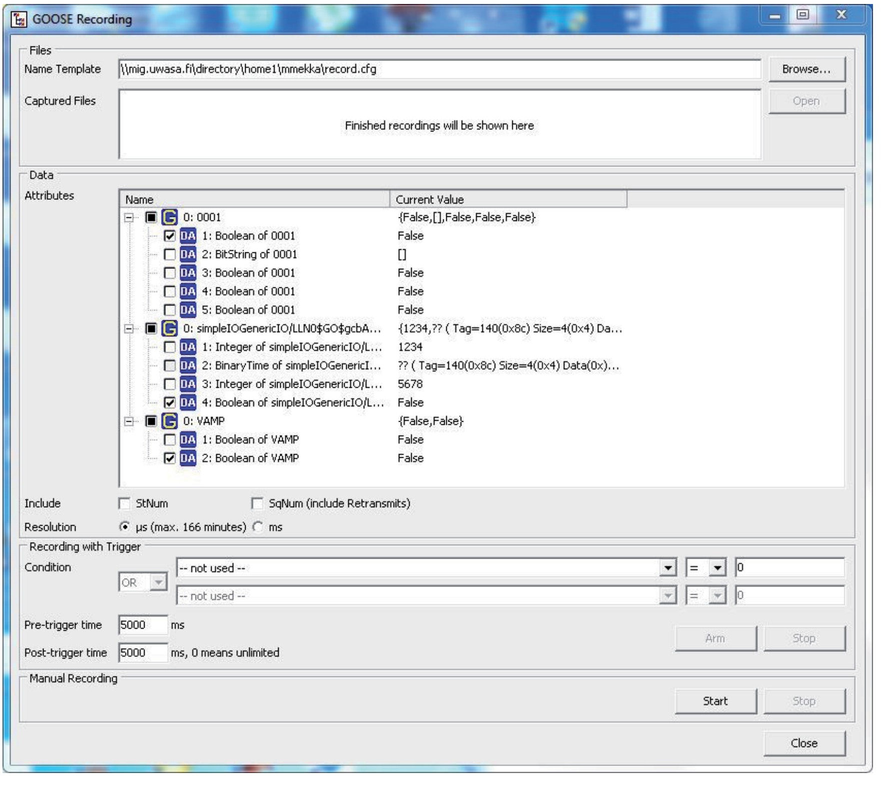

Figure 4.
GOOSE recording application.

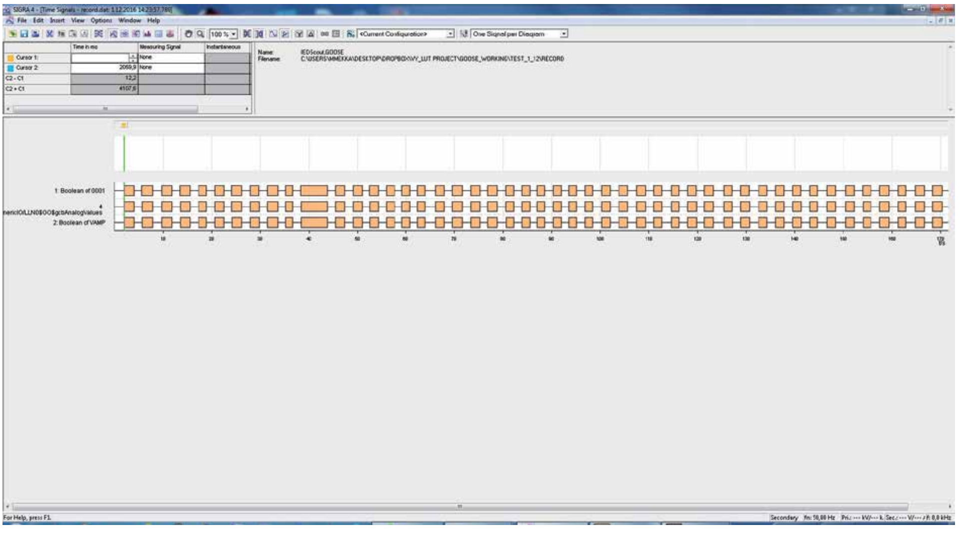

Figure 5.
Recorded signal in Sigra fault analyzer tool.

9. Case study

For easy understanding of the smart LoM protection based GOOSE simple electrical system with simple Ethernet communication system network has been defined (modeling of the electrical system within the real time simulator is not focusing of this work) as in **Figure 1**. A laboratory setup for the electrical communication system network that includes Opal-rt simulator, different Light-weight and commercial IEDs, 1000Mbit/sec Ethernet link and Ethernet switch has been established. IEDs light-weight IEC 61850 based FPGA and microcontroller is designed and modeled according to the IEC 61850–7-420 DERs LNs. GOOSE publisher block is continuously publishing the status of the main supply and the ECP through the 146 bytes GOOSE message from the real time simulator. Light-weight native IEC 61850 IEDs based FPGA and microcontroller are designed and modeled based on IEC 61850–7-420 DERs LNs, whereas others IEDs are a normal commercial feeder protection relay, Vamp 52, and ABB 615. Different IEDs are configured as subscriber to the Opal-rt GOOSE messages. The subscriber IEDs use the extracting parameter from the Opal-rt GOOSE for proper implementation of the proposed LoM protection function. Two scenarios based LoM protection function had been specified. Testing for these tow scenarios had been carried out based on the above laboratory setup. The first scenario for the LoM protection function is by changing the DPST. ECPConn data object of the main supply status from "true" to "false" in Opal-rt. This changing of the main supply DPST.ECPConn data object from "true" to "false" indicates that the main supply is not electrically connected to the electrical grid. Now here is regardless to the main supply operation mode. While scenario two, is by changing the main supply operation status by the DRCS.ModOnConn data object from "true" to "false". This changing of the main supply DRCS.ModOnConn data object from "true" to "false" indicates that the main supply is electrically connected however it is not within the operation mode. In practice this means that the circuit breaker is closed but there is no power supply available (e.g. due to main transformer failure). The changing statuses in scenario one and two are published within Opal-rt GOOSE massage. Both scenarios present two cases of the LoM that need to be predicted and detected within the DUT and publish dispatching GOOSE messages based on the new detected status. In our case study the LoM prediction and detection tasks are implemented through the exchanging of the GOOSE messages over the communication system network. Moreover, main and standard deviation of the GOOSE messages round trip latencies had been measured and calculated in next section.

10. GOOSE round trip latencies results and discussion

GOOSE latencies was measured for the round trip GOOSE based LoM laboratory setup and results are presented. The status of the main supply DPST.ECPConn or the DRCS.ModOnConn data objects was monitored. If one from the above mentioned data object indicate or show "False" indication it signify the disconnection of the main supply from the electrical grid or the main supply is electrically connected to the grid but the connection is not in operation, respectively. In both cases there is LoM a situation and DERs must be disconnected or changed to the island operation mode. By publishing the main supply status within the multicast GOOSE message it is eventually distributed to all the subscribers and LoM situation is properly handled even with high penetration of DERs. According to the test scenarios 100 trials of DPST.ECPConn and DRCS.ModOnConn status changes had been made and published within GOOSE messages from the Opal-rt simulator. Different IEDs

GOOSE round trip				
	BBB	**Vamp52**	**ABB**	**FPGA**
Mean val. ms	11.2	18.8	3.6	4.2

Table 1.
IEDs latency in millisecond.

are subscribing to Opal-rt GOOSE messages and monitoring the status of the main supply. While, another GOOSE message are published from the subscriber IEDs upon receiving and processing the Opal-rt GOOSE. All the GOOSE messages are recorded with the IEDScout for the round trip analyzing purposes.

Different subscriber IEDs are inherently able to monitor other data objects from other LNs that may include in to the designed ICD file. These data object status may be used to observe and response to all the different changes in the main supply status, which enables also some advanced operational scenarios. From the above tested scenarios, LoM protection function and may other functionalities have been proven to be possible both with the newly introduced light-weight IEC 61850 FPGA and embedded microcontroller. According to the achieving, results different round trip times for the communication channel had slightly vary depending on the communication channel and receiving end IED. The results also behave according to normal distribution model, which was expected. Since there was no other traffic within the communication channel in this test, and GOOSE messages with high priority (4) and short packet length were used the Ethernet communication system turned out to have very high reliability. Using the normal distribution probability density function the mean of the round trip latency of the GOOSE messages latencies had been calculated as illustrated in **Table 1**.

From (1) round trip latency was for BBB 11.2 ms and FPGA 4.2 ms. Based on the results, it is clear that the FPGA is a more promising instrument with less round trip latency (4.2 ms) that could better be used for the smart grid or microgrid central controller. In addition, the round trip latency for the FPGA is less than the other IEDs in which that was expected. Since the FPGA has Dual-Core ARM Cortex™-A9 (925 MHz) processor as well as 10/100/1000 Mbps Ethernet with the high-speed bus to exchange data between the hard processor system (HPS) and FPGA whereas the BBB has AM335x 1GHz ARM® Cortex-A8, and 10/100 Mbps Ethernet.

Lastly, we recommend that it is the time indeed for the researcher to really start looking/implementing these developed light weight IEDs, standards and testing them, in a way that we can see where the system/standards vulnerabilities might lay/practically do real-time measuring/evaluating in order to evaluate the IEDs development and fall the standards knowledge gaps. Also, measure and improve the energy system resiliency [17].

11. Conclusion

In this chapter, the monitoring, control and protection solutions and their relevant communication system have been designed based on IEC 61850 and implemented on hardware platforms, FPGA, BeagleBoneBlack and commercial IEDs. The development process and performance of LoM monitoring and control scheme on a light weighted intelligent electronic device has been investigated. The performance of the IEDs has been evaluated through hardware-in-the-loop test in terms of communication latency, processing time, and finally the performance of control action. The FPGA has performed better compared to BeagleBonBlack and is more suitable for micro-grid central controller. It is worth to mention that such an open-source flexible light-weighted IED based on IEC 61850 can provide a base to advance research in the direction of (Micro)-grid automation and control.

Abbreviations

IED	intelligent electronic device
FPGA	field programmable gate array
LN	Logical node
LD	Logical device
GOOSE	Generic Object Oriented Substation Event
R-GOOSE	Routable Generic Object Oriented Substation Event
SAS	Substation automation system
SV	Sample Value
R-SV	Routable-Sample Value
MMS	Manufacturing Message Specification
SoC	System on Chip
ACSI	abstract communication services interface
XML	eXtendable Markup Language
DER	Distributed energy resources
SCL	system configuration language
SCD	Substation Configuration Description
ICD	IED configuration description
WAN	Wide area network
QoS	Quality of services
DUT	Device under test

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Chapter 5

The Role of Energy Storage with Renewable Electricity Generation

Kamlesh Kumar and Babu Jaipal

Abstract

Renewable energy resource like solar and wind have huge potential to reduce the dependence on fossil fuel, but due to their intermittent nature of output according to variation of season, reliability of grid affected therefore energy storage system become an important part of the of renewable electricity generation system. Pumped hydro energy storage, compressed air energy storage, flywheels, capacitors, and super conducting magnetic storage technologies have been developed, but many of these are limited in their capacity, characteristics and site dependence. Currently battery energy storage system is not much adopted within grid, but with development their density, versatility and efficiency it is observed that BESS- (battery Energy Storage system) will be adopted in large quantity.

Keywords: energy storage, pumped hydro energy storage, compressed air energy storage, flywheels, capacitors, super conducting magnetic storage technologies renewable electricity generation

1. Introduction

Energy demand for single consumer to power station is varying throughout the whole day, and there is variability and uncertainty in the power quality, also there is imbalance of energy demand and supply which is completed using fossil fuels. These create environment pollution and global warming effects, that's why our main focus is diverted towards renewable energy resources; on the other hand these are variable and intermittent nature of energy generation so for their flexibility, stability and reliability energy storage technologies are put into practice. By transmitting the stored energy temporal as well as geographic gaps between demand and supply can be filled, also the areas having poor energy infrastructure or not electrified can be energized with the reliable source of energy storage (ES) [1]. Also, as there is no direct connection between consumer and electricity generation sources, Whole power generated at power station doesn't reach to the consumers, and large amount of energy is being lost in the form of losses, in this way current gird system become inefficient. System can be made more efficient by using battery energy storage system in gird, by running plants near to their full capacity, and also by using maximum amount of power generated at power stations [2]. In power distribution system battery energy storage system is provided in two ways, either storage is provided at distribution substation or at distribution feeder also SCADA (supervisory control and data acquisition) equipment, control schemes, and economics of scale can easily access using centralized storage technologies [3]. Power quality is maintained easily with the installation of comparatively sized batteries in the installation of large solar PV plants, battery energy storage control system is done either automatically or using solar couple system [4]. Majority of energy storage within grid is present in the form of pumped hydro storage plants about 125 GW, it makes about 3% of global power capacity [5]. Pumped hydro energy storage, compressed air energy storage, flywheels, capacitors, and super conducting magnetic storage technologies have been developed, but many of these are limited in their capacity, characteristics and site dependence. Currently battery energy storage system is not much adopted within grid, but with development their density, versatility and efficiency it is observed that BESS will be adopted in large quantity [6].

2. Literature review

Although fossil fuel complete our desire of electricity but on the other hand these are destructing the planet, so now day's renewable energy resources including hydroelectric, geothermal, solar thermal, biofuels, biomass, wave, tidal, and wind are being used to generate electrical power. More importantly, wind and solar are more developed due to their environment friendly characteristics [7]. There is uncertainty in the output of solar and wind or it can be said that their output is not constant, and depend on season whether it is sunny days or cloudy and also the location for proper required wind speed. This uncertainty in output of these renewable energy resources result in the requirement of energy storage devices for the reliability and improvement in economy of power system [8]. Major problem associated for renewable energy resources is the inconsistent power output, that can easily be reduced and solved using battery energy storage technology, along with that it result in decarburization of energy mix and mitigation of CO_2 emission, and global warming effects. BESS can easily be adopted in off grid as well as in on grid system, also at any location in the power system from generation to consumer. Batteries installed at solar photovoltaic PV and wind power plant allow owners to store the energy when energy prices are low or there is inexpensive and uneconomic to supply to grid, and can be released to use during high prices time. Batteries installed with PV system and wind generator at household level increase self-produced and self-consumption electricity, a household PV system with battery system result in increment of self-consumed energy about 30% without storage to 60–70%, along with that efficiency is increased and also additional power requirement from grid is decreased [9].

Now a day most of the storage in every country is the pumped hydro storage with the capacity of 200 MW, about 25 MW of electrical power is generated using pumped hydro storage plant, out of that 22 MW is being generated in United States. These plants are basically used during peak demand time, also providing water for the nuclear and steam power plant to enhance their performance efficiency and frequency control and regulation [10]. Another bulk storage technique in which air is compressed at the time of low demand with low energy prices, and during peak hour power can be generated at low cost with respect to stand alone gas turbines [11]. Because of new technology in concentrated solar thermal power system and photovoltaic system, demand of energy storage system is increasing in offshore platforms, and telecommunication installations (which are remote area power supply system), mobile applications, emergency backup, gird connected renewable power plants, and stressed electricity supply system [12].

This study shows the renewable energy generation and energy storage analysis in the Finland, It is committed that by year 2050 greenhouse effects will be reduced to 80–97% as compared to year 1990 [13]. Finland is dominating on run of river hydropower with limited capacity of 5.5Twh approximately, during months of December–April in winter season water is stored in reservoir and in summer season, that stored water is used to generate electrical power [14]. It is examined that energy storage technologies can play an important role for getting proper benefit of solar resources, along with that gas storage, thermal energy storage, stationary batteries and power to gird technologies are also discussed [15]. Solar photovoltaic and wind are variable sources of power generation; about 70% of total energy generation is being generated using these technologies, about 51% of renewable energy generation is stored and 47% is directly utilized [16]. This study is about United states, inspite of knowing the benefits of energy storage technologies, only 2.5% of total electric power of United States is being stored (out of that most part is hydro pumped storage system), which is about 10% of Europe and 15% of Japan energy storage [17]. About 99% of worldwide storage capacity of 127000 MW is pumped storage, at second compressed air storage with capacity of 440 MW. Electrochemical energy storage has lot of system friendly characteristics i.e. high round trip efficiency, no any pollution, flexible energy and power characteristics, long life and low maintenance. Because of compact size of batteries, these are suitable for distributed locations, also can reduce variation in output voltage of solar PV and wing power plants [18]. From this study it is estimated to increase the renewable generation around 60–80% by the year 2030, which is currently about 20% of total generation of the country; at same time, high cost of battery and un availability of suitable location will result in the limited installment for compressed air energy storage and pumped hydro storage technologies [19].

3. Summary of empirical literature regarding impacts of energy storage technologies

Ref. no	Year	Storage technologies	Summary and conclusion
05	2016	Pumped hydro energy storage	Electricity can be generated at lower price using pumped hydro energy storage system, also solar and wind power plant installation can result in cost free surplus energy.
02	2016	Battery Energy Storage System	Installation of variable renewable energy resources and battery energy storage can play an important role for 100% renewable energy based Finland.
[7]	2015	Pumped hydro energy storage	The wastage of energy either solar or wind can be minimized using pumped hydro energy storage system
[19]	2015	Battery Energy Storage	The efficiency, lifetime cycle, discharge time and weight of battery energy storage technology are considered as superior to all other storage technologies. Lithium ion batteries are only used in small electronic devices, but not for large amount of storage because of their high cost and limited performance characteristics.
[20]	2015	Thermal, pumped hydro and battery Energy Storage	Thermal energy storage, batteries, sodium Sulphur, lithium ion, pumped hydro storage and compressed air energy storage are suitable technologies for large scale storage of the order of 10–100 s of MW h.
[21]	2015	Hybrid energy storage system of batteries and capacitors	Hybrid electrical energy storage system of batteries and super capacitors result in increment in battery life and reduction in their cost.
[22]	2015	Compressed air energy storage, flywheel, batteries, super capacitors, hydropower and hydrogen energy storage	The variation in electrical power price as well as in their price can be avoided with the installation of electrical energy storage devices, also enhancing decentralized generation technology.

Ref. no	Year	Storage technologies	Summary and conclusion
[23]	2014	Electrical Energy Storage	Small capacity energy storage devices can be encouraged at negative electricity prices.
[24]	2014	Remotely located renewable energy storage	In poorly interconnected island grid system or remotely located renewable energy based system, electrical energy storage are behave as an added value energy resource.
[25]	2014	Battery Energy Storage	Wind and Solar energy generation result in dispatch ability and reliability problems in decentralized generation, which are mitigated with the help of EES systems; redox battery is concluded as most promising technology.
[26]	2014	Hybrid Electrical Energy Storage	Different techniques are analyzed for enhancing the performance of hybrid electrical energy storage system with keeping low cost, along with their merits and de merits.
[27]	2014	Battery and Electrical Energy Storage	The installation of renewable generation in distribution system result in changing in design and operation of power system, hence battery energy storage as well as other EES system are used to support the existing power system as well as developing power system infrastructure.
[28]	2014	Electrical Energy Storage	It is concluded from the study that electrical energy storage system integrated voltage control system are more accurate, and valuable as compare to conventional voltage control schemes.
[29]	2014	Electrical Energy Storage	As EES has some issues, their policy and barriers, their solution in North America are being discussed.
[30]	2013	Battery Energy storage	It is concluded that for gird integrated storage, it is important to enhance the life cycle in order to improve the scalability of battery technologies.
[31]	2013	Battery energy Storage	Zn-air batteries and NANiCl batteries are promising technologies for buildings, due to their high energy density and power capability, and high life cycle.
[32]	2013	Super capacitors storage	Long life cycle, high charge and discharge efficiency, and high power density characteristics of electrochemical super capacitors technologies are the key features to use these technologies into aerospace, automobiles, and portable electronics.
[33]	2013	Hybrid Electrical Energy storage	Optimal hybrid electrical energy storage system result in about 60% more return on investment as compare to lead acid battery system.
[34]	2013	Hybrid Electrical Energy Storage	Residential user connected to gird connected hybrid electrical energy storage system, can get benefit of lowering the electricity price by storing energy during low price hours and releasing that energy during high price time.
[35]	2012	Battery Energy Storage	Emission control of power plants can be efficiently done with the help of battery energy storage system.
[36]	2012	Fuel cell	It is concluded that a more optimal cell with efficiency of more than 90% can be developed with same densities.
[37]	2011	Hybrid Electrical Energy Storage	It is concluded that proposed Hybrid energy Storage System HEES system result in improvement of capacity utilization, and in cycle efficiency up to 108% and 127% for dc power demand profile and high current pulsed power profile respectively.

Ref. no	Year	Storage technologies	Summary and conclusion
[38]	2011	Electrical Energy Storage	Proposed method can reduce the fuel consumption and power capacity installation of peak load units up to 50%.
[39]	2011	Super capacitor Storage	From super capacitor to battery and battery to super capacitor charge migration result in improvement I efficiency about 51.3%.
[40]	2010	Fuel Cell	By connecting energy buffer to the grid, active power can be provided as well as power flow can be smoothed.
[8]	2010	Electrical Energy Storage	Variable generation energy sources require more flexible operation and generation reserves, which are completed by energy storage system.
[41]	2008	Flywheel and Pumped hydro Energy Storage	It is concluded that development in flywheels and pumped hydro power also should play an important role in such a niche marketplace

3.1 Applications of energy storage technologies

Applications of energy storage technologies are categorized as follow based on their discharging length.

3.2 Storage technologies for power quality applications

Transient stability and frequency regulation are the part of power quality applications, which require less than a second it means rapid response, but their time may goes up to 10 minutes. Following technologies are used in these applications:

3.3 Flywheel

It stores energy in the form of rotating mass, because of high efficiency and rapid response these are suitable for frequency regulation [8]. This technology is many advantages like high efficiency, quick response, he life of service, low operation and maintenance cost, stable system, clean technology, but the energy density is low, easy to be self-discharge which is only suitable for short time applications.

3.4 Capacitors

Super capacitor and superconducting magnetic energy storage are two main carrier of electromagnetic energy storage. This technology has high power density, low maintenance and operational cost, quick response, long life span, and their charging and discharging rate is critical. These are used in transient voltage stability application due to their fastest response among all energy storage devices and energy is stored in the form of electric charges. But, these are redistricted to use in long time duration application due to their low energy capacity; with the advancement and research work their use and density can be increased in grid [8].

3.5 Superconducting Magnetic Energy Storage (SMES)

The coil of superconducting material store energy in the form of magnetic field, are fast responding energy storage devices, but are restricted to use in short duration discharge time and their total energy capacity [8].

4. Storage technologies for bridging power

When there is error in unit commitment and contingency reserves, these applications provide load forecast, contingency reserves and additional reserves, and require rapid response and discharge time. Lead acid, Nickel metal hydride, lithium ion and Nickel cadmium batteries can provide frequency regulation, on the other hand can limit battery life [8].

4.1 Storage technologies for energy management

These applications require continuous discharge rating for several hours; following technologies are used in the technologies.

4.2 Thermal energy storage

In this storage system energy is not stored and directly used, so some times this can be ignored as electricity storage technology, but can be equivalent to electricity storage in some applications. In solar thermal generator, solar power is store in molten salt or another medium is used to generate electricity [8].

4.3 Pumped hydro energy based storage

In this method of energy storage, potential energy of water is being stored by pumping water from lower reservoir to the higher level at low price or during off peak time and same stored water is used in the peak hours by operating turbine to generate electrical power. To transfer water from lower reservoir to higher reservoir wind and solar based pumped storage hydroelectric storage system are shown in **Figures 1** and **2**. Electricity can be generated at low price using this technique, but it requires appropriate geography and availability of sufficient amount of water. Currently this storage system is working as large scale energy storage, along with improving the daily capacity factor of power plants. According to Electric power Research Institute about 99% of the bulk energy storage around the world (127GW) is done using pumped hydro energy storage system [42]. Large PHES system has

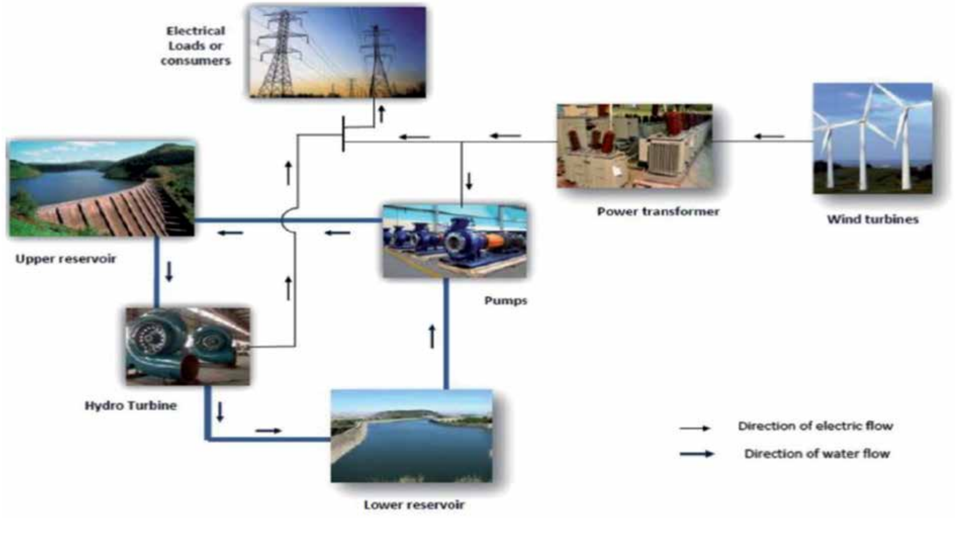

Figure 1.
Wind power based pumped hydro energy storage system [7].

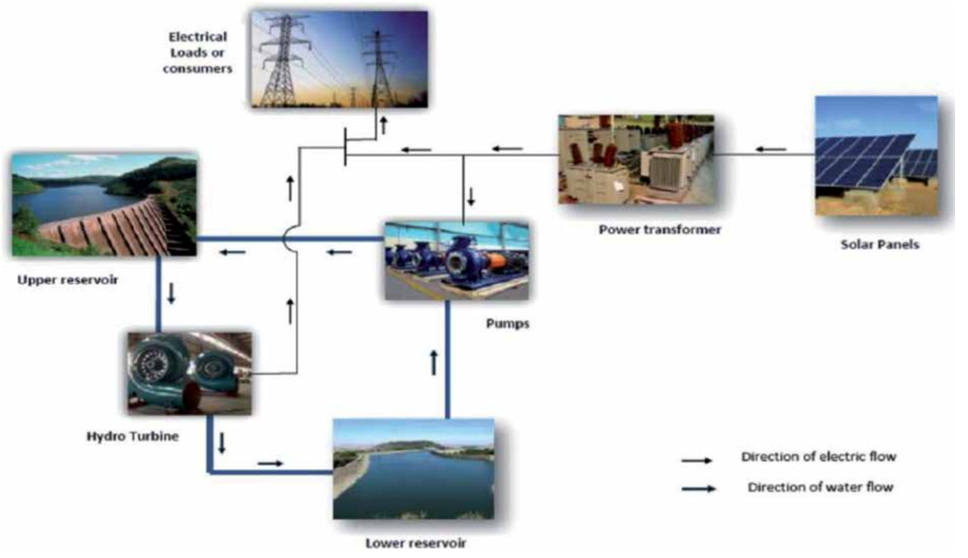

Figure 2.
Solar PV based pumped hydro energy storage system [7].

capacity of more than 10 MW, small PHES system has capacity from KW to 10 MW, and micro PHES system has capacity of 100KW and the Plants having capacity less than 5KW are known as Pico pumped hydro energy storage system. As installation of renewable energy is increasing, PHES is becoming an important part of energy generation system due to their efficiency in range of 70% to 80. In different geographically areas wind base pumped hydro energy storage systems are considered as most economical and technical competitive [43, 44].

As solar energy is available to us during day time about 6–8 hours in a day, hence to get the proper and maximum benefit of this solar energy solar based pumped hydro energy storage system PHES system is made; using that method the required energy is transmitted through the grid system and remaining excessive energy is used to store the water in upper reservoir from lower reservoir during off peak period, and by releasing that water during peak hours electrical power can be cost effectively generated. It has large capacity, long service and low unit cost, but due to geographical conditions impact this technology is somehow redistricted.

4.4 Compressed Air Energy Storage (CAES)

Air is compressed and energy is stored in an airtight underground storage cavern, at the time of energy requirement that compressed air is taken from vessel, heated and expanded in high pressure gas turbine, where that air is mixed with fuel and combustion takes place and exhaust is expanded through low pressure turbine to environment through chimney. CAES has compression ratio of 0.6–0.8 and heat rate of 4000–4300 BTU/kWh [8]. This technology has huge capacity, as well as operation time, and service lifetime, along with that it can supply combine heat, cold and electrical power. But, due to their low capacity and complexity, and location dependent this technology is also redistricted.

5. Heat storage

Latent heat and sensible heat storage are two basic types or technologies used in heat storage. In sensible heat storage, water (heat storage medium) is heated to increase the temperature; latent heat storage uses the regenerative material achieving phase change heat storage, which is implemented on the solar thermal power generation. During rainy season, electricity can be produced using photo thermal system; in this way output is able to adjust according to requirement. Thermal storage system have efficiency about 95%–97%, cost is low as compare to that of large scale battery storage about (1/30th).

6. Chemical energy storage

Hydrogen or any other synthetic gas is used as electrolyte and synthetized into methane gas with carbon di oxide, this technology is known as secondary energy carrier. This storage system is cleaner and can be storage system of above 100GWh energy, but their efficiency is low about 40%–50%, security is low and also cost is high. Many countries are using hydrogen storage system, in which fuel cell is basic manner to utilize hydrogen. Currently the main aim for its application is to improve its cost, efficiency and lifespan, leading to a prospect of better renewable energy utilization and large-scale hydrogen as the fundamental energy system.

6.1 Battery energy storage

High temperature batteries and liquid electrolyte flow batteries are two general types of batteries used in energy management system. In year 2009 sodium sulphur batteries were consider as most mature high temperature batteries; liquid electrolyte flow battery has this advantage that their energy and power component can be sized independently [8].

6.2 Types of batteries

Lead acid, Lithium ion, Nickel metal hydride, Nickel cadmium, sodium sulphur, Sodium Nickel chloride, redox flow and zinc air batteries are mostly used in energy storage system. Each type of battery has their own characteristic like storage capacity, life time cycle, cost and charging/discharging cycles. Sodium sulphur batteries response very quickly and their life cycle is about 15 years, but are expensive [45]. For small amount of storage applications, Lithium ion and nickel cadmium are attractive, but for higher amount of energy storage applications these batteries are expensive. According to IRENA 2015b, storage technology is chosen on the base of their parameters [46].

6.3 Lead acid batteries

This type of battery has low cost, and deep cycle, and are used in industrial applications as well as in on grid application since hundred years. But, due to their lower specific energy and power, lower cycle life and longer charging time, their capacity in large capacity renewable energy is less as compare to sulphur and Lithium ion batteries. These batteries are well suited for frequency regulation applications because of their low upfront cost, and with the advancement in research it is aimed to increase life cycle, charge acceptance, cost reduction, discharge performance. To improve the power active materials having low internal resistance and life cycle is improved using enhancing the design [9].

6.4 Lithium based batteries

Recently, lithium ion batteries are used in residential and commercial usage and in electric and hybrid vehicles, worldwide grid connected battery capacity is currently about 200 MW and is increasing very fast. Because of their high energy efficiency, compactness, maintenance free design, long life and versatility, these batteries are justified but for their precise management and charge control purpose electronic devices are used which make the system to be complex. With the research there will be improvement in their life cycle, energy density, cost reduction and charging/discharging characteristics and market value will be increased [9].

6.5 Nickel based batteries

This type of battery is specially used in those applications having long cycle or fast charging conditions and extreme climate. Nickel based batteries work correctly in low temperature (less than −40 degree centigrade) environment; also it has long cycle and design life as well as good cycling pattern. Hence in can be said that these batteries are competitive technology choice for the areas where renewable energies are stored and cyclically, and it is considered as world's most power full battery. In future with the advancement, their life cycle, and temperature ranges can be increased; alkaline batteries cannot be replace by any other type if battery because of their operational safety, reliability, performance and durability to face adverse environment [9].

6.6 Sodium based batteries

Long life cycle, high efficiency, fast response, and high energy density characteristics, make these type of batteries to be suitable for on grid applications; but it require high temperature and extra insulation and active heating. Sodium nickel chlorides are used at small level in on grid and off grid applications, but with the research advancement their recharge power and life cycle can be enhanced and that will result in reduction of their cost [9].

7. Challenges and future orientations of EES/the future for energy storage and renewable integration

As we are moving towards renewable energy for our electricity generation, and also with the development in battery energy storage technology and their life and cost, it is important to say that battery will be an important part of power system in near future. Battery storage system makes the grid to be more flexible and modernize, just like improvement of cycling performance of conventional thermal units at lower prices, coordination of hydro with solar and wind power plants, advancement in control system and communication [47]. With the development in battery energy storage system, their cost and performance characteristics are being improved, that make an important role in their market value. By storing energy using battery storage technology near to the loads transmission and distribution losses reduced, hence system efficiency is increased; stacked services and multiple value streams and services (which are easily monetize able in deregulated markets) are illustrated in **Figure 3**. The energy storage technology has promising application prospect in renewable energy generation grid integration, distributed generation, micro grid,

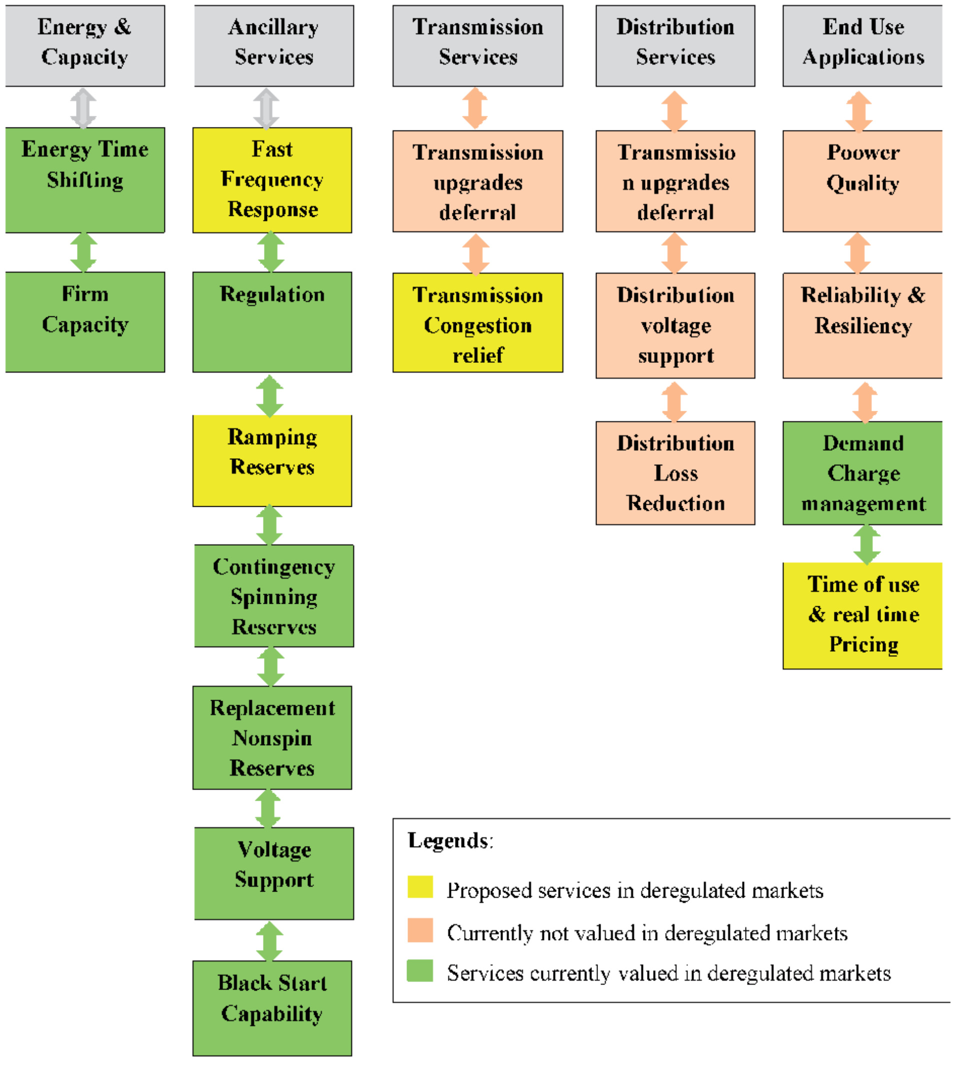

Figure 3.
Multiple value streams of battery energy storage [International Renewable energy agency 2016, Electric power research institute, & US department of Energy] [47].

transmission and distribution, smart grid and ancillary services. However, the large scale application of energy storage technology still faces challenges both in the technical and economic aspects. For the development in energy storage system, some new break throughs are required in capacity, long-lifespan, low-cost, high-security for electrochemical energy storage, high efficiency. Along with that simulation and operation optimization on storage technology should be focused in order to support theoretical as well as well practical knowledge for projects demonstration for promoting the commercialization and industrial system. At the same time it is necessary to establish a complete and rigorous professional cohesion, reasonable classification, transparency, openness and energy storage standards, which will provide strong support for research and development, production and application of energy storage, and promote the development of energy storage technology and related industries. Currently, lack of policies to support the technology, and high cost and other issues are main challenges for energy storage system in industrial applications. Two aspects should be considered in the future: on the one hand, it is necessary to propose energy storage system solutions with the participations from electricity users, electrical enterprises, researcher, economical organizations and social originations, and on the other hand, the suitable industry market mechanism and the subsidy policy should be promoted. Researchers should be promoted and encouraged for applications of energy storage in order to provide development model and achieve commercial operation of energy storage.

8. Conclusion

With the generation of electricity using renewable energy resources, the dependence on fossil fuels can be reduced; but these are variable and intermittent nature of energy generation so for their flexibility, stability and reliability energy storage technologies are put into practice. Major problem associated for renewable energy resources is the inconsistent power output, that can easily be reduced and solved using battery energy storage technology, along with that it result in decarburization of energy mix and mitigation of CO_2 emission, and global warming effects. Long life cycle, high charge and discharge efficiency, and high power density characteristics of electrochemical super capacitors technologies are the key features to use these technologies into aerospace, automobiles, and portable electronics. From super capacitor to battery and battery to super capacitor charge migration result in improvement I efficiency about 51.3%. As solar energy is available to us during day time about 6–8 hours in a day, hence to get the proper and maximum benefit of this solar energy solar based pumped hydro energy storage system PHES system is made BESS can easily be adopted in off grid as well as in on grid system, also at any location in the power system from generation to consumer. With the development in battery energy storage system, their cost and performance characteristics are being improved, that make an important role in their market value. By storing energy using battery storage technology near to the loads transmission and distribution losses reduced, hence system efficiency is increased.

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Chapter 6

xIoT-Based Converged 5G and ICT Infrastructure

Ahmed Y. Hassebo

Abstract

This chapter examines and explores the potential of how the capabilities of the emerging 5G cellular technologies can be integrated with a given mission-critical xIoT application (e., g., smart grid) to enable a truly converged xIoT-ICT infrastructure that would further enhance and enable the adequate support of the strict performance requirement of such an xIoT application. Since the smart grid believed to be one of the most necessitated IoT services. in this work, it has been nominated as a descriptive xIoT case. As the smart grid comprises an extensive collection of applications extended from mission-critical services which have rigorous necessities in terms of end-to-end (E2E) latency and reliability (e.g., real-time system protection and control utilizing PMU measurements) to those that require support of massive number of connected machine-to-machine (M2M) devices with relaxed latency and reliability requirements (e.g., smart meters). Based on time-to-market strategy, we identify and propose two different 5G-based business and architectural models that enable a truly converged power grid-ICT infrastructure, namely, near-term model and long-term model.

Keywords: IoT, 5G, ICT, Smart Grid, PON, Slicing, and Mission-Critical

1. Introduction

Distributed energy resources (DERs) comprising wind and photovoltaic (PV) systems, joint heat and power systems, energy storage, demand response (DR), and microgrids. In addition, plug-in electric vehicle (PEV), vehicle-to-grid (V2G) and supportive electric vehicle supply equipment (EVSE) systems are controlled to transform the landscape of the universal energy market. Nowadays, an international and domestic widespread change is pervading. Recently, as early as 2018, the grid automation and demand response expenditure has touched $70 billion worldwide and estimates depict that distributed capacity additions will surpass new centralized generation capacity additions [1]. The historic treaty developed from the latest universal Paris climate summit obligating all countries to act in contradiction to climate change will vividly fast-track the universal distribution of renewables and distributed generation (DG). It starts the launch of the conclusion of the fossil fuel epoch and the dynamic conversion to a novel clean DER-dependent universal energy market.

A universal integration of DERs into typical energy generation is fundamentally efficient to transform from the current conventional centralized grid to a strictly smart grid. To be truly smart, the power grid must provide a secure two-way flow of data throughout the entire grid assets, including millions of intelligent electronic devices (IEDs) such as sensors and smart meters, electrical appliances, switches, gateways, Supervisory Control and Data Acquisition System (SCADA) control centers, databases, and consumers. A universal, efficient, and economical DER implementation necessitates boosted positional knowledge so that the system operator is aware of devices and its location. The entire grid necessitates a boosted vision down to the distribution system and end user/device level. This will necessitate a superior dependance on the Information and Communication Technology (ICT).

Many utilities have already started investing in the distribution grid by deploying sensor systems and Advanced Metering Infrastructure (AMI). AMI is consisting of smart meters, communication networks and information management systems. Nationally, it is anticipated that about 65 million smart meters will be implemented by 2015, accounting for at least a third of all U.S. electricity customers [2]. To support AMI deployment, wireless mesh networks are typically utilized because they are more affordable than fiber optics networks. These networks can only support basic meter reading functions since they lack the bandwidth and latency capabilities required to support advanced distribution automation.

Recently, distributed energy resource management systems (DERMS) have been developed as smart software solutions to tackle the economic and technical challenges modeled by the propagation of customer-owned distributed resources. The efficient management of DER is the fundamental role of a DERMS [2]. In 2030 and beyond, the grid operations are expected to be dominated by the microgrids and DER. In addition, numerous theoretical, industrialized and regularization research and development (R&D) have been established to encounter this challenge [3].

The power grid network comprises four functional areas, incorporating bulk generation, transmission, distribution, and consumption which are normally disseminated in a huge zone. The associated communication network infrastructure must cover all of these four divisions and is split into several classified networks. These networks comprising home area networks (HANs), neighborhood area networks (NANs), field area networks (FANs), and wide area networks (WANs), as depicted in **Figure 1**.

Several different wired and wireless networking technologies have been proposed as the underlying communication infrastructure for the smart grid including broadband power line communication (BPLC), Digital Subscriber Lines, cellular wireless (2G, 2.5G, 3G, and WiMAX), IEEE 802.15.4 g-based wireless HANs (ZigBee communication protocols), wireless sensor networks (WSNs), high-speed wireless local area networks (WLANs), e.g., WiFi, and IEEE 802.11 s-based multihop wireless mesh networks (WMNs), etc. Typically, different networking technologies and standards are adopted in different parts of the grid, e.g., PLC and/or IEEE 802.15.4 g may be used in HANs, IEEE 802.15.4 g and/or IEEE 802.11 s may be used in NANs, while IEEE 802.16 (WiMAX) is used in WANs [4]. All these networks have to be integrated into one larger seamless network to provide efficient data and control flow.

2. Recent research growth: challenges and motivations

As the grid develops, several diverse devices and systems will be incorporated into the distribution grid involving those of the predicted universal AMI, microgrid and PEV implementation. Therefore, for the anticipated smart grid, E2E interoperability implementation among these systems and devices in a simple and affordable approach is considered as an overwhelming mission. Various interfaces among diverse grid systems and components have been recognized by the US National

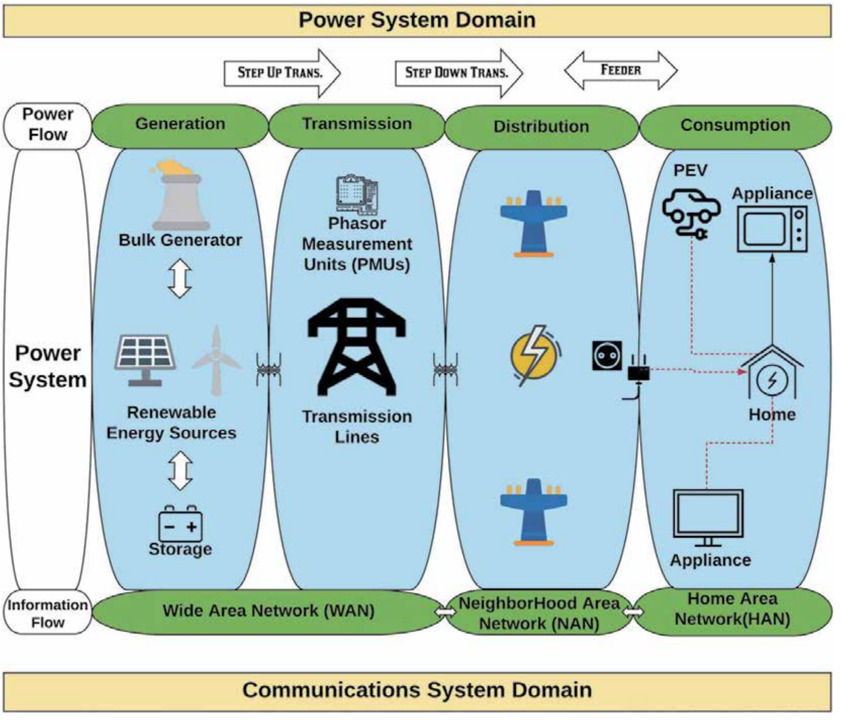

Figure 1.
Power grid components and power grid communications network.

Institute of Standards and Technology (NIST) Cyber security Working Group [5]. Devising a widely accepted seamless global communication networking technology standard across the entire grid segments will certainly greatly simplify the end-to-end interoperability challenge. As more and more devices and components are connected to future power grids, communication networks and computing are growingly integral to power grid operations and the notion of a truly converged power grid and ICT infrastructure is inevitable.

The potential grid communications networks possession, associated standards, and interoperability challenges are igniting a substantial dispute among all shareholders. The utilization of the services of the public commercial fixed/mobile networks or the dependence of the potential grid communications networks on the utility controlled private network is considered the center of the current argument. The Federal Communications Commission (FCC) recommends on the issue of grid data communications possession in its nationwide broadband strategy: "The nation should follow three similar tracks". First, reinforcing the current commercial mobile networks (Long Term Evolution (LTE)/LTE-Advanced (LTE-A)) to provision mission critical smart grid services. Second, enabling the utilities to share the public safety mobile broadband network for mission critical communications. Third, essentially, utilities are authorized to create and control their private mission critical broadband networks" [2–4].

The miscellaneous use cases of potential power grid applications varying from mission critical applications to relaxed latency applications. The mission critical applications necessitate ultra-reliable and strict E2E latency, for example, system protection. While the relaxed latency applications provision massive number of connected devices with relaxed reliability requirements and latency necessities, for instance, smart meters. Point-to-point (P2P) fibers among the controller and every device might be required to provide a strict E2E latency to the mission critical applications. Therefore, the ideal solution is to dedicate a private optical fiber network. a significant fiber capacity underutilization and fiber cost prohibitions conversely are due to a dedicated fiber network deployment for smart grid purposes.

In contrast, it has been agreed that utilizing significantly flexible and cost effective commercial cellular networks, for example, 4G LTE and/or LTE-A dependent Fifth Generation (5G) are significantly convincing technically and economically for the potential power grids. Due to its cost effectiveness and availability, using of 4G LTE is considered by multiple energetic service industries to support critical connections to smart devices, and sensors belong to their networks. However, typical 4G LTE networks cannot efficiently accommodate the diverging performance requirements of smart grid mission-critical applications in terms of latency, availability, and reliability.

Recently, Ultra-Reliable Low-Latency Communication (URLLC) paradigm has emerged to permit an innovative chain of mission-critical applications. These services comprising industrial automation, instantaneous operation, smart grid control, inter-vehicular communications for improved safety, and autonomous vehicles. URLLC is one of the most pioneering 5G New Radio (NR) features. URLLC and its supporting 5G NR technologies might become a commercial reality in the future, but it may be rather a distant future. Thus, it is most likely that deploying viable mission critical IoT applications won't be feasible in the near future, at least not before URLLC and 5G NR technologies become commercially available.

This study, driven by these challenges, investigates the evolving 5G cellular technologies potentially can be incorporated with the power grid to assist the implementation of a strictly smart grid (a congregated power grid ICT infrastructure). Numerous substantial economic and technical developments will significantly position LTE-A dependent 5G cellular technologies as a potential universal congregated grid communications standard. These include:

1. Smart grids, smart cities, smart homes, ehealthcare, and intelligent transportation systems (ITS) are considered as the IoT applications and services. To support billions of IoT devices/things with universal mobile connections, 5G will be considered as a groundbreaking solution.

2. The growth of LTE-A equipped Heterogeneous networks (HetNets) comprises a combination of macro-cell base stations (BS) and cost-effective low-power small cell (SC) BSs functioning over both licensed (e.g., femto cells and pico cells) and unlicensed (e.g., WiFi access points) bands [5–7].

3. Cell-based LTE-A equipped M2M and machine-type communications (MTC) [6, 7].

4. LTE/LTE-A has been already selected by US and EU federal authorities to be the technology for future public safety mobile broadband networks.

Based on time-to-market strategy, we identify and propose two different 5G-based business and architectural models that enable a truly converged power grid-ICT infrastructure, namely, near-term model and long-term model [8]. Utilization of the public commercial 5G cell-based network along with public commercial passive optical network (PON) dependent fiber-to-the home/node (FTTH/FTTN) is the near-term model which is the main focus of this study. In this model, utilities can control the provisioning of the cell-based communication devices (LTE-A-equipped M2M module/SIM card). The fixed/mobile operators should stringently synchronize with the utilities to modify a portion of the core network (CN) and information systems [9]. The Telecom operator in the near-term model, should have the control of the fixed PON FTTH resources (wavelengths) as well as radio network resources and frequency licenses.

The concept of the evolving 5G network slicing is the base of the second long-term model [10]. The 5G network slicing has been empowered by the latest swift networking developments in mobile edge computing and storage proficiencies, software defined networks (SDN), and network functions virtualizations (NFV). Extensive various IoT applications (Verticals) are to be supported by 5G, each vertical with its own distinctive set of service, performance necessities, machine type communications, and numerous logical (virtual) networks. Each virtual network is designed for a particular vertical, which must be built on the top of the common physical 5G infrastructure. Each logical network is denoted as a 5G network slice. Each network slice comprises of a combination of common and dedicated resource instances, for example, radio spectrum or network equipment, and virtual network function (VNF). Consequently, each slice will have its own virtual mobile CN as well as its own radio access network (RAN) functionalities. All network slices would be different and independently configured. Thus, under the second model, the 5G-network slice that is assigned to the smart grid must:

1. Have its own set of resources and functionalities

2. Totally isolated from all other network slices

3. Fully managed and controlled by the utility or a third-party provider independent of all other network slices [4].

3. The near-term model: a hybrid fiber/5G-based converged power grid-communication networking infrastructure

The near-term model utilizes public commercial 5G cellular network and technologies along with public commercial PON-based fiber-to-the-Node/Home (FTTN/FTTH) residential access network.

The evolving 5G cell-based network technologies are the core of the anticipated architecture. This architecture utilizes LTE-A equipped M2M communications and HetNet infrastructure as the solitary cellular technology that effortlessly extending from HAN to NAN to MAN to global. Moreover, the projected architecture uses an affordable fiber-dependent SC backhaul infrastructure, which exploits the present fibered services linked with a PON-dependent FTTH/FTTN domestic access network. Consequently, the projected hybrid-networking infrastructure implies the fiber network reliability and the community cell-based network flexibility.

The projected community cell-based network allows utilities to wirelessly connect to the universal distribution grid assets. Assets comprising smart meters, smart home appliances, PEV charging infrastructure, microgrids, substations, feeders (connected from substations to the client location), circuit breakers, transmission towers, and mobile workforce. Related to the grid assets, there is at least one cost-effective static embedded chip set (LTE-A equipped M2M unit), or mobile in the case of PEVs, that transmits and collects data to/from the macro-BSs, micro-BSs, or another M2M unit. The direct M2M communications is merely necessary in the

HANs and microgrid/PEVs. On the other hand, the communications among the other M2M components are dedicated for data forwarding only.

Per 3GPP standard, LTE/LTE-A comprises of an improved BS called evolved NodeB (eNB) and a mobile CN called evolved packet core (EPC) on the core side. Basically, EPC logical components comprises of mobility management entity (MME) in the control plane. On the other hand, the bearer plane is composed of the serving gateway (S-GW) and the packet data network gateway (P-GW). Practically, as one physical network defined as access gateway (A-GW), both gateways can be implemented based on vendor support and deployment scenarios [11]. The collected control and monitoring traffic is processed by the manager and then transmits the commands back to the $DERMS_i$ manager. The manager may forward these data before and/or after processing it to the control center and utility data.

3.1 Proposed hybrid fiber-based & LTE-A enabled HetNet & M2M communications architecture

Figure 2 illustrates the proposed architecture covering a utility's service territory in the coverage zone of a single macro-BS and numerous micro-BSs. Macro-BS coverage area may be extended to include at least one substation that are adjacent electrically, connected to the same node on the transmission system (necessary to regulate the power network), smart grid assets, as well as electric storage. Utility control, data center(s), headquarters, enterprise office locations, bulk power locations (owned by the utility), optical line terminal (OLT), EPC, and M2M application server, are all connected through dedicated fiber links.

A Public microgrid $DERMS_i$ manager is assembled with each optical network unit (ONU), which receives control data traffic from a group of public microgrid's central controllers (MGCC). In other words, LTE-A equipped M2M modules

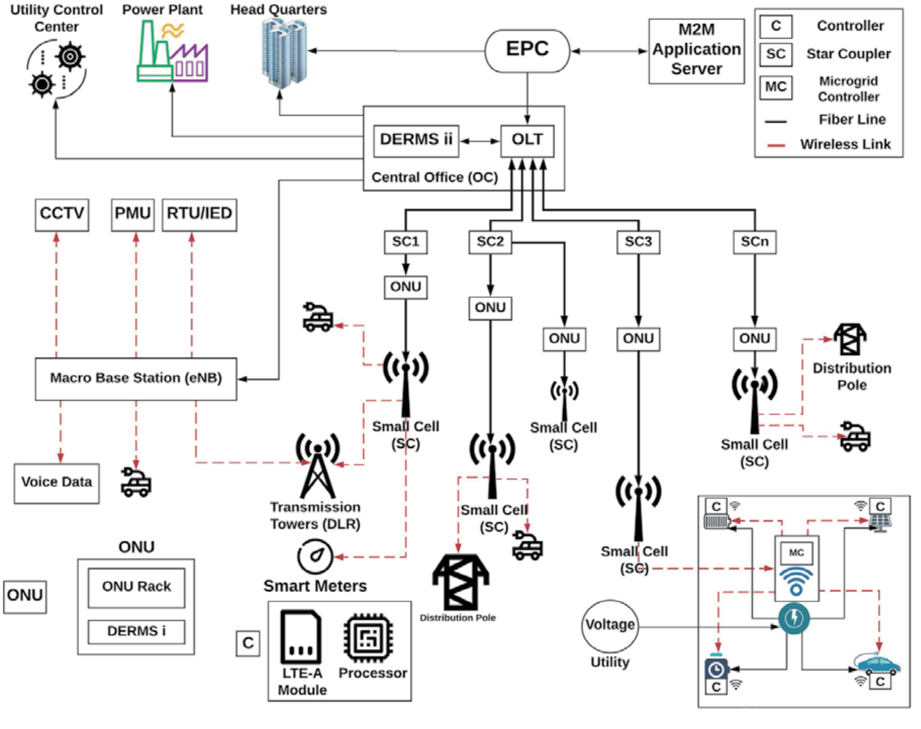

Figure 2.
The schematic diagram of the proposed architecture.

through the SC serving these constellations and/or through direct M2M communications if they are positioned inside the acceptable contiguity distance identified by LTE-A standards. The received monitoring and control data is processed by $DERMS_i$ manager and returns the commands to the group of MGCC. While the second higher level $DERMS_{ii}$ central manager is positioned with the (OLT) at the central office (CO), which collects the grid's control traffic from the first level $DERMS_i$ managers through the fiber dependent PON infrastructure for higher reliability. The received control data are processed by the $DERMS_{ii}$ central manager and then broadcasts the commands to the $DERMS_i$ manager. $DERMS_{ii}$ may also forward these data and/or after processing it to the utility data and the control center(s). The direct wired fiber-dependent communications between the $DERMS_{ii}$ central manager and the first level $DERMS_i$ manager is significantly highly reliable, which guarantee swift delivery of the critical mission control data. It is noted that MGCCs and $DERMS_{ii}$ can decide to bypass the first level $DERMS_i$ managers and communicate directly through the PON and HetNet. Because the $DERMS_{ii}$ central manager has a universal knowledge of the entire local distribution grid's portion assets inside this specified domestic zone, it can manage, and control the whole distribution grid applications in this local portion. For example, efficient energy management and optimization models development, advanced metering, demand response (DR), smart electric Vehicle (EV) charging, and distributed generation. It is noted that the anticipated architecture supports the flexibility of supporting such management and control operations either in an entirely integrated method, an entirely distributed method, or a hybrid method that uses both approaches.

Additionally, the CO can accommodate numerous OLTs, and each OLT can operate more than one PON and, hence, at least one $DERMS_{ii}$ central manager may be accommodated at the CO. Domestic NAN/FAN architecture may be extended to a worldwide scale widening from NAN to MAN to WAN to a universal would span several interconnected COs. At each CO, all instantaneous monitoring and control traffic will be efficiently processed and forwarded by a group of $DERMS_{ii}$ central manager and then collected from all communication endpoints, which are served by several PONs and HetNets. The instantaneous knowledge of the whole universal grid status and assets will be identified significantly by the utility data and control centers. This provides the power grid with the potential of self-healing capability, efficient resilience, reliability, and survivability mechanisms.

3.2 PON-based SC backhaul infrastructure

A new challenge for the backhaul is introduced by an extensive implementation of SC, which must support connections at enough capacity and assured quality of service (QoS). The quantity of SC sites in a specific macrocell zone can grow up to numerous hundreds (e.g., large city center). All SC necessitate fast backhaul connection. Consequently, the connection implementation between the mobile CN and the SC BSs becomes challenging. The key challenge is how to provide cost-effective, scalable and flexible mobile backhaul solution to connect a massive number of SCs to the mobile CN. To tackle the backhauling challenge, I propose and utilize an economical fiber-based SC backhaul infrastructure, which exploits the current fiber facilities connected to a PON-based FTTN/FTTH domestic access network [12–14]. Due to the distribution of the current fiber assets, the projected PON–based backhaul architecture, in which the SCs are housed with the present FTTN remote units (ONUs) is much more cost-effective than traditional cost prohibitive P2P fiber backhaul schemes.

The HetNet backhaul RAN architecture could be developed from the PON architecture essentially by superimposing the SCs with the ONUs, while exploiting the available present fiber backhaul over dark fibers and operated ONUs linked with the PON-dependent FTTx domestic access network. The SCs is implemented using a low-height (2–4 m) antenna affixed on or adjacent to the ONU (e.g., near to a light post). The CO accommodates the OLT, which links with metro/EPC through the metro terminal equipment located at the CO. The PON and LTE-A based SC systems are autonomously operated where the HetNet RAN system is expected to have its own management and control functions independently from the PON. Each SC is expected to be positioned with an ONU or treated as a generic user attached to it. The ONU and SC can be communicated as long as they support a common standard interface. Consequently, the OLT, EPC, ONUs, and SCs, are completely anticipated to provide a common standard interface (e.g., 802.3ah Ethernet interface). [13, 14]. Each ONU is expected to have two diverse Ethernet port ranges; the first port range will support wired users, while the second one will support wireless M2M grid traffic. The port ranges will be used by the ONUs to identify and differentiate between wireless M2M grid traffic versus typical PON fixed users.

A tight coordination and cooperation between the utilities and telecom carriers or preferably an integrated power-grid-communication network is required in order to reap the full benefits of such hybrid architecture. Because power and communications companies are generally separate commercial enterprises in North America and Europe, implementing this vision will require considerable government and large-vendor effort to encourage various enterprises to cooperate. In any case, utilizing public, commercial mobile and FTTN/FTTH residential access networks for smart grid requires tight coordination and cooperation between both parties. Given the utmost importance of the power grid for the welfare and national security of the nation, integrating these two sectors should be given highest priority.

3.3 Addressing the interoperability challenge

The system is called interoperable when the information and communications systems are capable of sharing and interchanging data as well as to be integrated with the other systems and applications. Information interoperability has three types: (1) Morphological interoperability: this type of interoperability guarantees that the same data has an identical structure and similar format. In addition, it is referred to as a structural interoperability. (2) Semantic Interoperability: It allows different types of information systems and applications to exchange information based on predetermined conditions. It ensures the message is received at the user end. (3) Syntactic Interoperability: This type of interoperability did as same as the Semantic interoperability, however, it is not guaranteeing that the receiver received the message [15].

LTE-A equipped M2M module is implemented in every grid asset (Components, controllers, appliances, equipment, and etc.), as LTE-A is an all IP-based network. Therefore, telecommunications among the whole grid assets depend on an IP-dependent communications protocol. The E2E interoperability among billions of distributed multiple vendor's communication devices is facilitated through the whole distribution grid. This is substantial as the complex several vendors' interoperability standard challenge is persuasively tackled and reduced to a central commonly customary specific protocol – the Internet Protocol (IP), the core protocol of the public Internet. Because IP is the global dominant network protocol, most of the commercially available software and hardware systems are capable of handling IP traffic, hence making IP the logical choice for most networking applications including the power grid of the future [3].

4. The long-term model

The second long-term model as depicted in **Figure 3** is depending on the developing concept of 5G-network slicing, which is permitted by contemporary swift networking progresses and improvements in mobile edge computing and storage capabilities, software-defined networking (SDN), and network functions virtualization (NFV). An extensive distinct IoT vertical industries (applications) are anticipated to be supported by 5G. Each of which have its own distinctive collection of performance and service necessities, MTC, and numerous virtual networks. Each virtual network is customized for a given applications and must be created on the top of the common physical 5G infrastructure. Each logical network is denoted as a 5G network slice. Each 5G network slice comprises of a mix of dedicated resource requests. For example, radio frequency spectrum, network equipment, and VNF. Thus, each slice will have its own virtual mobile CN as well as its own RAN functionalities. All network slices would be different and independently configured. Thus, under the second model, the 5G-network slice that is assigned to the smart grid must:

1. have its own set of resources and functionalities
2. totally isolated from all other network slices
3. Fully managed and controlled by the utility or a third-party provider independent of all other network slices.

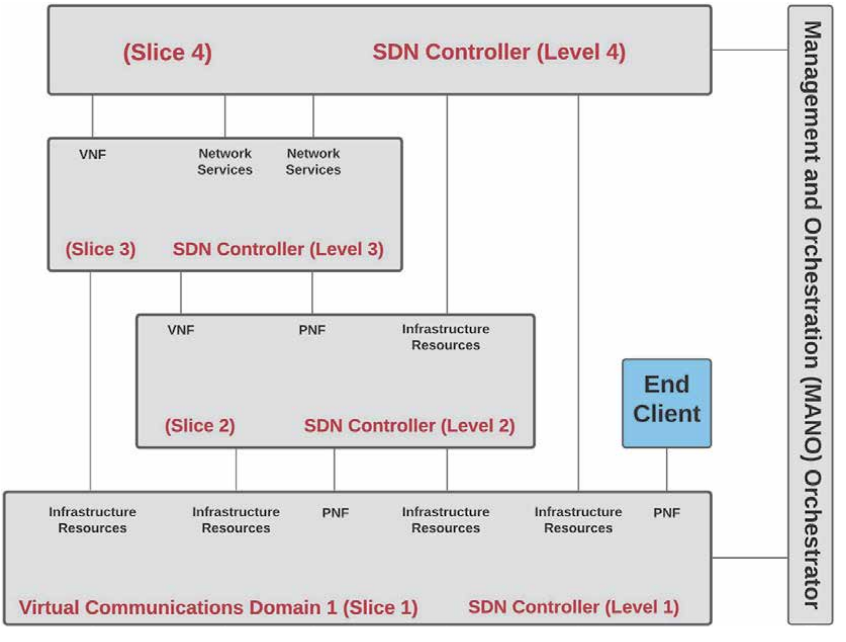

Figure 3.
Multiple hierarchical arranged SDN controllers.

5. Conclusion

This work has assessed and investigated the prospective of the emerging 5G cellular technologies capabilities to be incorporated with the power grid to allow the accomplishment of an actually smart grid. Based on time-to-market strategy, we have proposed two different 5G-based commercial and architectural models that enable a really congregated power grid-ICT infrastructure, denoted as a near-term model and a long-term model. Exactly, this work has formulated a proficient universal hybrid fiber/5G- based converged grid-communication networking infrastructure to facilitate effective and extensive DERs implementation. The salient feature of the proposed architecture is that it facilitates and ensures seamless end-to-end interoperability among the millions of multiple vendors' communication devices distributed throughout the entire distribution grid. Furthermore, it enables the development of the assessment tools and practices, which can be used as initial guidelines by utilities and/or grid operators, to specify ICT requirements needed to support full advanced distribution automation, including wide-scale integration of DERs and enhanced system resilience.

Conflict of interest

"The authors declare no conflict of interest."

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Electrical grids worldwide are experiencing major changes in terms of energy generation, transmission, delivery, and distribution in order to enhance the entire system's control, reliability, efficiency, and safety. Advanced energy systems and technologies such as renewable sources of energy, energy storage systems, and electric vehicles (EVs) as well as equipment such as sensors, smart meters, and communication devices along with innovations in computing technologies, machine learning, and data analytics are used to modernize the electric grid and the way it is planned, operated, and managed. This book provides an overview of several aspects of grid modernization including micro-grids, smart grids, energy storage, and communication systems.

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