Department of Mechanical and Aerospace Engineering

Proposed Design of Distribution Network Considering Sensor Measurement Strategy on Active Network Management: a Case Study

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Abstract

One of the most complex systems ever created is the electrical power system. Smart grid power systems give new capabilities in networking, distributed systems, enhanced monitoring, automation, distributed data, reliability, and security. The transformation from traditional to intelligent is more noticeable at the distribution grid level. Through the integration of low carbon technologies (LCTs), smart distribution networks pave the way to decarbonization. Wind, PV, and energy storage enhance the grid's flexibility, but their inconsistent behaviour causes network restrictions. A new Active Network Management (ANM) paradigm can address network limit disturbances like thermal rating, voltage, and fault levels. Instrumentation plays a crucial part in this concept. Energy Technology Centre (ETC) as a case study demonstrates the utilisation of virtual power plants (VPP). This thesis aims to investigate a detailed design of instrumentation part of the active network management concept in a VPP and its future possibility in the ETC. The detailed design of the instrumentation part in ANM helps to measure the parameter more precise. The first step consists of a literature review explaining the VPP, ANM concept, G100 export limit, and sensor measurement strategy. The ANM scheme and its instrumentation are explained more thoroughly in this section. The thesis then proposes a design for the sensor and measurement strategy for local active network management for the distribution network of the power system. This schematic design helps to install appropriate sensors at a suitable location in an ANM concept at ETC. The benefits and flexibility of smart grids are explained in detail after illustrating the schematic modelling. The proposed work focuses primarily on the effectiveness of PMU, locally distributed SCADA, and IoT-based sensors in the distribution system. The proposed schematic model also shows that renew adding storage systems can further increase renewable energy sorting excess energy can increase prosumers' participation in flex tariffs, thus reducing their cost and putting flexibility in their favour. Using appropriate sensor and measurement strategies to address network constraints, ANM is a compelling concept for distribution networks.

Keywords: *Distributed Energy Resources (DER), Network constraints, Active Network Management, sensors, PMU, SCADA*

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List of Abbreviations

ANM	Active Network Management
CT	Current Transformer
DER	Distributed Energy Resources
DG	Distributed Generation
DNO	Distributed Network Operator
DSO	Distribution System Operator
ESS	Energy storage System
ETC	Energy Technology Centre
EV	Electric Vehicle
HV	High Voltage
IPCC	Intergovernmental Panel on Climate Change
LCT	Low Carbon Technologies
LV	Low Voltage
MV	Medium Voltage
NOAA	National Oceanic Atmospheric Administration
PMU	Phasor Measurement Unit
PT	Potential Transformer
PV	Photo Voltaic
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SCADA	Supervisory Control Data Acquisition Control
SETP	Scottish Enterprise Technology Park
SIES	Smart Integrated Energy Systems
SPEN	Scottish Power energy networks
TNO	Transmission Network Operator
TSO	Transmission System Operator
USEF	Universal Smart Energy Framework
VPP	Virtual Power Plant

1.0 Introduction

This chapter discusses the background and motivation, objectives, and approach to the presented project topic. The thesis focuses on the detailed design of instrumentation measurements considering local Active Network Management (ANM) to achieve network capacity reinforcement deferral and constraint management at the distribution grid level. In the background context, briefly explains climate change and environmental issues, its impact on the energy sector, and the necessity of moving to the renewable energy sector from the non-renewable energy sector. It identifies the possibility of achieving carbon neutrality in the power sector under the UK government's recent policy to reach the 2050 target. This thesis aims to develop a strategy for addressing network disturbances such as temperature rating, voltage, and fault levels caused by the penetration of flexible assets in the distribution network. The original contribution of this research is to propose e detailed design of sensor and measurement strategy in an ANM scheme which helps the Energy Technology Centre (ETC) to attain sustainability and integrate more low carbon Technologies (LCTs) with maximum power generation. Further focuses on the fusion of measurement device Phasor Measurement Unit (PMU) with SCADA and its possibilities for the distribution system. This thesis is organized with an introduction section, a literature review, a technical assessment and a local ANM design proposal chapter including the case study, then investigating the potential impact of instrumentation strategy. The next section discusses the outcomes, limitations, and future possibilities. Finally, the report summarizes a brief conclusion.

1.1 Thesis Background and Motivation

The second-largest share of greenhouse gas emissions [3] now comes from the energy sector, which also holds the key to preventing the worst impacts of climate change the greatest challenge facing humanity. Scientists have recorded the worldwide surface temperature using thermometers since 1880. A study by the IPCC shows that floods and fires will become more frequent and fiercer if we fail to limit global warming to 1.5°C above pre-industrial levels [4]. To reduce global CO_2 emissions, we should achieve net zero emissions by 2050, up to 1.5°C in temperature. At COP26, more than 200 countries participated and supported the Glasgow Climate Pact, which accelerated the pace of climate action. The global accord could speed up climate change action if all nations comply with their obligations [5]. Governments have the power to enact laws and policies that will lower greenhouse gas emissions. As part of a 'Ten Point Plan of Green Strategy', the UK government invested £12 billion and shared some risks associated with pioneering new industries, such as the ban on new petrol and diesel cars by 2030. Towards a productive net-zero economy by 2035, the UK will be powered by clean electricity [1]. A recent IEA report says that with a 5 % rise in electricity demand in 2021 renewables are expanding quickly [6].

Low voltage distribution networks are often passive, with electricity generated flowing from the transmission system to the prosumers. The smart grid is an emerging digitalization concept and is more prominent in the distribution grid level of the power systems. It gives absolute reliability of supply and power generation with distributed energy sources (DER). It assures less environmental impact of electricity production which enhances the efficiency of the power delivery system. Due to the increase in demand for higher quality power, flexible assets, and renewable energy sources (RES) are integrated at the local level of the distribution network. This includes wind, solar-thermal, photo voltaic solar panels (PV), energy storage like hydrogen as well as CO_2 capture storage. According to the UK government's Energy Trends report, renewable energy production increased by 13% from 119.5 TWh in 2019 to 134.6 TWh in 2020.

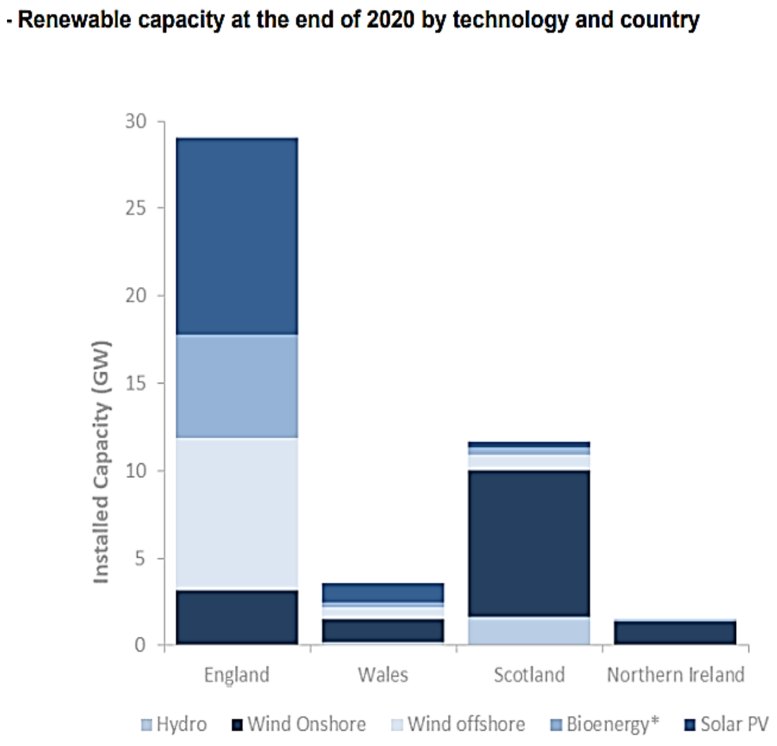

Figure 1:Renewable capacity of the United Kingdom [1]

The graph shows that in the UK, the onshore wind increased by 0.8%, with Scotland accounting for 47% of the extra capacity. East of England experienced the highest growth with 2.1%, with solar PV capacity increasing by 1.8%. The research shows that the quantity of electricity now generated from renewable sources is inadequate to achieve net-zero carbon neutrality by 2050. Increasing the proportion of RES in the distribution grid is one strategy for reducing greenhouse gas emissions in the utility sector and making renewable energy more available to prosumers [17][52]. The intermittent nature of renewable energy makes it difficult to assess how much electricity is produced at any given time and how to adjust to changing generational patterns. It causes instability, power quality problems, voltage unbalance, and fault constraints [4]. Even though its penetration opens the path for a low-carbon future, the consequences of their stochastic nature on the existing grid system must not be underestimated. This realization leads to finding out the solution to increase the integration of flexible assets on the distribution side by mitigating network constraints. Customers can choose their electricity by implementing distributed energy resources. This helps decarbonisation avoid transmission and distribution reinforcement. SIES 2022 (Smart Integrated Energy Systems) is a project focusing on low-carbon energy systems that can host and use a high proportion of renewable power sources. This project will show how the Digital Energy Utility Market Service (DEUMS) works by expanding the Virtual Power Plant's (VPP) functionality to include interaction with energy markets, integration of local and regional energy systems, and interaction with energy markets (as a non-traditional participant, or NTP) into the market more visible and easier to control. Grid connectivity and flexibility are now being looked at, including the possibility of charging stations for electric vehicles and G100 export limitation scheme devices.

1.1.1 Aims and Approach

This thesis aims to conduct research into the thorough design of a sensor measurement, monitoring, and control approach in distribution networks that are integrated with flexible assets. The research will include a case study of the ETC.

- A focused literature evaluation, to the extent that research has been done on the subject.
    - The repercussions and potential for future flexible assets, Distributed Energy Resources The methodology that was used was:
    - Active Network Management scheme for the goal of showcasing VPP at ETC
    - G100 export limitation scheme with a study on Flexible markets such as Piclo.

  - o Instrumentation in ANM, with a particular emphasis on the Phasor Measurement Unit, the SCADA system, and the Smart Transformer.

- Developing a technical evaluation approach for building the detailed architecture of the distribution network of the ETC case study, as well as enhancements on the instrumentation section of the local ANM concept.

- Presenting the findings and debating them by contrasting the demand profile with the renewable profile while making improvements at flexible assets of the ETC energy pool.

2.0 Literature Review

This chapter gives an overview of the thesis's important components and addresses the numerous technical assessments that are pertinent to the thesis. Initially explains the Distributed Energy Resources (DER). Secondly describes the potential energy flexible assets and network restrictions that may arise because of increased DER at the distribution networks. Next, the study includes a detailed review of current concepts and devices, their future possibilities, and existing projects such as VPP, Active Network Management (ANM), and G100. Finally, the sensor and measurement strategy for an ANM is discussed, particularly for the measurement of reactive power, apparent power, active power, temperature, voltage, and current are considered. This session includes a detailed study on a smart transformer, Phasor Measurement Units (PMU) and Supervisory Control and Data Acquisition system (SCADA). Finally explain about the ETC, the case study which has been chosen.

2.1 Distributed Energy Resources (DER)

The electrical power system is divided into three phases: generation, transmission, and distribution [22]. In this paper, the work is concentrated on the distribution networks side. A comparison between these stages is needed before examining the distribution side as it is the voltage that differs between them. The below-mentioned figure describes the simple electrical power transmission system with a standard voltage in the UK. The high voltage transmission is 400 kV and 275 kV through 3 or 6 cables [29]. In the next stage, the medium voltage distribution is 132 kV through 3 to 6 cables distributed to the high industries. Finally, the low voltage distribution network is 33-11 kV used by small industries and houses. There are additional 66kV and 6.6kV options for distribution, which might be useful depending on demand and isolation. Consumers are now receiving 230 (single-phase) / 400V (three-phase) voltage.

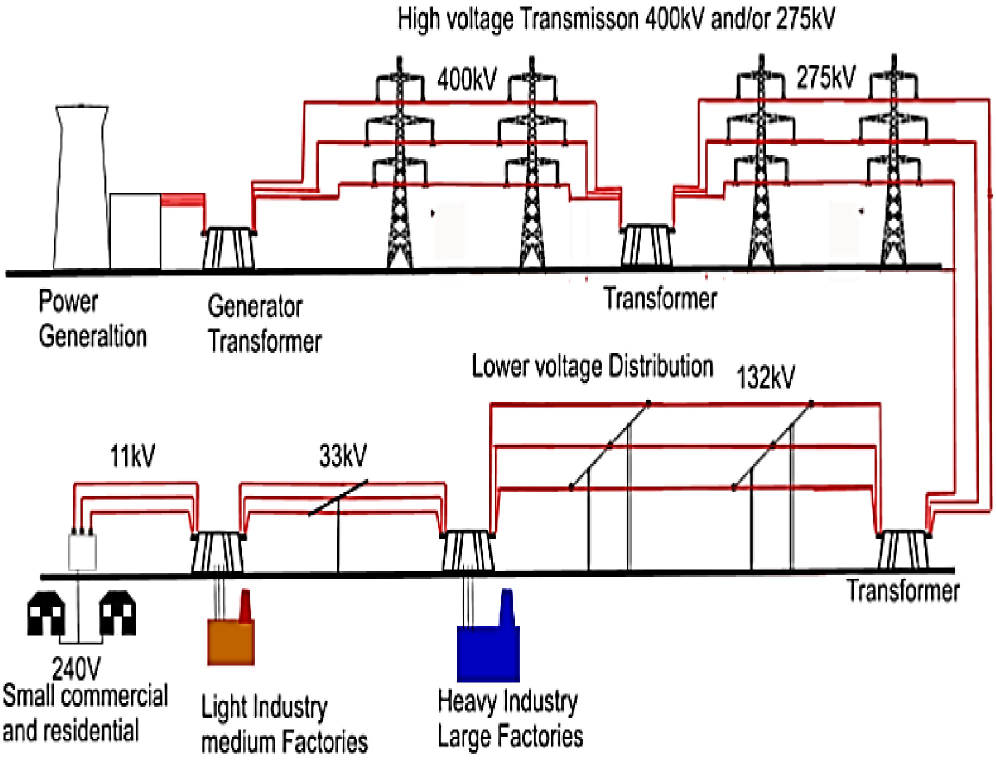

Figure 2:UK electrical power transmission system [106][82]

Distributed energy resources (DERs) also known as demand resource is a small-scale power supplies on the distribution network grid level. Integration of RES at the distribution grid level is an innovative and effective technique to generate more energy [22][25]. They are power production resources often positioned near load centres and may be employed individually or collectively to benefit the system**.** It may be categorised as virtual or physical assets. Virtual assets are sometimes referred to as VPP, with integrated generators, batteries, and solar panels. The capacity of physical DERs is typically less than 10 MW and includes solar arrays, small wind farms, storage batteries, electric vehicles, generators, and others [25].

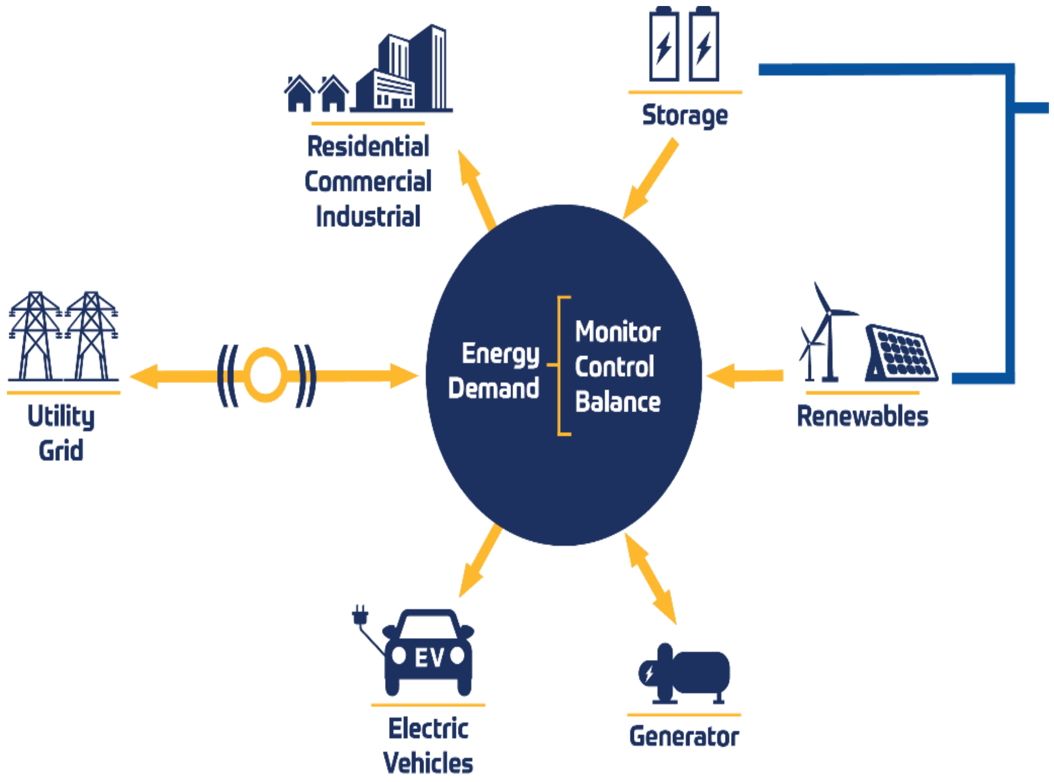

Figure 3:Diagram of Distributed Energy Resources [83]

The self-owned and managed electric utility that led to a new route in the energy market is the primary advantage of DERs. Figure 3 shows the diagram of DER. The usage of battery energy storage helps in the bi-directional flow of energy according to the demand and the supply. It may be supplied independently, which increases its dependability. DER is composed of a communication system, an automated control system, synchronised and connected instruments ensuring in-phase power generation and electricity flow, and meters that measure DER supply and demand. Software integration is the most essential role in the functioning of virtual DER. The DER mitigates the duck curve by contributing daytime energy to the grid, and storage may be used to postpone system upgrades [25]. It maintains energy prices and regulates energy demand by optimising use [25][83]. Additionally, the incorporation of more DER reduces the carbon impact and leads to the production of green, clean energy. Recently the penetration of DER is high and helps in transferring the conventional network into a bi-direction flow of power.

2.2 Flexible Energy Assets and the Network Constraints

Not always achievable is the reinforcement. For instance, in isolation or constrained places, it is difficult to create and distribute additional energy [27]. Customers in this situation required a non-firm connection that is more flexible, where the generator may restrict export periods or transmit more capacity to the energy flexible market. The most important flexible assets are battery storage energy systems and electric vehicle charging infrastructure. However, the integration of these flexible assets causes network constraints and affects the function to give maximum output from the non-firm connections. The high concentration of dispatchable or non-dispatchable energy sources will convert the distribution network from a unidirectional flow system to a bidirectional flow system with a complex flow [28]. This causes significant disturbances in the networks. In contrast to the transmission system, the distribution network has shorter lines, higher power angles, and higher frequency levels [28]. Thus, it demands measuring exceedingly small values for phasor measurements at the distribution level. This grid level will be more susceptible to mistakes and provide more difficulty.

The network limitations are separated into three categories: voltage restrictions, thermal constraints, and fault constraints. Fault constraints are also known as short circuit constraints and monitor peak current when a short circuit occurs in a network. It may be analysed in terms of peak break current by disconnecting the switching gear and peak make current from the circuit breaker. Because wind and solar power are not always available, the voltage and how it affects frequency and voltage are affected. PV causes rapid swings at low distribution levels and affects the amplitude of the steady-state voltage. Thermal Constraints occur in RES because of a rapid shift in network congestion. When load generation exceeded a certain threshold, the power flow reversed from the consumer end. When this reverse power flow exceeded the limit power, the power line began to heat up, resulting in thermal limitations. Thermal Constraints may be analysed with the use of current flow and power flow analysis. Using quasi-continuous static flow and voltage analysis, voltage restrictions may be analysed. Peak current, short circuit analysis, duration, frequency, and transient analysis may be used to analyse the fault restrictions.

2.3 VPP -Virtual Power Plant

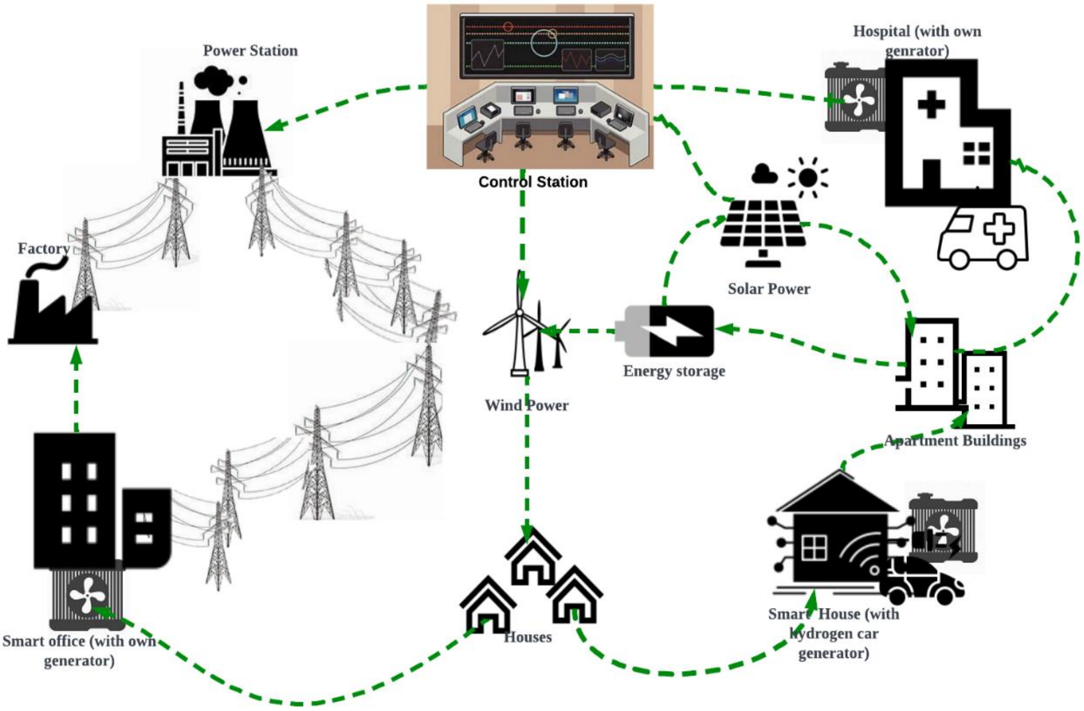

Figure 4:Virtual Power Plant [84]

A VPP is an outcome of digitization that capitalises on the possibility to enhance clean electricity, demand-side flexibility, and industry integration [15]. The VPP consolidate all independent energy sources through intelligent planning, scheduling, and bidding for services based on dispersed generation [37]. The VPP is being introduced into the electricity industry to increase DER and demand-side flexibility. After the COVID pandemic, the VPP helps to digitalize the world. Consequently, the reinforcement costs of the network can be deferred while the reserve power requirements are lowered and helping to stabilize the supply-demand.

The VPP is a new concept that manages DERs such as battery storage, building load, RES, and gas generators. Asset owners can invest in renewables via the penetration of renewables on the distribution side, which leads to the prosumer idea. This policy is frequently enacted to improve the stability of traditional utilities by introducing additional plants with higher efficiency [15]. VPP's key important aspects are frequency management, reactive power control, distribution forecasting, and communication. In addition to providing load supply-demand stability, flexible load variance, unit function, power output failures, system reserve failure, and lower carbon emissions, it also reduces some of the constraints. It also serves as a virtual layer [15]. Considering the penetration of energy sources, voltage spikes unbalance, and high-frequency surges are the most common power constraints. The VPP system can be used for solving these problems. The algorithm focuses mostly on solar or wind energy production, building load control, and electricity price forecasts [15]. VPP's control system focuses primarily on electric grid stability, energy flow monitoring, troubleshooting, synchronisation, optimum load sharing and optimization.

The VPP can be classified as technical VPP(TVPP) and commercial VPP (CPP)according to stabilisation and cost. The TVPP is more focused on financial issues, and fault detection whereas CPP optimize and schedules the production of DER units. Table 1 shows some of the main functions of both CPP and TVPP.

Table 1:Commercial and Technical VPP

Commercial VPP	**Technical VPP**
Energy forecasting	Demand Response
Optimization and schedule production of DER	Cyber security
Profit maximizes	System manage network
Big data	DER transmission line, technical clarity to the operator

VPP classed by DER includes non-renewable sources such as nuclear reactors, biomass, biogas, gas turbines, and fuel cells and renewable sources include solar thermal, wind power, hydropower, and tidal power. In terms of energy Storage Systems (ESS) classification, the VPP capture energy in the off-peak situation and distribute it optimally. Additionally, this maintains the frequency and voltage level of DER and supports improved battery energy storage [15]. Load control in VPP is based on changing certain energy consumption from the electrical period. Communication technology has been used in DER, ESS, and load. Communication standards are based on the quality of services, transmitting duration, frequency, and loss rate. For instance, IEC 61850, IEC 60870-5-104 SCADA device protocol TCP/IP, polling, and event acquisition [37]. However, the VPP's energy storage capabilities are limited, and its multi-inverter system dynamics may be unstable. The VPP's energy management system (EMS) handles difficulties by controlling energy transactions through bi-directional communication. It also manages dispatchable and non-dispatchable units, storage units, and loads in a power system to reduce costs and maximise profits. It also makes use of the DER big-scale industrial economic dispatchable algorithm. In the future, VPP, peer-to-peer (P2P) commerce, and certain advanced communication protocols will be required [15]. System layering technologies, instrument modelling, and abstract service communication will all be included in the advanced communication protocol (ASCI) [37].

2.4 Active Network Management

In the United Kingdom, electricity prices are rising, and energy demand is higher than last year. Energy. Trends and Price Statistical that was released in April 2022 by the government says that 42.4% of electricity generation is from renewables [29]. The paradigm of DER like solar power, wind power and energy storage is gaining popularity nowadays because of intrinsic flexibility [30]. Even though integrating renewable DER helps decarbonization, its intermittent behaviour causes network constraints as discussed above. For instance, if a system consists of a PV array with 12 MW, a wind farm with 15 MW, and a battery with 10 MW, theoretically combined maximum output will be 37MW. Pragmatically it is not possible as solar PV output will be fluctuating during the windy season and the battery will not always want to export its full output to the grid when it is sunny. This uncertainty is known as intermittent effect or diversity due to the output profile from different technologies. Reinforcement is a method to avoid this, but it is expensive and time-consuming. Initially, Load Management Scheme (LMS) were used in the distribution networks to tackle the constraints [107]. The most significant problem associated with this approach is a procedure that regularly disconnects DER to address and mitigate the constraints that also halt new DG. Here the alternative option emerged as the ANM concept. It is the new evolution in the SMART grid system.

Location and time are the most principal factor in the ANM concept. It does not yet have a definitive definition [31]. Effective use of this concept can reduce the need for expensive energy network reinforcement to get maximum power from these flexible assets. A network reinforcement is a situation in to decide the generator in triggering the grid upgrade is expensive and time consumption. The ANM concept is dynamic, repetitive, and time-limited asset management instead of passive management. The analyses are based on real-time monitoring measurements, and control existing flexible assets such as load energy supply, EV, and battery in a more sophisticated method. Its primary objectives are infrastructure utilisation, decreasing circuit overload, improving voltage profile, and maximising distribution system output. It manages the constraints better than any other method and the real-time measurements help to keep the network protected under predefined limits and network design rules. It also mitigates cable overheating, and voltage spikes [6]. This helps to collect incessant data required to regulate demand, maximise the generation and reduce cost by approximately 90 %. The implementation of ANM is around £500k and can connect more swiftly [51]. Customers would save $271 million by 2030 due to the deployment of the ANM, according to reports [32]. It also paves the door for the reduction of 19592-tonne CO_2 carbon emissions. The ANM also eliminates the DG from the system or ramps down the generators rather than disconnecting all generators to reduce network constraints and facilitate the integration of the new DER [107]. The usage of an ANM system can also be beneficial to underground cables and transformers [6]. The principle used in ANM is The Last in First Out (LIFO) method uses the ANM concept, which implies that one curtails was recently introduced. The network parameters for the ANM are reactive power, active power, apparent power, voltage and current [32]. Measurements are also different related to which network constraints are meant to mitigate. For instance, power system operating parameters such as generator output, nodal voltage, reactive power flow, dynamic ratings, the frequency at load, EV, battery, and fault location using appropriate sensors.

The ANM architecture is classified into centralised, decentralised, and hybrid respectively [27]. Considering the sensor and measurement strategy, SCADA is used for efficiency in response time. Communication platform IEC61850 uses in ANM and Remote Terminal Unit (RTU) for local control. However centralised architecture is more preferred in these three classifications. In the hybrid model. Single point failure removal is in a centralised structure whereas communication reduction is considered in the decentralised part. The ANM control system may either be physically located on-site or may be accessible via a communication system that connects the operator to the control device. The algorithms are also based on a control strategy. Studies show that methods of fuzzy logic, machine learning, adaptive particle swarm algorithm, state estimation, and generic algorithms are being used in the ANM concept. Active or reactive power flow management, Voltage Control, Load generation dispatch, and increased visibility of network cable or state estimation are some of the control techniques performed in the ANM. The active or reactive power flow management has a control strategy to mitigate the issues to the generator, permitting power flow closer to the thermal rating of lines. In voltage control, it mitigates issues such as voltage rise and step by regulating the amount of reactive power or real power in more than one generator, storage operating point in the grid devices such as tap changing transformer. Voltage regulation is significant in introducing low carbon technology and new flexible assets. Dispatch of load generation network helps to balance the network. It charges during low load and discharges during high load. It also considers enhancing the visibility of network cable as an alternative for more transducer usage.

2.4.1 Centralised/coordinated control strategy (DMS)

In this control strategy, the substation will be the central part from where it controls the rest part of the system. The communication system and data transfer are essential in this control strategy. System for the Management and Control of Centralized Distribution (DMS) Control, Coordination of Distribution System Components, and Coordinated Voltage Control using intelligent techniques are the three types of methods practised as part of Control Strategy [102]. Both fundamental and sophisticated distributed management systems use the centralised DMS. The disconnecting of DG in the event of high network restrictions is a basic DMS function but advanced DMS considers restricting components that can adjust voltage through data flow between network nodes. In addition to this, it considers two new centralised control functions, namely the volt/Var control and the best feeder realignment [102]. Even though ANM save money it would result in a loss of some energy sales. In the above-illustrated diagram restriction and diversity will be less due to the same solar used for generation instead of battery and wind.

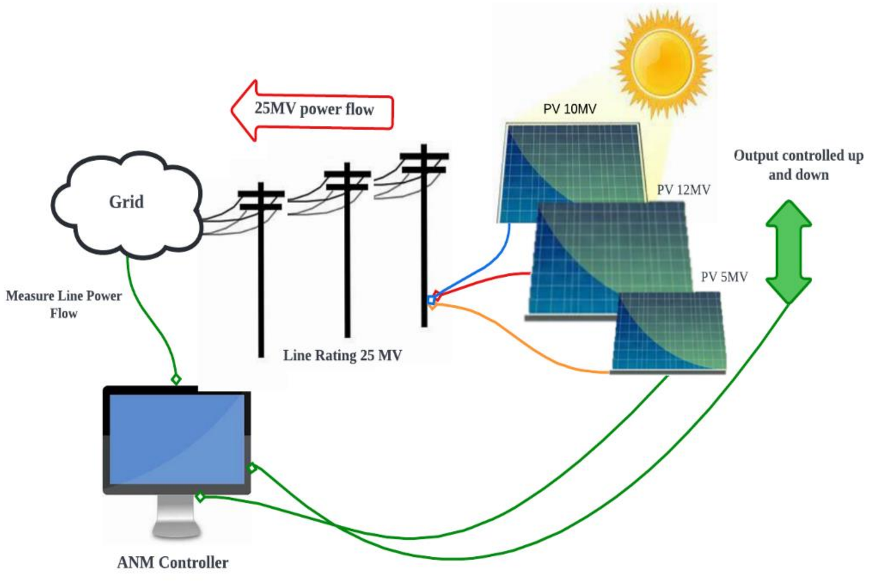

Figure 5:Concept of ANM with PV [6]

In the above figure, the concept of ANM is explained by illustrating the solar farm [6]. The overhead power line rating 25 MW and three solar connected with outputs of 10 MW, 12 MW, and 5MW.It has shown if three PVs give maximum output, the total output from the solar panel exceeds the line rating and causes constraints. Three ways to avoid this problem are replacing with a bigger one, adding another line and finally ANM which is cost-effective and more efficient to give maximum power output from assets. It can be done by connecting an instrument to measure power flow from the line and giving that signal to an ANM controller that is linked with one of the solar panels, here 5MW panel and it is controlled up and down to limit its output without exceeding 25 MW.

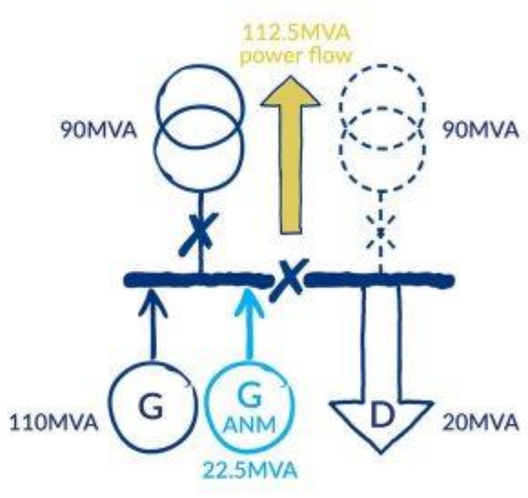

Figure 6:Concept of ANM with Transformer [37]

Western Distribution Network has introduced interesting categories in ANM such as Z ANM and B ANM categories [6]. They considered the worst-case scenario as the failure of ANM, generators showing maximum output, and the circuits or transformers switched out. The above-mentioned figure shows the Z ANM category concept to connect more generations. The remaining transformer is 90MVA with one out. The maximum allowable power flow through that transformer is 112.5MVA. As illustrated above, the Z category ANM system may add 22.5MVA of generation by subtracting 112.5 from 90 MVA. As a result, the Z ANM can generate only an additional 20.5% of electricity.

However, the ANM face challenges such as a monetary loss if curtailment occurs more than expected and secondly the total load connected to the ANM. If the ANM controller failed, more than line rating power overflow and it damages the entire system [27]. Co-simulation and the real-time dynamic simulation in a power system are still hard even in this concept. Some of the existing projects are given below.

Table 2: ANM projects (case studies) [33]

Project Name	Digital network Operator (DNO)
Capacity to Customers (C2C)	Electricity North West
Customer Led Network Revolution (CLNR)	Electricity North West
CLASS	Electricity North West
FALCON	Western Power Distribution
Flexible Plug and Play (FPP)	UK Power Networks
Lincolnshire Low Carbon Hub	Western power distribution
Low carbon London	UK Power networks
NINES	Scottish and Southern Energy
Orkney RPZ	Scottish and southern energy power distribution
RESPOND	Electricity north-west

2.5 G100

As previously indicated, the integration of flexible assets on the distribution grid level is one of the greatest ways to boost power production and availability to prosumers. Technical design requirements for Export Limitation Schemes (ELS) that are installed on the Customer side of the connection point and restrict net site export to less than a predetermined maximum [81]. G100 is a part of the forefront Multi-function Controller Platform (MCP). It provides a set of hardware and software components that are modular and scalable, has a large capacity, is secure, are future-proof, and are substation-hardened. These components are designed to make the implementation, operation, and management of automation systems easier. G100 installed in a network can reliably control the export limit [18]. In the SPEN-introduced programme, the maximum permissible generating capacity is 3.68 kW. The export limit in this thesis' ETC case study is 200 kVA. It is possible to increase the limit throughout the process of integrating more RES into the distribution network by making use of devices that comply with the G100 standard. Primary functions include technical design criteria for ELS, active power exported at the connection point, voltage limit at the distribution system, area managed under active network management, and generator output control by demand and supply needs [81].

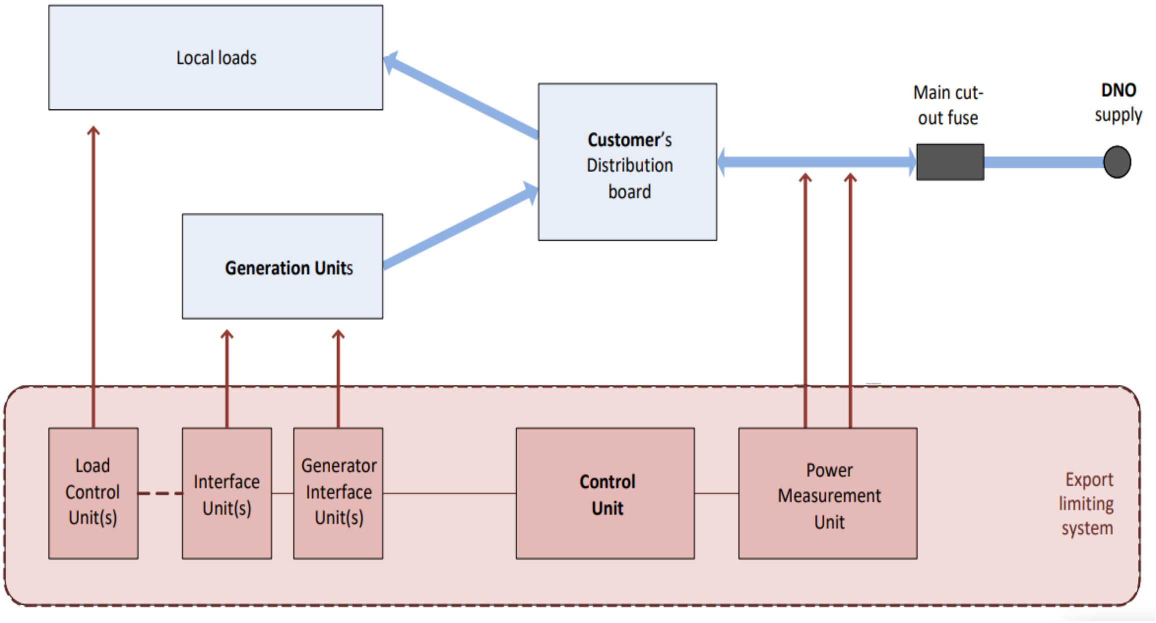

Figure 7:ELS Diagram[81]

The aforementioned figure is an ELS diagram for an arrangement of asynchronous generators [18]. The steps start as the customer requests for the ELS and arrangements has done for protecting the entire power system by giving commands whenever it exceeds the limit. It figures out the maximum power station capacity at both high voltage (HV) and low voltage (LV). In this thesis paper, the ELS is suggested at the distribution level grid. The G100 may be installed in power plants close to generation units and functions as an ELS when switchgear, transformers, cables, and overhead wires are present [81]. The ELS must be able to lower the produced electricity or disconnect one or more Generation Units if there is insufficient demand. An ELS must be able to reduce output or disconnect one or more Generation Units if demand is not high enough. Solar PV systems and other RES may also benefit from this protection.

2.6 Instrumentation; Sensing, Measurement and Data Acquisition Strategy

In the electrical power system, instrumentation plays a key role. System operators can have a better understanding of the condition of the electrical grid with precise measurements. [10]. Power delivers to consumers through the distribution step. Medium voltage (MV) and low voltage (LV) power lines, substations, pole-mounted transformers, and distinct types of sensors for monitoring characteristics necessary for various purposes are typically made distribution networks [98]. Gathering data is essential in a supply chain. Due to the advancement of low-carbon distribution technology and the modernization of power plants, its endpoints have increased. [113]. The SCADA system was used at first for data collection; however, this method is inadequate for the collecting of data for future large-scale systems. [8]. However, SCADA is the most common method in any industry for data acquisition. Since its sampling number in second is very less, precise information to detect fault constraints is hard and a phasor measurement unit (PMU) is introduced in this situation. Improved sensor and monitoring strategies are required for obtaining output characteristics from the substation, different DG output, and the condition of overhead wires to improve performance in an ANM. It is critical to understand the sensing and measuring principles that apply to these types of devices in the distribution network. Understanding the performance characteristics of each sensor type used, as well as their appropriate position and the rate at which data can be extracted (sample rate), is critical in a power system. This makes the commissioning of devices used for output in each situation simple. In past years, utilities and grid management system developers have recognised the need for distributed intelligence, particularly at the distribution level. In the distribution network level grid systems, the development of electrical and thermal measurement is most critical to reducing the network constraints. The definition of instrumentation required inside the field trial network for network characterization and commissioning will be the crucial stages [10].

Significant concepts such as observability and system state that may be used to guide the design of sensor systems for physical phenomena with a hierarchical model are major challenges in the field of sensing, measurement, and data gathering. Second, sensing and measurement, specify the amounts to be detected, sensor kind and placement, and signal characteristics. This portion of the thesis is more intense. Data acquisition is also an essential step since it analyses sensor data collection and transmission. Finally, communication for sensor networks and network architecture that describes the components, structure, and external aspects of sensor networks are considered. Based on any combination of inputs and system states, it is possible to infer the state of a system only from output measurements. Moreover, electrical network system instrumentation necessitates observability approaches, such as temporal, geographical, and topological knowledge of all grid variables and assets. Since this thesis focuses mostly on network management, monitoring equipment for voltage, current, actual power, and reactive power have been described and researched.

The DG output control system requires both operational and verification measures [112]. Over-instrumenting the field network trial network was necessary to achieve characterisation and assessment goals. It was essential to arrange measurement equipment in the most precarious and thermally sensitive location, which makes it challenging to precisely analyse the thermal behaviour [112]. The consequences of not accurately predicting the temperature limit might be severe. As of 2015, the criteria for electrical, thermal, and meteorological monitoring were laid forth by The NOAA [112] [10].

Table 3:Electical Parameter in Instrumentation[10]

Electrical Parameter					
Overhead Line (OHL)	**Power Transformer**	**DG**	**Load**	**Grid supply point**	**Circuit Breakers**
P, Q, V,I	P, Q, V1, V2	P, Q		P, Q, V	Operational status

Table 4:Thermal Parameters in instrumentation [10]

Thermal Parameter		
Overhead line	**Electric Cable**	**Power Transformer**
T (core operating and surface operating)		T (hot spot, top oil, and bottom oil)

Table 5:Meteorological Parameters in instrumentation [10]

Meteorological Parameter		
Overhead Line	**Electric Cable**	**Power Transformer**
Wind speed, wind direction, Ambient temperature, Solar radiation	T (Ground, ambient) ground thermal resistivity	Ambient temperature, wind speed, wind direction, solar radiation

From the above table, it is evident that temperature and electrical measurements will be in the same place, indicating a correlation between their behaviour. It reduces the time necessary to install suitable sensors. Measurements of the DG and near-substation transformer would be more advantageous for tracking asset penetration-related restrictions. Instrumentation is required for explicit distributed network characterization and constraints dissemination.

2.6.1 Smart Transformer

Under measurement devices, a recently emerged intelligent device is a smart transformer. The smart transformer is a power electronic embedded intelligent device that provides controllability and functionality for the betterment of low voltage (LV) distribution level networks. With a projected market value of $4.55 billion in 2028, the smart transformers are expected to be implemented at a total price tag of about $2 billion in 2021 [11]. Providing precise measurement, control, and monitoring utilising the internet of things (IoT), particularly the narrow band IoT (NBIoT) low-energy form of the IoT, may have a considerable influence on the smart grid [109] [88]. With the help of cloud storage-related activities in the sophisticated power grid, the IoT offers essential sensing, measurement, and actuation. The smart transformers are used in a secondary substation [88]. The main components of a smart transformer include the solid-state transformer (SST) and smart control system (SCS) respectively [109]. The SST includes digitally controlled power electronics and hardware that provides various control functionalities. It will be installed at the secondary substation that converts 11 kV to low voltage 0.4 kV [109]. Mainly used for the phase voltage regulation, power flow control to reduce the thermal strain at peak times and maximising the network capacity, and reactive power control by offering independent voltage regulation at both LV and HV ends. It also gives the low voltage DC (direct current) supply by conversion with the help of the power electronics. This demonstrates the function of a smart transformer, and the software component includes a smart algorithm based on monitored data. The use of Power Line Carrier technology in communication serves to secure signalling. Control parameters include DC voltage set point, HV voltage set point, LV AC (alternating current) active power set point, LV AC reactive power setpoint, LV voltage set point, and thermal loading set point [109].

The NBIoT includes a cellular mode and LPWAN (Low Power Wide Area Network). It helps to measure the air quality and weather forecasting measurement for the protection of services on the grid [108]. Based on the distribution network focus, it provides the load demand with load-side smart meters. Smart metres make it possible to estimate the dynamic tariff, get pricing data, regulate electric appliances automatically, monitor power quality, receive outage notifications, identify theft, measure load, and integrate demand-side resources [88]. The communication is also bidirectional. Usage of smart meters with IoT integration can constrain the readings of smart meters and keep them accurate. The data acquisition using SCADA with

NBIot is efficient in monitoring and converting electrical parameters into lower digital data. Electricity distribution systems rely on precise voltage and current measurements. In this context, PMU installation has been increased. It is the synchro phasors that measure voltage and current phasors discussed in the next session in detail. Fault location systems have already been used by Europe and Australia. According to the most recent data, $95 billion will be spent globally on smart sensors, while smart metres and information technologies cost around $45 billion [96] [11].

2.6.2 Phasor Measurement Unit (PMU)

The evolution of the smart grid is demanding accurate measurements, especially electrical measurements. Before this protection system decisions are mostly based on the local measuring of electrical parameters such as voltage (V) and current (I). To achieve advanced levels of distribution grid planning, monitoring, control, energy management, and safety, it is necessary to perform a dynamic grid analysis that takes into consideration both the magnitude and phase angle of the voltage. It has been established that there is a requirement for monitoring phasor values of voltage and current to overcome network restrictions in a grid [14]. For effective management, understanding the measurement point location of voltage and phase angle in the grid is necessary [12]. A phasor measuring unit (PMU) is a device that analyses voltage and/or current waveforms at the point of grid connection using synchronised sampling with a common function of time for all sites, which is supported by the Global Positioning System (GPS) [28]. The PMU measurement is used for mitigating the disturbances in the power system by monitoring and analysing the magnitude and phasor angle of electrical phasor quantity in the electric grid due to the integration of DER. It can also report the magnitude, phase and frequency of an AC waveform and help to take preventive actions against blackouts. Since it synchronises multiple with a precise stamping from a different location using GPS, it is often known as synchro phasors [14]. The PMU detects the DC, switching, phase-detection pulse, terminal voltage, terminal current, three-phase current, and three-phase voltage of the unit in real-time [114]. With perfect time synchronisation, voltages and currents may be measured at several locations. This helps in dynamic visualisation and precise monitoring of the control systems [14]. This characteristic gives the precise measurement in the distributed system. PMU may be a standalone device or an add-on feature included in an intelligent electrical device (IED) in a substation. It plays a key role in active network management in distribution systems Since the phase angle changes every microsecond [28]. The sampling rate is going up from 12 samples /cycle to 60 samples/cycle [38]. µPMU is also available in the advanced distribution measurement technologies that give information regarding dynamic and transient states by up to 120 samples per second [20]. PMU is not extensively implemented yet. It also protects the power system by providing wide area measurement and online security analysis. The main functions are stability analysis and monitoring providing a dynamic snapshot, quicker reclose operation, bidirectional flow possibilities by observing current and voltage waveforms, loads with fast dynamic, and state estimation direction measurement by a state vector.

In a smart grid with DER integration and active loads, it helps the dynamic approach of voltage/var/Watt control as dynamic modelling requires instantaneous active and reactive power quantities. PMU also helps with fault detection in parallel lines as it provides precise time-stamped data from PMU's clock.

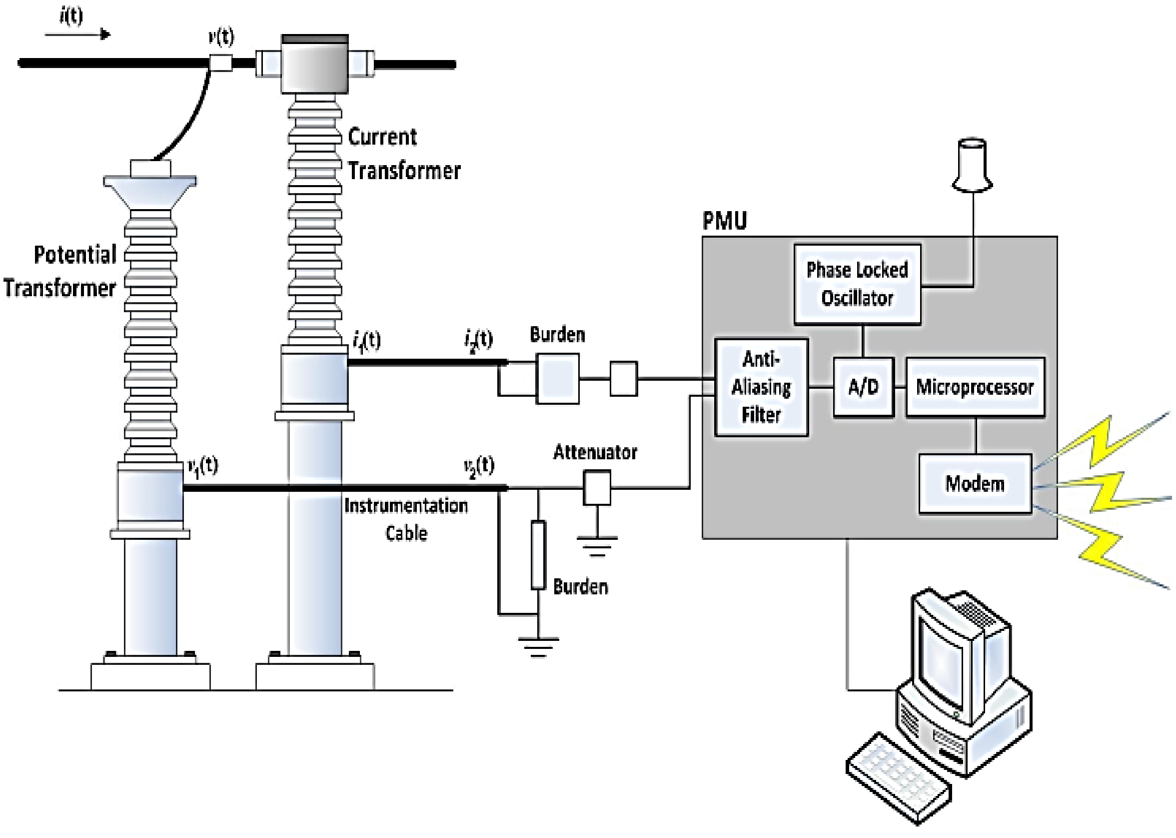

Figure 8:Schematic Diagram of PMU [85]

The GPS with twenty-four modern satellites is commonly used in PMU. It is connected external to the PMU as its internal oscillator maintains the time accuracy. The PMU measure the data stored in local storage and this data assembles by PDC. Figure 8 shows the schematic diagram of PMU. The analogue current and voltage values from the secondary windings of the CT and PT will be sent in rapid succession to the anti-aliasing filter, a low pass filter, to match out frequencies that are more than or equal to half the Nyquist rate to get a sample waveform[38]. The GPS and phase locker oscillator provides the required synchronised high-speed sampling. For oversampling, the Anti-Aliasing filter (AAF) in the above-illustrated figure is used. It uses a high sampling frequency and a high cut-off frequency of the analogue AAF to achieve this effect. The signals for current and voltage are then transformed to the proper voltages using suitable shunts that have a range of ± 5 or ±10 V. It is then connected to an analogue to digital converter (A/D). The analogue and digital converters (A/D) transform analogue signals into digital ones. It is also amplitude discrete time and discrete amplitude signals. Using discrete frontier transform (DFT) technology, the microprocessor computes a positive sequence to assess all current and voltage data. Additionally, analyse the frequency and pace of change. The Modem is a device that modulates an analogue carrier signal and encodes and demodulates digital information from the signal. The signal being transferred is the modem. Its primary purpose is to convey the decoded signal and reproduce the original digital data. By the IEEEc37.118/IEEE C37.224 synchrophasor standard [44], the PMU communicates with the Phasor Data Concentrator (PDC), which serves as both client and server, and then the SCADA system. The communication standard protocol is IEEE c37.118 between the PMU [47] and the PDC and uses fibre optic links. The data from PDC is given to SCADA which enhances the measurement values accuracy. The PMU reports 30 to 60 measurements per second whereas SCADA gives 2 to 4 measurements per second. The reactive and active power can either be derived at PMU or PDC stage. IEC 61850 has been used to make it easier for transmissions in nearby and faraway substations to work together.

The Universal Time Coordinated (UTC) states that the time tolerance might be as high as 10 microseconds [14]. Co-ordinating PMU with network and SCADA activity will be more efficient economically and get technical data in real-time to adjust disturbances in grid level. Reports show $800M costs in the year 2021 for the installation of PMU [109]. When using PMU, the ratio error for measurement is about 0.1 per cent with phase errors that are smaller than 1 mrad [96]. It helps to find out the fault detection that protects relays. The power outage cost around $25 to $180B which makes a huge loss. Due to the smaller line lengths, the PMU can reduce the phasor uncertainties and employ advanced signal techniques making it an advanced measuring device in power systems.

2.6.3 Supervisory Control and Data Acquisition (SCADA)

SCADA is a combination of hardware, software, controllers, network, and communication that uses in industrial processes and power systems to evaluate, track, collect, and process real-time data [24]. Power network automation relies heavily on instrumentation and control devices to regulate and monitor the power system. Its usage started in electric utility systems in 1940 and developed to advance telemetry from the year 1970. Alan Cone says that SCADA is a critical solution for connecting distributed assets to generate actionable intelligence and the first step in interoperability. The SCADA can be used in a centralized or distributed way, locally or long distance. Its main functions include data acquisition, network data communication, data visualisation and control, respectively. It can get data directly from devices like sensors, valves, and motors. This data can be displayed using software called Human Machine Interface (HMI) [21]. In this study, the function of the SCADA system in a distributed network system is explained in detail. By deploying a SCADA system, the automatic power distribution infrastructure, including substations and transformers, is effectively monitored, operated, and maintained. It is a cost-effective approach for mitigating power interruptions caused by DER penetration and enhanced distribution network management by optimising overall network performance and increasing system dependability and sustainability [21]. SCADA serves as an alert system by detecting power line and substation faults. Since data is monitored in real-time, limitations may be remedied rapidly. The SCADA system can automatically maintain electrical parameters such as voltage and current from the isolator switches and circuit breaker, take immediate action without interrupting the entire system, and reduce the need for line workers, thereby ensuring their safety and increasing their productivity. In addition, it can manage transformer voltage taps, trending, and alarms to notify operators of power supply. As a result, the power production from low carbon technologies (LCTs) that are connected to the distribution level grid is increased.

The common system components such as sensors, RTU, telemetry system, data gathering centre as a computer which sends commands to the SCADA system, communication infrastructure connecting RTU, and Programmable logic Controller (PLC). However, PLC is a digital computer used for automation in the industrial electro-mechanical process.

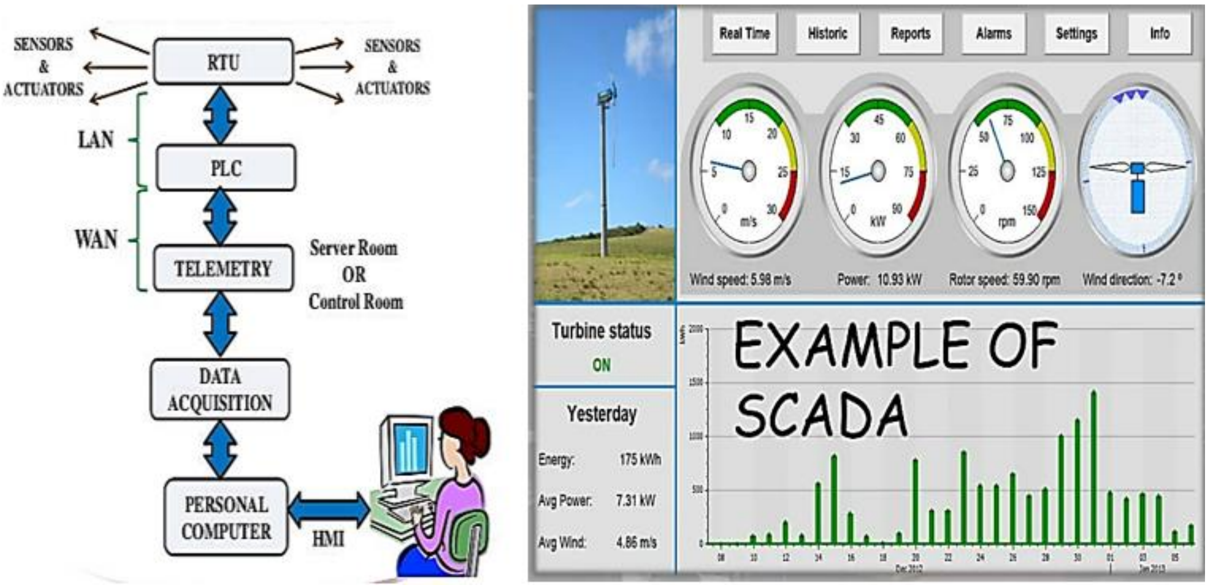

Figure 9:SCADA Block Diagram & visual example [86][23]

The above-illustrated figure shows the block diagram and visualisation on the HMI screen of a SCADA system. The visualisation on the screen shows the wind turbine status including real-time, historic data, reports, and alarms. SCADA's initial generation will be monolithic, its second generation dispersed, and its third generation networked [65]. The parameters that will be collected from the field instruments include substation transformers, power sensors, IEDs (intelligent electronic devices) smart sensors, smart meters, and digital fault recorders (DFR). Microprocessor-controlled RTUs connect with field devices and communicate with SCADA systems by transforming their data into an understandable language. This data is then transferred to the HMI, the interface between human and machine. In Distributed trend, the processing can be distributed across multiple local stations and shared information in real-time. Since each station is responsible for the task, the cost will be less and avoid the entire system failure. Finally, the automation generation control that can control generator output will be enabled by SCADA. Some of the limits are troubled alarms, lack of trained personnel to operate SCADA and the initial cost is approximately $1000[63].

2.7 Energy Flexibility market

The objective of the energy flexibility market is to open new options. When low carbon technologies are included at the distribution level, consumers have control over their power costs since they are aware of every aspect of their usage and can simply schedule their consumption. The flexibility needs to adjust the generation and consumption in utility systems. The DNOs are the companies that distribute electricity to the customer side. EDF, SSE, Scottish

Power, British gas, EON, and nPower are among the companies that possess DNO licences in the United Kingdom. British gas is the UK's largest green supplier energy company with more than 13 million customers [93]. FUSION by SPEN is a project that focuses to provide expertise and more flexible assets [54]. The FUSION project enables the development of small-scale resources and local markets via the use of a network solution, the USEF while reducing carbon emissions by 3.6 tonnes and earning $236 million by 2050 [90]. Octopus Energy which supplies 2 million green electricity now provides different tariffs such as octopus fixed, flexible octopus, business tariff and EV tariffs [91].

The SIES 2022 project's goal is to provide a digital energy utility management service that can manage local and regional energy systems and markets [92]. Piclo is a renowned software company that focuses on service flexibility [75]. The Piclo is a cloud-based platform that supports system operators and offers integrated services. It launches international partnerships to access more local flexibility. This assists the DSO in obtaining local serviceability. TSOs and DNOs compete for flexibility providers such as electric vehicles (EVs), battery storage, and local energy supply on one side of the market DNOs. In this thesis, the design has been illustrated by considering the flexibility of the market Piclo. The procurement process includes market visibility, qualification, and bidding. This helps users to purchase and sell existing flexibility contracts, the exchange schemes assist a secondary marketplace.

2.8 ETC Case Study

ETC is a partner of the Smart Integrated Energy System (SIES) project 2022 ERA-net consortium that aims to decarbonize energy systems and manage energy pools using a VPP capability to include energy market interaction, local and regional energy system integration of VPP. Energy Pool has pledged to work with energy users and states to achieve carbon neutrality by 2050[110]. The ETC has an interest in two energy pools Myres Hill wind turbine site and Scottish Enterprise Technology Park (SETP) [19]. According to [19], the system's electrical architecture is comprehensive. It is possible to generate electricity from a wind turbine, solar panels, and a PV, heat pump, as well as thermal storage and a Biomass boiler using integrated energy assets [40][2]. The building has been updated to meet demand management and produce minimal levels of CO_2 [2]. Renewable and low-carbon energy sources partially satisfy the remaining energy demand by power generated from a photovoltaic array and wind turbine respectively [40][2]. This paper focuses on Energy Technology Centre by proposing a detailed design considering its sensor and measurement strategy for ANM.

ETC's principal emphasis is on the advancement of energy conversion systems in renewable and low-carbon areas. Substation capacity 1000 kVA assigned from Rankine transformer is supplied to SUERC Building with capacity 400 kVA, Torus Building with capacity 250 kVA, NERC Building with capacity 125 kVA, ETC with capacity 100 kVA and Technotots Building with capacity 80 kVA, respectively. The below figure shows the ETC image captured by google earth.

Figure 10:Energy Technology Centre [77]

2.8.1 Scottish Enterprise Technology Park (SETP)

The SETP, situated in East Kilbride, Scotland, is a facility in which the government and various enterprises conduct research. As stated before, ETC has a stake in the two energy pools. One of them is the SETP's energy infrastructure. The National Grid (275 kV) physically connects Myres Hill with SETP. Decarbonizing and adaptable assets are being considered for inclusion in the SETP considering the increased flexibility of the energy market and the SEIS 2022 objective. Today, the SETP is primarily concerned with assisting technology-based companies in growing and disseminating new prospects [87]. On the ETC site in the park, City University's Helix test laboratory is a key feature of the SEIS project. The SETP is fed by two major substations situated at Common farm and Leonard's Chapel. These major substations contain seven local HV or LV connection points and two 11 kV connection terminals, namely the East

Kilbride point and the Strathaven supply point. Due to limitations at the Common Farm substation, however, the listed substations are incapable of accommodating extra load [19]. Unlike the Leonards' Chapel substation, however, the common farm substation is under DNO's authority and future load expansion is feasible.

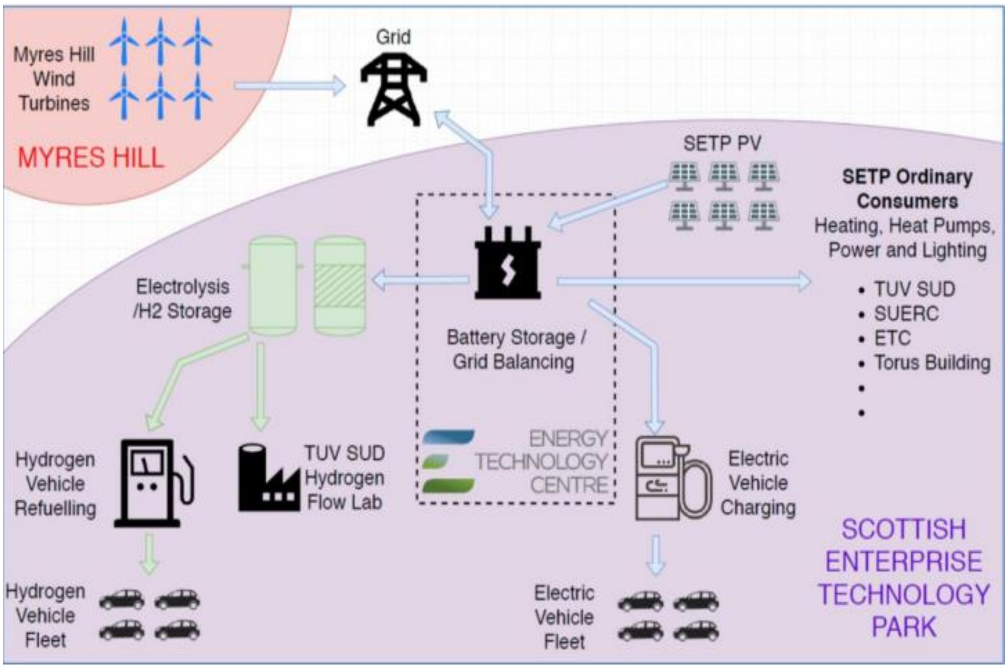

Figure 11:The Proposed Energy system on SETP (SIES 2023) [19]

An electrolyser for hydrogen generation and electric heating for buildings linked to the ETC system is shown in Figure 11 of the proposed system. Predicted increases in demand will allow for greater integration of distant industrial units by using a larger quantity of power on a single bus. Due to the proximity of the three transformer sites to the ETC, increasing load at this centre is a viable alternative.

This thesis will examine the increased load added on the ETC due to time constraints. As this thesis focuses mostly on local ANM, it is also feasible to increase the load to three places using this idea. For example, the 11 kV near the TUV-NEL gas lab may be made accessible since it is not in use and can provide around 1600 kVA of capacity for remotely switched connections [19]. The Fleming Transformer is the second choice since it is supplied by the Common Farm substation, which gives the possibility of a link. With a 100kVA capacity, the ETC network is the most desirable option for the increasing load. According to the paper created by Clark, it may be supplemented with a more environmentally friendly option such as a big thermal storage system, electrolyser, or hydrogen fuelling station with a total load of 500 kVA.

2.8.2 Myres Hill site

The Myres Hill location is an intriguing ETC energy pool. It is supplied from the Giffnock supply point through the Mearns Castle (11kV), which has some reserve capacity as the main substation. By its remote position, the plant must contend with voltage restrictions [115]. The overhead line has a nominal capacity of 100 A at 11 kV. The first substation at Myres Hill serves an 800 kVA transformer, while the second 11 kV Myres Hill substation powers two wind farms run by Thorfinn Wind A Ltd. (combined 1.9 MVA) [19]. The overall rating is shared by two operators, Myres Hill test site and Thornfinn Wind-A Ltd. SPEN imposes a 200 kVA export restriction since it is near to the power limit of the supply grid link. Due to time constraints, the thesis concentrates on ETC. The National Engineering Laboratory (NEL) runs the national wind energy test site at Myres Hill. The facility features 18 test pads for small-scale wind turbine design, and a tiny wind farm is found here, surrounded by the well-known Whitlee Wind Farm [89]. However, it may connect extra equipment such as an electrolyser up to 800 kVA within the export limit. According to Clark's ETC report, added generating capacities such as battery storage, PV, or wind turbines with a rate limit of 375 kVA also allow and load up to 2 MVA (volt-ampere).

2.9 Literature Review: Conclusion

The purpose of the literature review is to explore and acquire in-depth information about ANM and related instrumentation. Initially, the thesis has reviewed the literature on DER, flexibility assets, and network restrictions to better understand this topic. Second, the ANM idea is analysed with a focus on the advantages of G100 devices. Although the ANM literature identifies several factors that impact power systems, this research focuses on the sensor measurement, monitoring, and control technique for a local ANM distribution network idea. PMU and SCADA are used in the proposed design of the local ANM. The literature review on these two helps in identifying their main benefits and designing the instruments for ETC's local ANM. Finally, a short literary analysis of the ETC case study, covering the SETP, Myres Hill location, and flexible market advantages is conducted. Further study might be undertaken on the other energy pool of the SIES project and appropriate measuring devices. Additional research in this area might assist them to choose which area to prioritise in the SIES 2023.

3.0 Technical Assessment and Local ANM Design Proposal

3.1 Introduction and Methodology

After the detailed literature review, the proposed architecture of instrumentation in local ANM of distribution network integrated with flexible assets has been designed in this section. The ETC energy pool is selected for this detailed design as a case study. The steps involved in the methodology are

- Data collection after detailed research on the possible sensors and measurement units for active network management in distribution networks.
- Create a detailed design architecture of distribution network with flexible assets integration; focus on
  - Instrumentation; Sensor measurement, monitoring and controlling strategy in an active network management

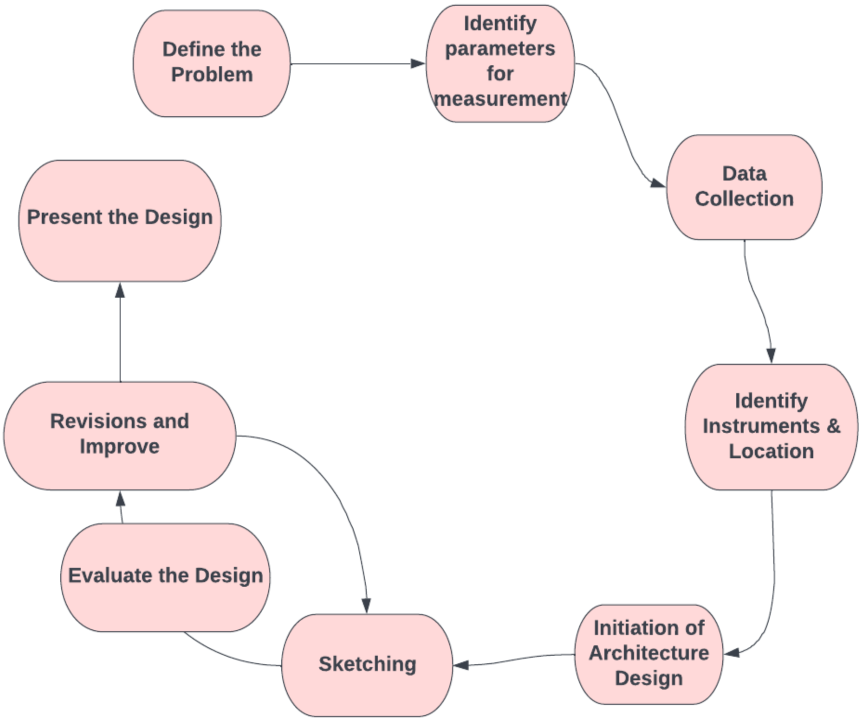

Figure 12:Steps of a design process

The above figure shows the design process of the instrumentation part in a power system. Initially, the problem has identified due to the integration of non-dispatchable energy resources such as wind and solar. The main constraints due to intermittent behaviour are thermal, voltage and fault constraints. The ANM concept has been successful in thermal constraints more than voltage and fault constraints. Instrumentation is a significant part of the system to measure the parameters that need to analyse and observed to mitigate these issues. The next step is identifying the important parameters for measurement. The fluctuations in voltage and current are the most significant measurement for the power flow analysis.

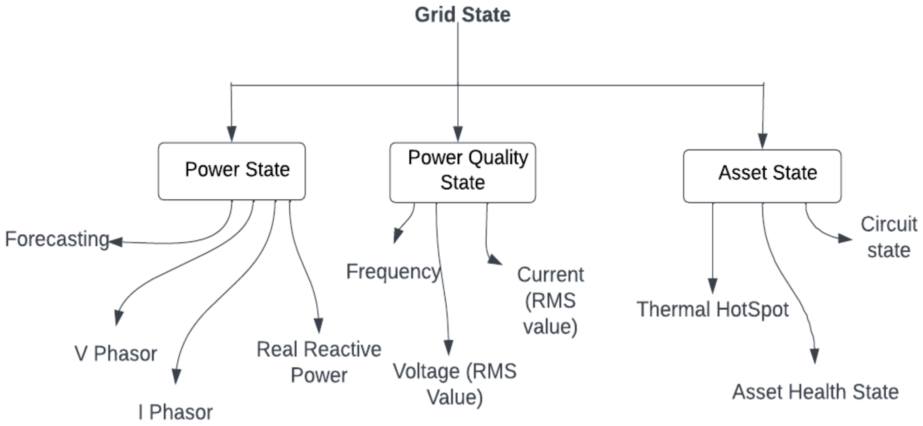

Figure 13:Grid State Elements [8]

The identified parameters are classified into three states such as power state, power quality state and asset state. Listed all the measurements for supporting grid stability and ANM. The values of the phasors for voltage, current, and frequency are the most crucial factors. The data has been collected according to the selected case study and identified the main problems. Even though there are limitations to getting data, sensors need to be installed and their location selected based on research, assumptions, and available data. Comparing the cost, and importance of the use of sensors, classified each sensor according to the measuring parameter. The main measuring unit is PMU, as it gives the output of phasor measurement of voltage and current. The next step is initialising the architecture design by considering all factors, placing each sensor, and measuring the unit based on the location selected and sensor usage. In each section, the diagram sketching has been improved by a detailed review. The sketched diagram has been evaluated by considering the demand of the building meeting and what actions were considered to mitigate the constraints situation. The evaluated design checked with load demand and assumptions on curtailment of the generation units in the case study. Considering the case study that was chosen, the model created for the network constraints before this research was also helpful. By repeated iterations and checking design quality, the final architecture has been designed with available data of the case study.

3.2 Design Proposal for the ETC: Case Study

A detailed design of instrumentation with the ANM concept of the ETC has illustrated in this section. Before explaining the working principle of each sensor measurement unit and strategy, a study was conducted and collected details about the present sources of generation, demand, supply, and the load of the ETC building. The ETC is fed from the Rankine transformer[19]. At present, the ETC has a 10 kW capacity Photo Voltaic (PV) system with 40 solar cells captured from google earth, and a 12 kW capacity wind turbine is being installed. Since the generation of these two energy sources is very small, additional load and generation could be possible with ANM [19]. The Rankine transformer fed to other buildings such as SUERC with 400 kVA (Kilo Volt Ampere) (360 kW) capacity, Torus building with 250 kVA (225 kW)capacity, NERC with 125 kVA (112.5 kW) capacity and lastly Technotous building with 80 kVA(72 kW)capacity. The Rankine transformer capacity is 1 MVA (900kW) respectively[19]. Since the capacity of generations is in kilowatt (kW) units, the above-mentioned capacity of the building and transformer is changed into kW by multiplying the power factor (P.F) by 0.9. This assumption, which was made based on anything less than 0.9, would incur a penalty. Because the system load that has a poor P.F will demand more current than a load that has P.F [41]. The ETC data from [40][41][77] includes the low voltage generation such as Steam Generator, Wind Turbine, and PV Park. The loads include the main Compressor, Basement, Hydraulic Pack, Cooling Pump Backup Compressor Electrolyser, and Thermal Storage[42][77]. A new wind turbine with more capacity than the existing wind turbine and more packed PV systems in this design with the ANM has been proposed in this design. Instrumentation plays an important role in mitigating network constraints. In this design, the thermal constraints are more focused and sensor identification is more detailed for controlling the thermal constraints. However, voltage and fault constraints can't be avoided. For the betterment and maximum output from the flexible asset, these two also need to be considered and suitable sensor measurement strategies are proposed.

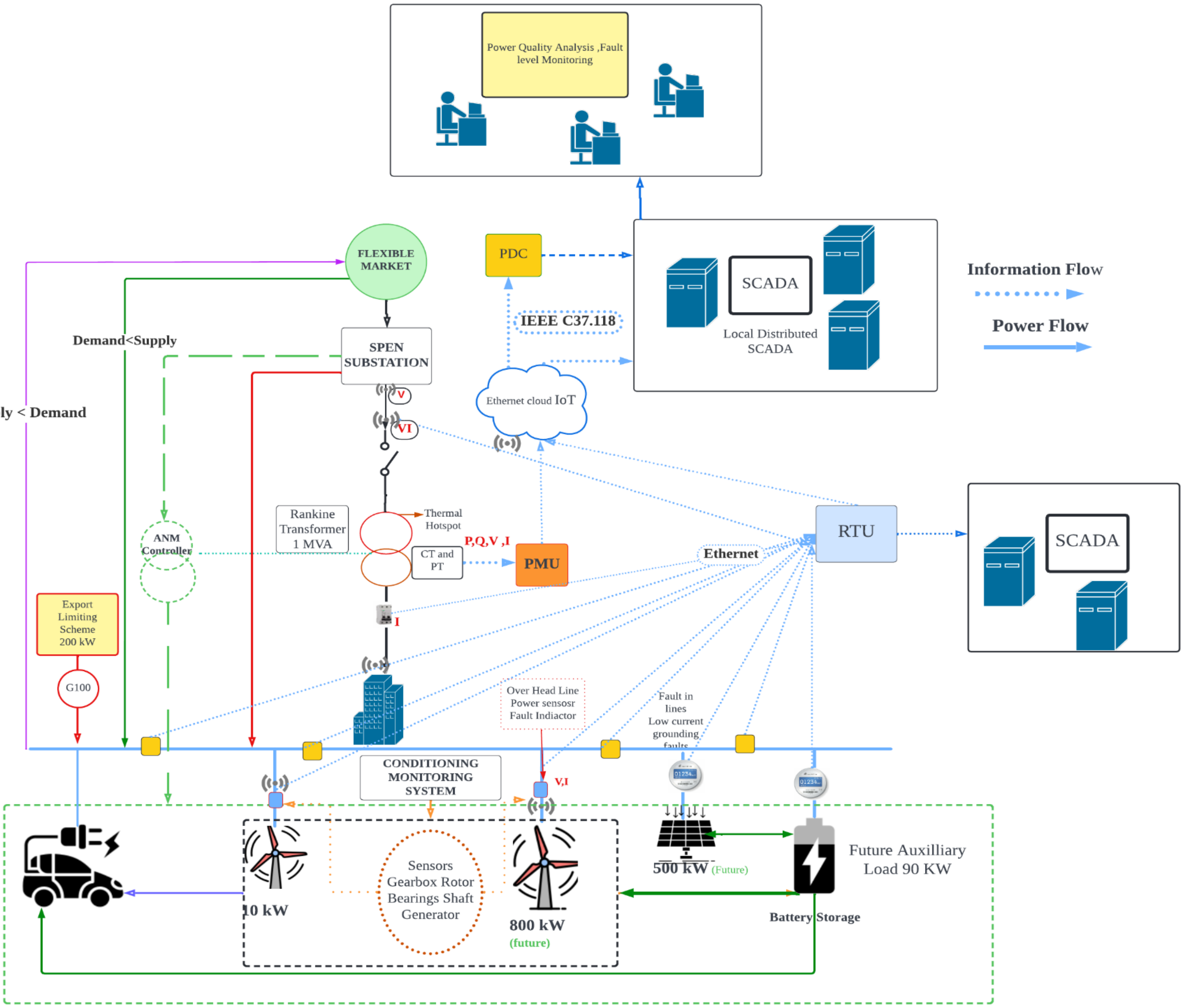

Figure 14: Detailed design of Instrumentation part in ANM of the ETC building

The design consists of a flexible market such as Piclo where energy export and import take place according to the supply and demand. As discussed in the literature review chapter, Piclo is one of the leading independent marketplaces in the UK, especially working for flexibility in the services[80]. On one side of the market, Transmission System Operators (TSOs)and Distribution Network operators (DNOs) bid on the flexibility providers such as electric vehicles (EVs), battery storage, and local energy supply DNOs. In this case study, the Piclo bids on the ETC distribution network's power supply from the generation unit. Location, capacity, and voltage level are used to determine bids. From DNO-DSO transition enables grid flexibility by actively controlling and acting on the distribution network [55]. The Piclo Flex simplifies the end-to-end process in DSO. This helps the DSO to procure local serviceability. SPEN is converting and one of the bidders in Piclo Flex and constructing its competing flexibility market on the USEF named FUSION, the new SPEN project [56].The function of Piclo by developing software to make the grid more green and smart that supports ANM.

The design demonstrates SPEN with Rankine transformer and that connected to the ETC building. The fault constraints measurements can be calculated from the short circuit analysis, and peak current obtained from the circuit breaker. It is demonstrated below the ranking transformer. In between the transformer, the circuit breaker and switchgear has shown. The intermittent behaviour of the flexible assets wind and solar is very minute and small values are essential for its diagnosis and mitigation. For this measurement, the phasor angle measurements of voltage and current have to be considered. Even though merging units are available which can connect to the current and potential transformer to measure parameters without change in primary equipment and minimizing wiring [44], it is not used for direct phasor measurement. Detecting 50/60 Hz current and voltage AC waveforms at 48 samples per cycle in a PMU makes it a valuable utility measuring device[67]. Secondary windings of the CT and PT may be used to take measurements of the magnitude of the current and voltage values, respectively [116]. Apart from this, hot spot measurements in the transformer are also useful to find the thermal constraints by monitoring current flows. Four overhead line sensors are also designed on the overhead buses of generation units. It works as a fault indicator. From [19] ETC data, it has been set by an export limiting scheme, G100 to limit the flow back of power from the generators. The wind turbine parameters which cause the constraints can be monitored closely by fixing a signal conditioning monitoring unit in two turbines. A smart energy meter is connected to the PV system to measure the energy utilities by the electric load[50]. Finally, the measured data is transferred using an RTU and then local distributed SCADA through the ethernet, IoT. The PMU data also can be transferred through the SCADA systems and the user interface can be visualized the trends and history of each monitored measured or an automatic system will send appropriate signals back to the system and the constraints can be mitigated. These are included in the VPP’s ANM concept.

In the above-mentioned design, the ANM controller can be seen connecting the entire distribution network system from the transformer way to the generation unit. The controller sends signals to the generation unit according to the output getting from the measurement units and it will decide the power flow from the sources based on demand. Thus it controls reverse power flow, and network constraints by sending the appropriate command. The DGs connected at the bottom part of the design are the future suggestions except for the 10 kW wind turbine. The solid line shows the power flow connection and the dotted blue line shows the communicainformationation flow. The future auxiliary load of 90 kW has shown near to the generation due to the limited space in figure 14. Even though the above-mentioned future load is considered in the ETC building, the sensor part is more explained in detail. The basic principle of the ANM is Last in First Out (LIFO). LIFO, also known as the priority order of curtailment of distributed generators unit, supervises the generator access to available capacity in real-time [72]. Even though the LIFO method is not economically efficient [73][74], it is commonly used in active network management at present. In contrast to shutting down the entire DG during constraints, the ANM concept can monitor in real-time and curtail generators or send commands to prevent power interruptions without affecting another unit. The later connected DG will curtail in first that not impact the generators connected first. This is a simple arrangement and proved to reduce thermal constraints efficiently. However, it causes issues in constraining voltage disturbances. A recent study shows that the Optimal Power Flow (OPF)-LIFO and Principle of Access (POA) LIFO method gives priority to the generators in weaker sections [72]. If DER output rises, the design demonstrates the need for a battery storage system in the ETC.

At present, the ETC's peak demand is 90 kW, which it is unable to supply with its own generating units (wind turbine and PV). To fulfil demand, the grid must deliver electricity based on the ETC data. Assuming a 500-kW capacity, PV may be added in the future by referring to Google Earth and calculating the area. Apart from this 800-kW wind turbine, the system can generate more than 1MW of electricity. Considering the other buildings served by the Rankine transformer, the total power will be around 800 kW, excluding the requirement of the ETC building. The need can be met in the future by the ETC building's generating unit. Due to the export restriction, it may sell electricity back to the energy market during low demand periods of up to 200 kVA. However, the ESS system, and load bank system may introduce and store surplus power production in addition to supplying electricity to the grid after satisfying five building demands. Currently, the ETC and Torus buildings are linked by a physical cable. Later, the electricity from the generating unit such as wind and solar, ETC may be used by all buildings through a virtual link and PV system extension on the roof. The installed ESS can be monitored using a smart energy metre, which measures the system's energy use. The ESS focuses on increasing the security of a decarbonised energy system and the utilisation of renewable energy resources to minimise reliance on non-renewable resources and achieve the net-zero carbon objective [68]. Lithium-Ion batteries are the most often utilised battery energy storage solution for grid-scale energy storage due to their extended life cycle and high efficiency. Nonetheless, as noted in the literature review session, cost-cutting options and an effective recycling programme are required to minimise their environmental impact [71]. Battery storage balance for a future hydrogen storage project and thermal storage is also being explored for the ETC's future [19]. The ESS additionally considers fuel cell failure in the electrolyser. This design primarily focuses on the sensor element, which provides measurement value and may oversee based on constraints.

4.0 Investigation of Potential Impact of Local ANM Instrumentation for the ETC Case Study

This section describes the measurement unit and instruments used for sensing, monitoring and control in a proposed ANM schematic model of the ETC case study illustrated in section 3.2.

4.1.1 CT and PT

The current transformer (CT) and potential transformer (PT) are the main instrumentation external sensors where voltage and current measurements take [70]. These both are instrumentation transformers. The CT step down the high current and passes through the sensors to low compatible with measurement instrumentation. The output range of CT includes ±10V as common [70]. The Rogowski coil (rope CT) measures line current. It is more costly than a similar CT [70]. A high current is flow through the utility. To manage the constraints on the distribution side, the Rankine sensor implements with CT and PT since a high flow of current occurs and effective active management of the system needs this parameter reading. The CT will reduce the current and the amount of current needed to reduce writes as the CT ratio [69]. In this case study, the current ratio is unavailable and more focused on the instrument to convert the stepdown values into the phasor values. Measure distribution line voltage is not difficult as transmission lines. Like CT ratio and PT ratio tells how much quantity needs to step down. For instance, 11000/110 mentioned on PT means 110 voltage output will get from PT [69].

4.1.2 PMU

The accurate measurement as stated in the literature study to measure the voltage and current phasor values is the PMU. The installation of low-carbon technologies at the distribution level has increased the electricity demand, giving grid operators less control over the system and making it difficult to predict when the load will peak, resulting in voltage drops and other disturbances like oscillations, and power outages [71]. It also gives the power frequency values, change rate and binary data that are also precise time-stamped and given to the PDC. The data measured from various locations are tagged with time stamps by GPS and sent to the main control unit [67]. It allows high precision time synchronisation which is important as a mismatch in frequency supply and demand of grid[71][77]. The frequency imbalances lead to power outages. PMU's rapid monitoring technology can identify events and patterns in grids, allowing for preventative measures such as blackouts [97]. It has an anti-aliasing filter, an A/D converter, a GPS unit, a PLL oscillator, a microprocessor unit, and a modem transmitter, all of which are linked closely to the Rankine transformer [38]. The analogue current and voltage values from the CT and PT secondary windings are delivered swiftly to the anti-aliasing filter, a low-pass filter that filters out frequencies greater than or equal to half the Nyquist rate[38]. With GPS and a phase locking oscillator, high-speed sampling is achievable. GPS receivers show location and time. Signals are converted from analogue to digital using A/D converters.

Table 6:Functions of PMU [20]

PMU	
Reporting Period	10-60 samples/second
System Observability	Stead and dynamic state
Network Monitoring	HV and MV
Measure Quantities	P, Q,F,PF,3phase I,V phasors
Sensor Accuracy	Amplitude: ±1% Angle: ±1%
Sample Rate	Up to 2880 s/s
Cost Level	High

The aforementioned table shows some of the distinct features and measurement parameter details of the PMU. A distinct amplitude and time signal are present. All current and voltage signals are assessed using DFT by the microprocessor. Consider how regularly and swiftly things happen. Digital information is encoded and decoded by a modem. The modem sends the message. It sent the decoded signal and copied the original digital data. The PMU speaks to the PDC, a client and server, and subsequently to the SCADA system, per IEEEc37.118/IEEE C37.224 [47]. It was designed to detect 2880 60 Hz waves per second[38]. It can detect 2,880 waveforms per second for 60 Hz systems, which is why it was included in the design [38].

4.1.3 SCADA

As discussed in 2.6.3, the SCADA is the main part of the measurement and control strategy. It controls and monitors the field sensor in this above-mentioned design by collecting and processing the real-time time data through the control action RTU [17]. Since the design is based on the ETC and considered SPEN substation based on fed from the Rankine transformer, the proposed SCADA is decentralised and locally distributed. The common system components are RTU, telemetry system, Human Machine Interface (HMI), data acquisition server, and communication server. The RTU supports the control decisions and helps to send appropriate commands.

4.1.3.1 RTU

The RTU also known as the remote telemetry unit in the SCADA system is a microprocessor-integrated electronic device that helps with the communication of field devices and the transfer of remote data [24][111]. The RTU is either a single board or modular type. The modular has a separate CPU(central processing unit) module and plug into like motherboard PC and designed so that additional modules can be added. The inbuilt CPU uses a 16-bit or 32 bits microprocessor memory card capacity of 256 kilobytes(kB) [18].In this distribution network system, IEDs and wireless sensors are communicated with communication media as ethernet mainly instead of the RS485 communication protocol. The ethernet(IEEE 802.3) [19], a bus network broadcasting on the same medium is the most commonly used communication protocol and latest than TIA/EIA-485 or RS485 [63], physical layer standard. Unlike multidrop in RS-485, ethernet has one-to-one connection features collision detection mechainism[20]. Also, ethernet uses isolated transformers cut down the common mode interference and experience fewer signal losses even though it is more expensive than other communication protocols [21].

4.1.3.2 User Interface

A component of equipment that requires human-machine interaction and communication, such as SCADA and PMU systems, is the user interface, sometimes referred to as the human-machine interface (HMI) [66]. The HMI includes the display screens that show the trend, history, alarm data, keyboard and mouse. It is important to meet user expectations and the effective functioning of the distribution network. In this design also, the user interfaces are proposed instead of one centralised user control to enhance reliability and effectiveness. It also helps to work with one system file without affecting any other part of the system. The communication protocol between SCADA software and User Interface is such as distributed network protocol (DNP) and Modbus TCP/IP [63]. In this design, the combination of SCADA and PMU is proposed for getting more precise and fast measurements. Some of the differences between these has shown in below Table 7.

Table 7:Diffrences between PMU and SCADA [66][106]

PMU	**SCADA**
Digital, analogue and Phasor measurement	Analogue measurement
A sampling rate of 2-4 times per cycle	Resolution at 60 samples per cycle
Data update once in 20 ms	2-10 s (slow)
Time taggered data	Latency and Skew
Responds to system steady & dynamic behaviour	Responds to system static behaviour
Oscillation Monitoring	Small signal stability
Wide Area Monitoring Control	Local Area Monitoring Control
Suitable for modern technologies	Depends on Old technology
Dynamic Observability	Steady State Observability

4.1.4 IoT (Internet of Things)

As mentioned above sections, the SCADA systems in a utility help to control, monitor and analyse data in real-time by interacting directly with sensors and other measuring equipment The IoT is an innovative and potentially revolutionary technology that includes sensors[14]. The fundamental weakness of SCADA systems, however, is the absence of monitoring in an active network system. The integration of SCADA systems with IoT improves scalability, interoperability, and security in power systems [14]. Overall measuring the device's effectiveness, and communication accessibility as it interconnects with sensor devices and helps to maintain a real-time record of the distribution network system. IoT technology helps to cut down on operating costs and other costs so that profits can be increased[15]. It enhances the data acquisition that allows for better understanding and extraction of data[14]. One of the major advantages of integrating IoT with SCADA is its cloud assistance. These concepts use large arrays of remote internet reserves and store information in a cloud instead of handling by local computers [14]. The predictive analysis included a detailed report, automation with the power system is the promising factor using the IoT. The design illustrated above shows all the data from sensor devices such as overhead line sensors, energy meters, and PMU fed to the SCADA and other data centres through the IoT. Users' experiences can be mapped to create human-computer interfaces via wireless sensor networks and the Internet of Things (IoT) [57].

4.1.5 Hotspot Temperature Sensor

A hot-spot temperature monitor with a fibre optic sensor determines the temperature of a transformer [58]. The winding's hottest region termed a winding hot spot, is the real limiting factor and key component of the ageing factor of a transformer [60][59]. As the prosumer demand for electricity increasing, heavy spike loads cause the increase in temperature of the transformer [60]. It measures the heavy current flowing in the transformer and measure the parameter temperature gradient and top-oil temperature that helps to detect the temperature constraints. Hot spot temperature is a combination of gradient temperature and top-oil temperature [58]. Direct current losses and eddy losses cause heat generated in the transformer. It can also control the transformer cooling units [58] and gives signals directly to the SCADA through RTU. The Rankine transformer hotspot continuously monitors, allowing it to function safely close to the critical temperature. The hot-spot temperature monitor at least includes a mechanical dial indicator, oil temperature sensor, CT, and single-chip microcomputer [58].

This is more dependable and cost-effective than the fail-safe mode which is the best suitable for an ANM sensor strategy. Fibre optic sensors improved winding temperature measurement and help to get fast readings of temperature fluctuation during peak load effect 59]. The available optic fibre optic probe is evaluated to an accuracy of ±1.0°C over a temperature range of -20°C to 150°C [60]. The instantaneous winding hot-spot temperature enables the flexible asset to withstand overload and reverse power flow [59].

4.1.6 Overhead Line sensor

The capturing and processing of power line data can be done using line sensors [61]. It is an IP-addressable sensor implemented on the multiple nodes of the power grid. In this design, four-line sensors are demonstrated for the measurement of line rating. The connected sensors transmit the data including technical and economic for analysis and reduce the network constraints. It uses the advanced fault detection algorithm to sense faults in real-time. New line sensors are included in the cloud function which has been demonstrated in this design which sends all data to the RTU and from there IoT and finally to the SCADA. The power collecting reduces battery maintenance and sensor solar panel cleaning [62]. The network of line sensors also fault indicators are essential for detecting the fault precisely [61]. This reduces the need for line crews, patrol time and outage duration to perform the system checks [62]. Its measurement parameter includes the current, conduct temperature, and voltage characteristics [62]. This can also sense the direction of the current that captures the waveform data useful in the disturbances caused by the penetration of DER.

4.1.7 Smart Energy Meter

An Energy meter is used for measuring the power consumption in a system [20]. In this design, it is proposed a smart meter which can monitor and measure real-time energy consumption. It also reduces emissions, has a better output, and is cost-effective [20]. Smart energy meters are wireless networks [110] that are helpful for easy installation. The measured data can be stored and can be easily monitored daily, some of the mobile app settings are available to see the updates on the market and prosumer side. In this design, the data from the energy meter is transferred through the RTU and data acquisition has taken inside the SCADA. The communication hub [110] that sends data to the SCADA is IoT based cloud-based network.

4.1.8 Wind Power Conditioning Monitoring System (CMS)

Wind power (CMS) is a decentralised automatic monitoring system that detects faults in a wind turbine [49][53]. Its main application is the detailed diagnosis of various parts of the wind turbine. In the above-illustrated design, the conditioning monitoring is being implemented on both wind turbines. One of the wind turbines with a capacity of 12 kW is already an existing one [19]. The other wind turbine recommended in the future is with 800kW capacity. From [45], the wind speed around the area of the ETC building is 6.8 m/s. Since suggesting a big turbine for the future, the condition must monitor precisely. This also gives detailed information to curtail the constraints in the ANM concept. The possible applications using this condition monitoring system are finding the wear, breaking in teeth of a gearbox inside the turbine and finding out the displacement, and eccentricity of toothed wheels. And finds winding damage, overheating and rotor asymmetric of the generator network coupling systems. Diagnosing tower vibration gives system performance, crack information, fatigue, and environmental influence on the system. Inside the rotor, the damages caused by the lightning strike can be analysed. It can differentiate false alarms [49][53]. Apart from this, blade adjustment error, fatigue and crack formation on the rotor is evaluated using a conditioning monitoring system. The crack formation, fatigue, and wear of bearing and shafts are also applications in this system. In all these applications, the main advantage is frequency analysis using the Fast Fourier Transformation (FFT) method and evaluation gives permanent protection to the wind turbine. Finally, the maintenance message in the form of digital alarm signals or data transfers directly to the locally distributed SCADA through RTU. It can monitor while in operation without shutting down the entire system [49] which saves costs and effective evaluation. In summary of chapter 4.0, the sensors for measurement, monitoring and controlling in a local ANM of distribution grid level at the ETC case study have been explained in detail. The main sensor measurement units and instrumentation parts of the ANM are CT, PT, SCADA, PMU, IoT, smart energy meter, overhead line sensor, and wind power CMS. Most of the sensors are distributed at the substation transformer location, overhead power line and near the DGs as wind turbine, PV, ESS, and EV charging. The measurement units are then connected to the SCADA through RTU communication and finally to the User Interface to send appropriate commands during network disturbances.

5.0 Discussion of Outcomes, Limitations and Future Works

In this chapter, the discussion of outcomes includes the demand profile and renewable generation profile graphs. These two graphs are compared to knowing the demand and possibilities for future power generation from the flexible assets, how it can be more useful with Energy Storage Sources (ESS) and the role of the flexible market. The energy demand profile is important in knowing the total generation of renewable energy. It helps to ensure the supply of renewable energy and increase its production. The comparison of demand and profile graph is useful to know at which period it can be stored in a storage system and report to the flexibility market. Secondly explains a brief session about limitations in this thesis work and suggests future works as a continuation of this project. Finally, summarise the chapter with a general accomplishment section.

5.1 Demand Profile and Renewable Profile

The demand profile data was obtained from the profile library of Strathclyde University and then selected similar building data to meet the peak capacity of the corresponding five buildings that were powered by the Rankine transformer, with an emphasis on the ETC. The Renewable Ninja programme was used to simulate the renewable profile. According to Weather Energy data in Scotland, 80 per cent of the wind energy generated in the UK is enough to power 4,47 million Scottish homes [79]. Solar PV contributed to 0.2% of electricity consumption in the UK according to a 2015 report. Nevertheless, aims to contribute a total of 7 % according to the 2050 net zero carbon target the UK government. The ETC has two renewable generation units at present. From ETC data, a small wind turbine with a capacity of 12 kW and 10 kW capacity Solar Photovoltaic (PV) based on assumptions exist in the ETC generation unit. Two types of graphs are illustrated as result outcomes. For a better understanding of the total power needed from the generations units as RES, the graphs demonstrate by considering a peak day winter season and a peak day in the summer season. Since summer in the UK starts between June and August, most of the data has been collected from August whilst winter days are chosen from November to February. However, most of the peak demand shows during January, the data has been taken to illustrate the demand and renewable profile during this month.

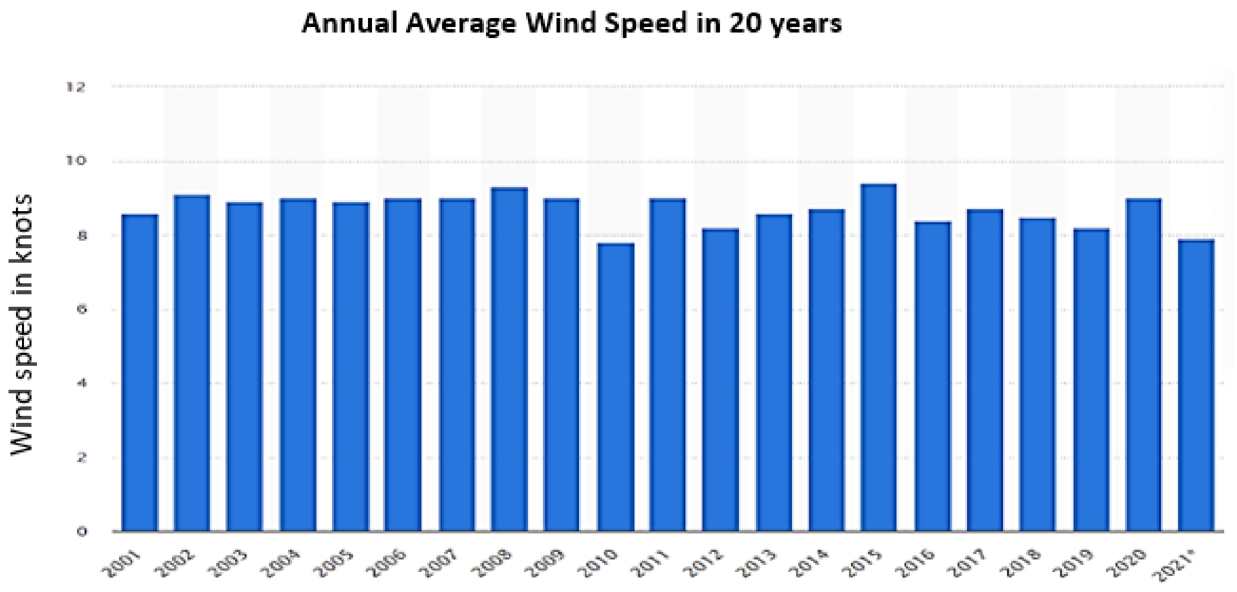

Figure 15:Figure 15-Annual average wind speed (2011-2021) [1]

In the above-illustrated graph, the average wind speed shows 7.9 knots (4.06 m/s) in the UK. Scotland is the windiest part of the UK due to the eastward-moving Atlantic depressions. Considering the ETC building location exists with 55.75°N,4.16 °W. The data has been downloaded from [45] based on location and evaluated the average speed of wind in the ETC building region is 6.8 m/s. The current production of power from generation units is not enough to meet the demand of the ETC building itself, although it has the potential to generate more renewable generation.

5.1.1 Before Improvements

5.1.1.1 A Summer Day Demand and Renewable Profile at ETC Building

The ETC building has two generation units such as a small wind turbine and solar PV as mentioned before. The solar PV consists of 40 cells [77] from the google earth map and the current capacity assumption from ETC data is 10 kW. The wind turbine capacity is assumed as 12 kW. Since the Rankine transfer is fed to the five different buildings, the ETC energy pool can produce more energy by penetrating much more efficient RES. From the above graph, the peak demand during a winter day is half of the demand during winter approximately 47 kW around 9.00 am. Due to the lack of data available, the demand has been considered from the profile library of the university Strathclyde and evaluated the building electricity consumption that likes the ETC.

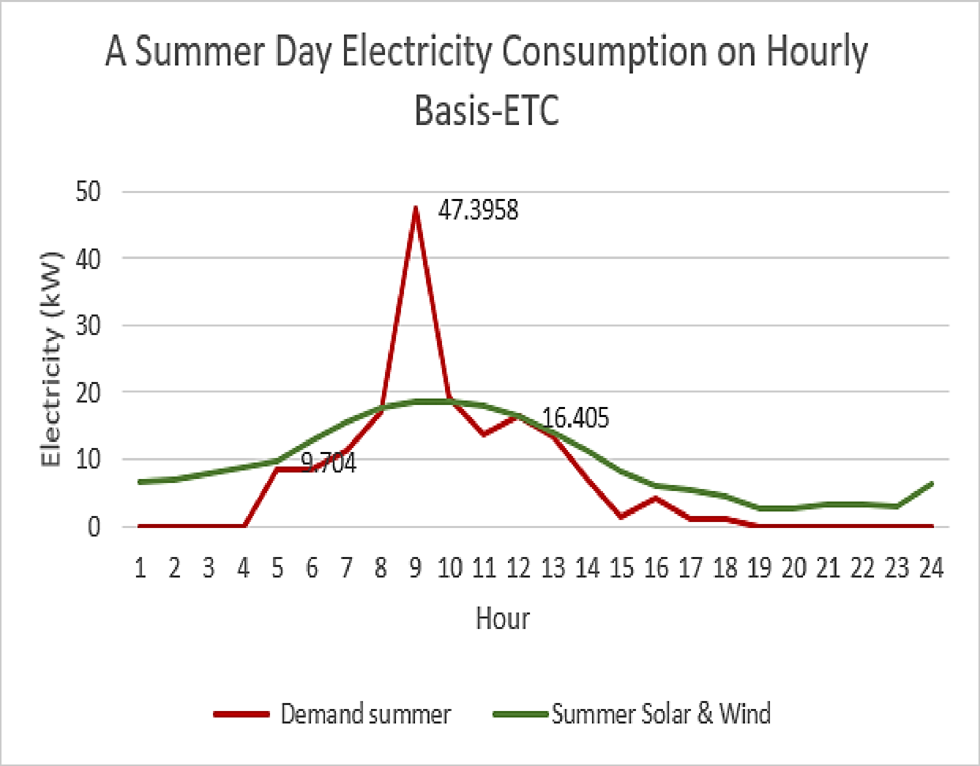

Figure 16:Summer Day Demand & Renewable Profile

During workdays, more consumption will be day time when the office starts. The graph demonstrates renewable generation as the sum of both wind and PV. Even though the electricity demand is lower in the summer than in the winter, ETC's RES cannot keep up with the demand. The maximum renewable generation capacity is only about 18 kW. The demand only can meet by taking electricity from the grid. Figure 16 shows the total generation of electricity from wind and solar that plot with the demand profile of the ETC building. The demand peak is 47 kW during the winter season. However, the current power output from renewables cannot meet the ETC demand. The demand is currently met by depending on the grid power. In a day, the renewable output of 16 kW can meet the demand during noon time. The demand load peak during the daytime and the renewable output is constant during this time.

5.1.1.2 A Winter Day Demand and Renewable Profile at ETC Building

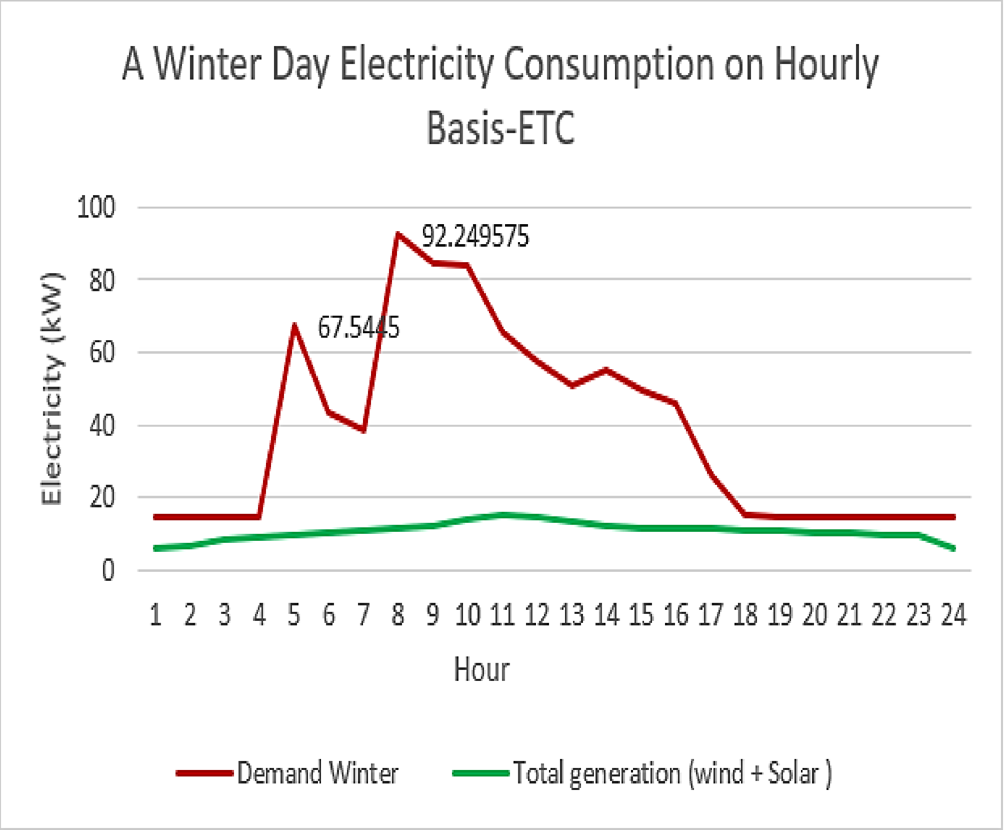

Figure 17:Figure 17: A Winter Day Demand & Renewable Profile

The above-demonstrated graph shows the electricity consumption on a winter day. The day from January month has been chosen to illustrate and compare the demand profile with the renewable profile. The demand at a peak of around 92 kW is during the winter season. The demand is peak during working time as same as a summer day. However as mentioned in the previous figure, the renewable profile is low compared to the summer season. The PV power is lower due to fewer sunny days. With this effect, the generation output unit and 10 kW PV can only give approximately one or less than one-kilowatt power output. Since Scotland is a windy country, the output from wind does not affect more and output is higher than in the summertime.

5.1.2 After Improvements

5.1.2.1 Photovoltaic with a capacity of 500 kW

From the below graphs before improvement, the current generation units of ETC buildings cannot meet the demand most of the time. The current solar panel consists of forty cells that can be increased to 60 cells on one side of the roof. Available 60 cells vary from power. Assuming the 60 cells with 250 kW capacity on one side of the roof as a suggestion. It gives a total 500 kW capacity by considering a total of 120 cell solar cells PV system by the entire roof system.

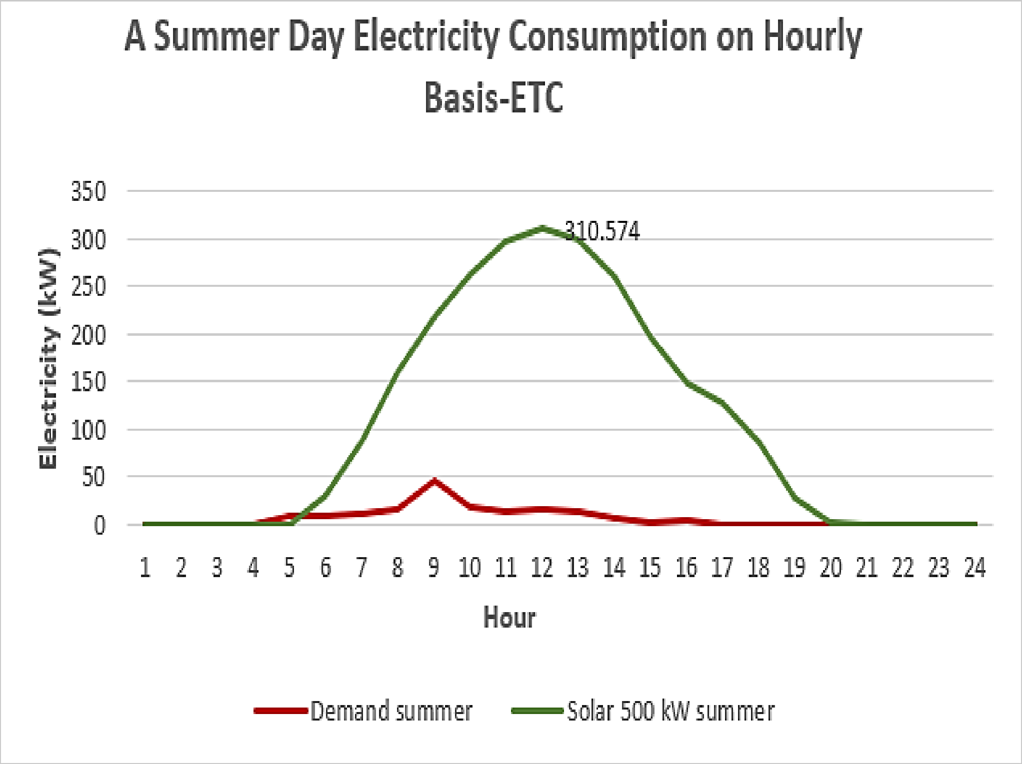

Figure 18:Summer Day Demand and Renewable profile after improvement (PV)

Assuming the system loss fraction is null, and the azimuth angle is around 170 ° from the renewable ninja simulation software, the tilt angle is calculated as 4 ° from the given latitude (55.75°N,4.16 °) of the ETC building from google earth.

$$Equation\ 1\quad Tilt\ angle = Latitude * 0.87 + 3.1 \qquad [13]$$

Even though the total capacity of PV is taken as 500 kW, the power output will around 300 kW due to some of the factors affecting generation including its intermittent behaviour. In this situation, the ANM concept can be used with the principle of LIFO. This concept was introduced for getting maximum output from flexible assets such as wind and PV. The above graph depicts the peak power output from the renewable profile as around 300 kW. During summer days, the demand is exceptionally low for the ETC building that shows excess power generation and uses by storing in an ESS or exporting to the market with good control of a G100 device as mentioned in the proposed design of local ANM. However, this graph only shows solar power generation for a better understanding of power production capacity.

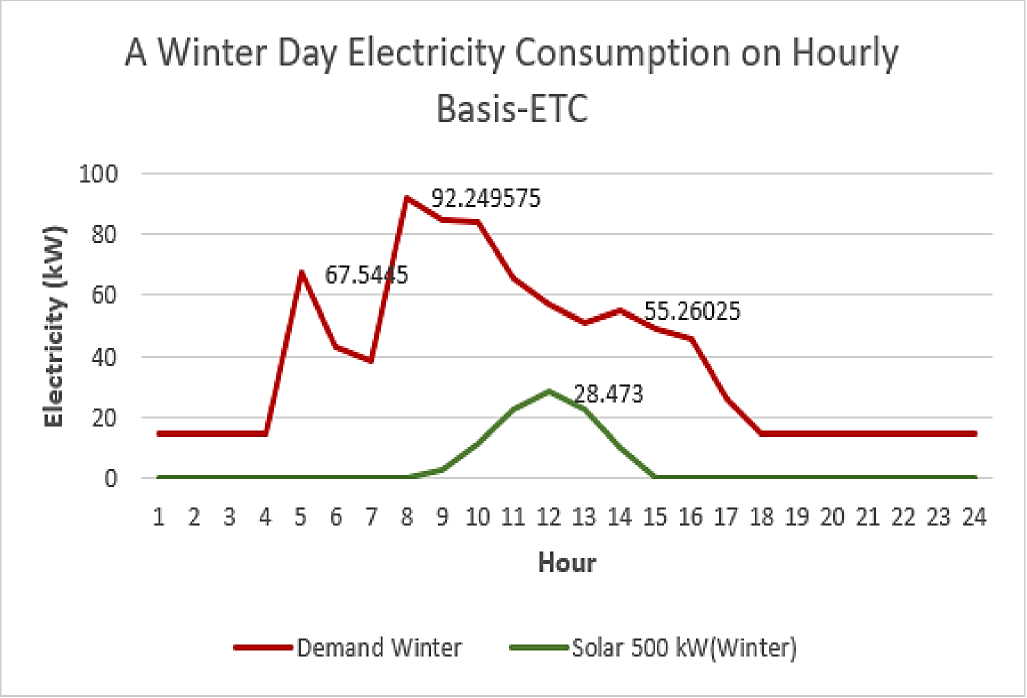

Figure 19:Winter day Demand and Renewable profile after improvement (PV)

This above-illustrated graph also shows the generation of PV during the winter season. Unfortunately, PV output will be less during the season. Even though the demand for ETC building can meet by PV generation during summer days, which is not possible on winter days. This graph shows how much power can contribute from PV only as same as Figure 18. The PV output can only meet 30 % of the total electricity consumption of the building. These PV variations can be actively monitored using suitable sensor measuring devices as discussed in chapter 3. During summer days, the sunny day will last up to 10.00 pm and can be used effectively. The power can be stored using an ESS and fixing an electric vehicle charging station can use the power from this during peak generation of power from PV systems. As the ETC report limit scheme is 200 kVA mentioned in ETC, the power can only be sold to the flexibility grid market under this limit. But this is possible during summer days when demand is low. On other days, this power can also utilize by other buildings that are fed from the

Rankine transformer such as NERC, SUERC, Technotos and Torus building. Considering the demand for these buildings including ETC, the demand goes beyond 800 kW where higher wind turbines need to be used.

5.1.2.2 Wind Turbine with a capacity of 800 kW

An operational wind turbine with a capacity of 12 kW has been installed at the ETC. However, to meet the demand of the capacity with this small wind turbine is not enough. The below graph is obtained from the simulation of renewable ninja software. These two graphs are the annual electricity consumption every month. Figure 20 shows the output when 12 kW capacity is used whereas Figure 21 shows the output of 800 kW capacity. Even though both graphs illustrate the output uniformly throughout the year, May, August, and October generations are less and the maximum is during the winter months and June also shows the maximum output. The total mean capacity factor is 41.9 % for the 800 kW wind turbine [77].

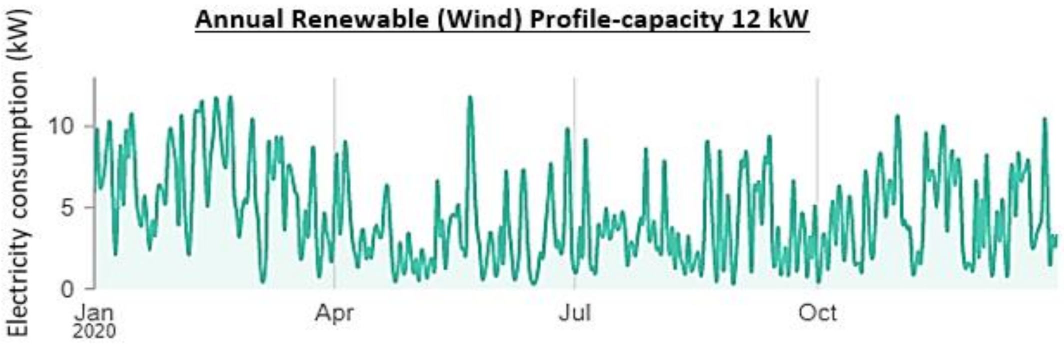

Figure 20: Simulation Result of Wind Turbine (12 kW)

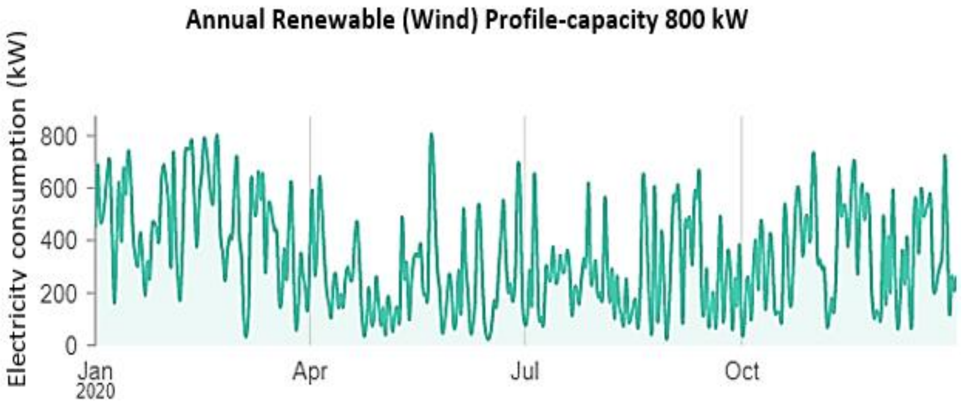

Figure 21:Simulation Result of Wind Turbine (800 kW)

The below illustrates graph figure 22 shows the demand response of ETC with 800 kW wind turbine output. Installing large wind turbines can easily meet the demand. However, ETC is interested in acting as an energy pool and delivering power from their generation unit to other buildings. If the demand is less than the supply, the power can export to the energy flexibility market or be stored in the battery storage system. This graph only shows how much power produces by a wind turbine on a summer day.

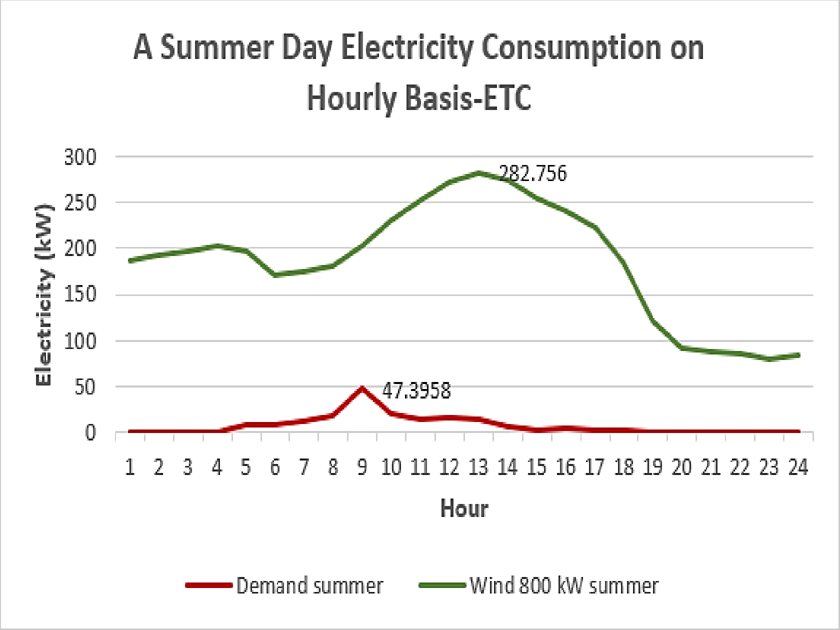

Figure 22:Summer Day Demand and Renewable profile after improvement (Wind)

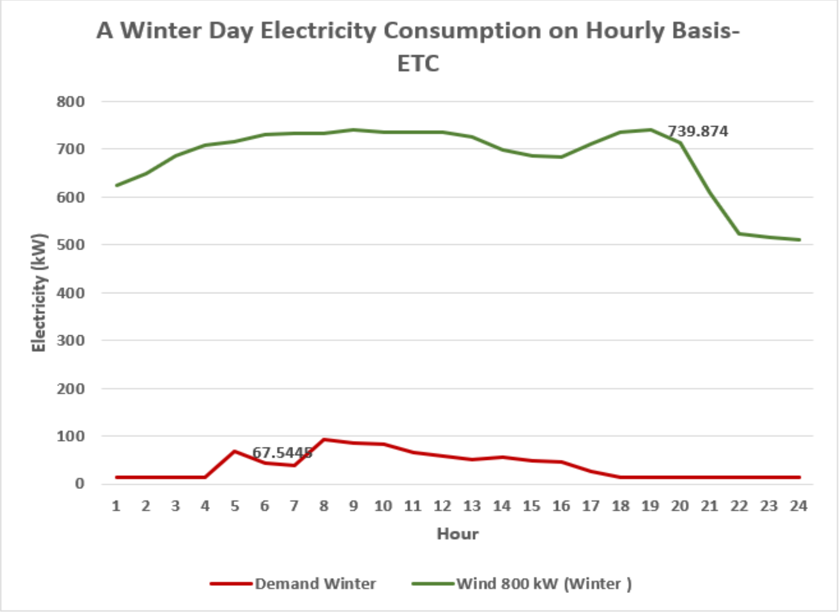

Figure 23:Winter Day Demand and Renewable profile after improvement (Wind)

The above-mentioned figure 23 shows the combined profile of demand and renewable source wind after installing 800 kW. Since Scotland is a windy country and 6.8 m/s wind speed at ETC, the generation from the turbine is maximum during winter days. The electricity consumption is high around morning and almost other times the demand is in the range of 50 and 60 kW. During the night-time, the renewable power output reaches more than 700 kW, and the demand is 10 kW to the graph. Thus, it can be stored in a battery storage system. However, this graph only shows the wind output, and ETC demand. Later the graph analyses more buildings that feed from the Rankine transformer.

5.1.2.3 Total Generation (PV and Wind Turbine)

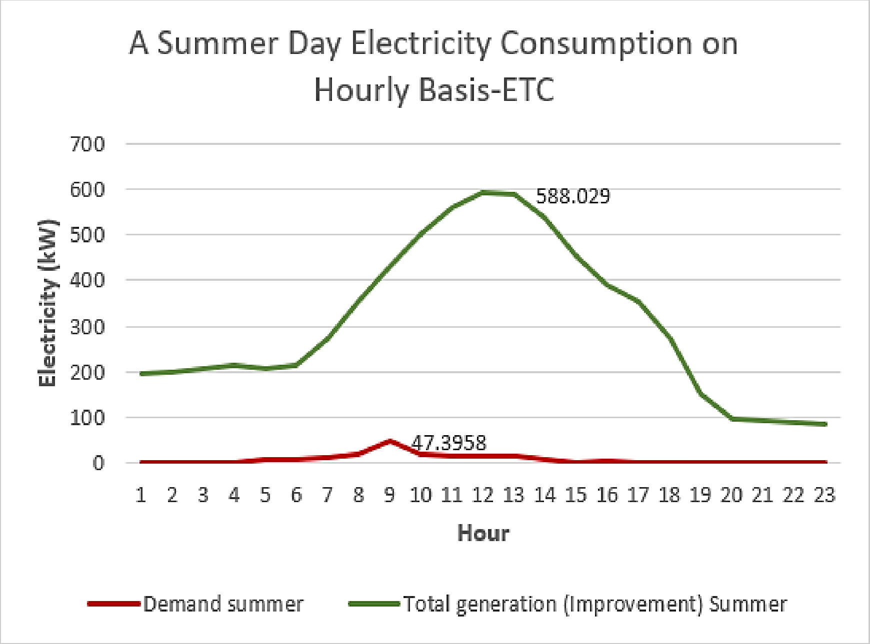

Figure 24:Summer Day Demand and Renewable profile after improvement (Total Generation)

The above graph shows the total output from the generation of the 800 kW, 12 kW wind turbine and 500 kW solar PV. As the average wind speed near ETC is 6.8 /s, the total power generation is high. Figure 24 shows the comparison of the demand profile with the renewable profile during a summer day as renewable production is more from wind than PV systems, and the output from renewable generation is maximum during 3 pm at around588 kW. Despite this, the smallest possible output from the overall generator meets double the level of demand for ETC.

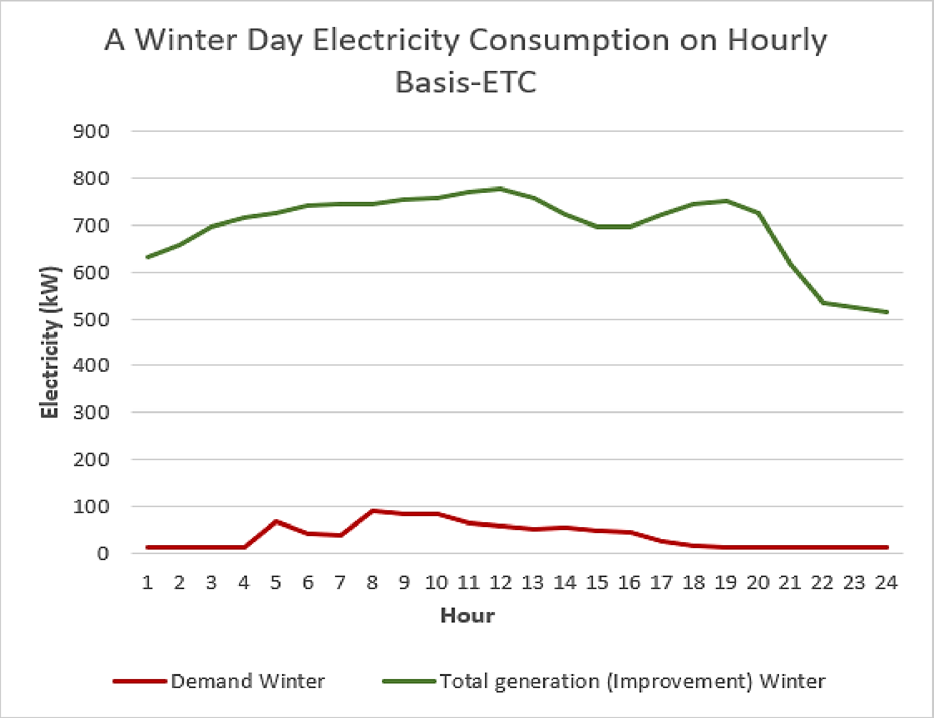

Figure 25:Winter Day Demand and Renewable profile after improvement (Total Generation)

The above graph is also like the summer day demand profile. The only difference is the generation output is constant and gets a maximum of 800 kW at least one hour a day. The wind is more during the winter season around 776.663 kW and this helps to get the maximum output from the wind turbine and is useful for meeting the demand and distributing the unused power.

5.1.2.4 ETC and Torus Building

The Torus Building and ETC building are remarkably close and less than 200 m by assumptions from google earth. The Torus Building, ETC building relate to a physical wire. Assumed the physical wire connection helps to get the power from the generation unit of ETC to meet the Torus building demand. The peak demand for the Torus building is 225 kW. The below two graphs illustrate the generation that can meet the two building ETC, and Torus demands during a summer day as well as a winter day. As mentioned earlier the demand during summer days is lesser than on winter days. This shows the combined demand is half the value of the demand for winter. The winter day and summer day renewable power generation is differ by 150 kW approximately . The winter day maximum renewable generation is 744 kW whereas the summer day peak renewable is around 600 kW. The total generation shows the combined wind and solar power . Thus the wind power output is always giving near to the total capacity in both season unlike PV.

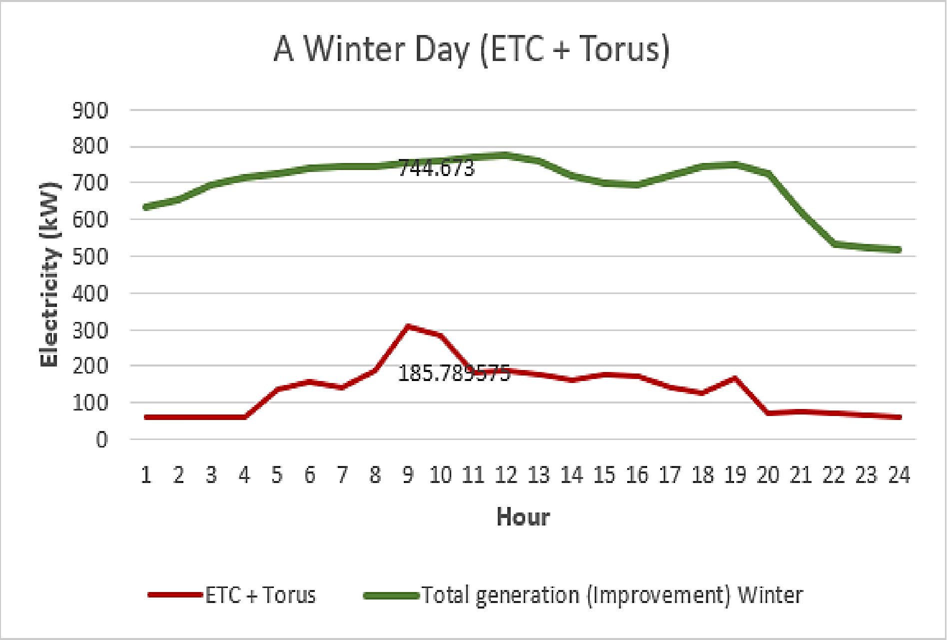

Figure 26:Winter Day Demand and Renewable profile (ETC+Torus)

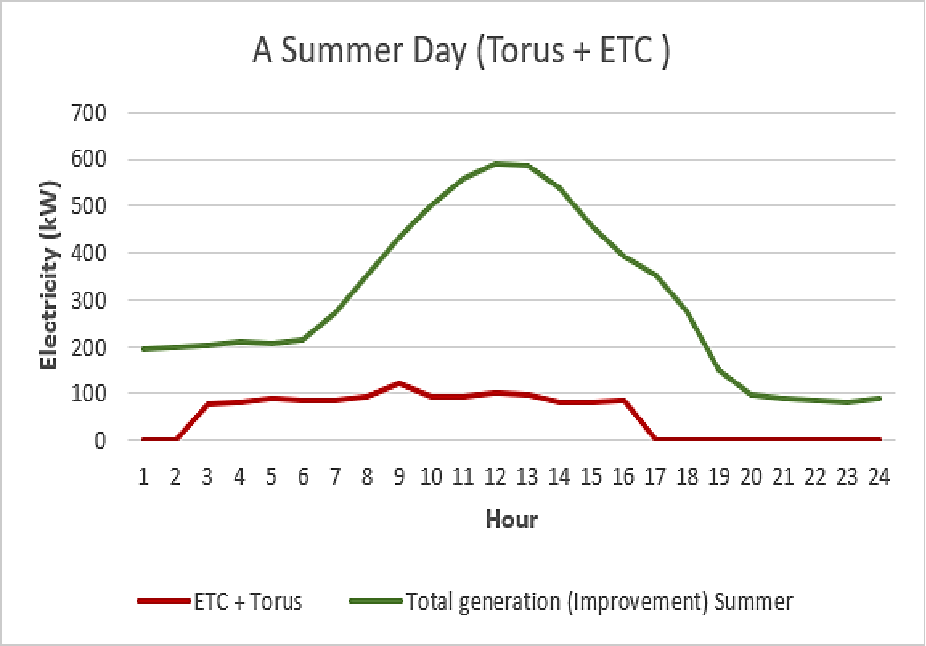

Figure 27:Summer Day Demand and Renewable profile (ETC+Torus)

The summer peak joint demand is 122 kW, and the winter peak demand is approximately 310 kW. The demand is maximum during the starting time of the office. The early morning and night time demands are minimum and the generated power can be transferred to the energy storage system after exporting to the flexible market.

5.1.2.5 Combined Demand of ETC, Torus, NERC, SUERC and Technotots and Renewable Profile

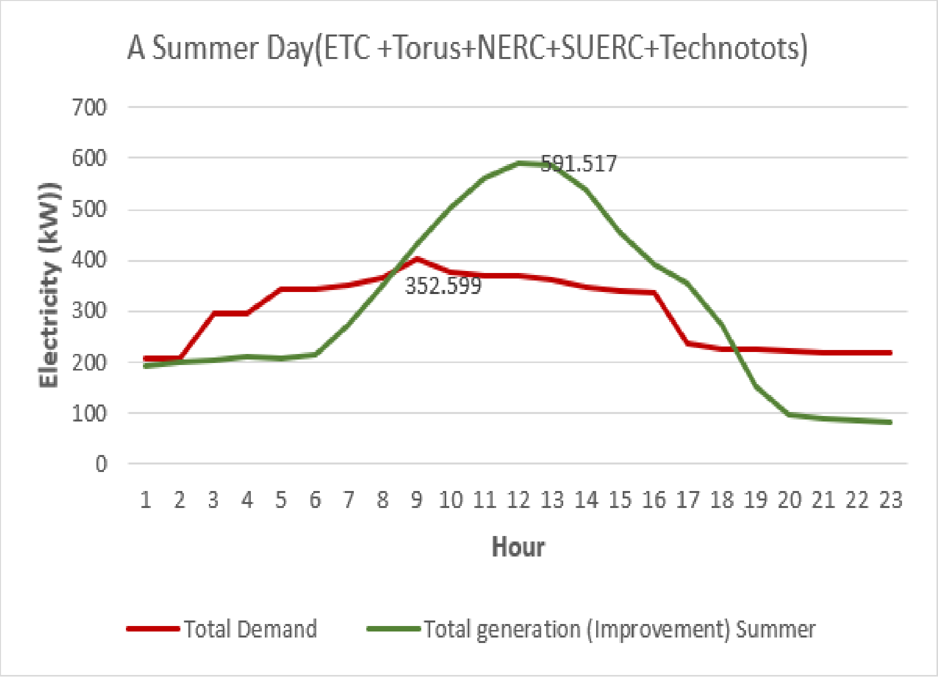

Figure 28:A Summer Day Total Demand and Renewable Profile

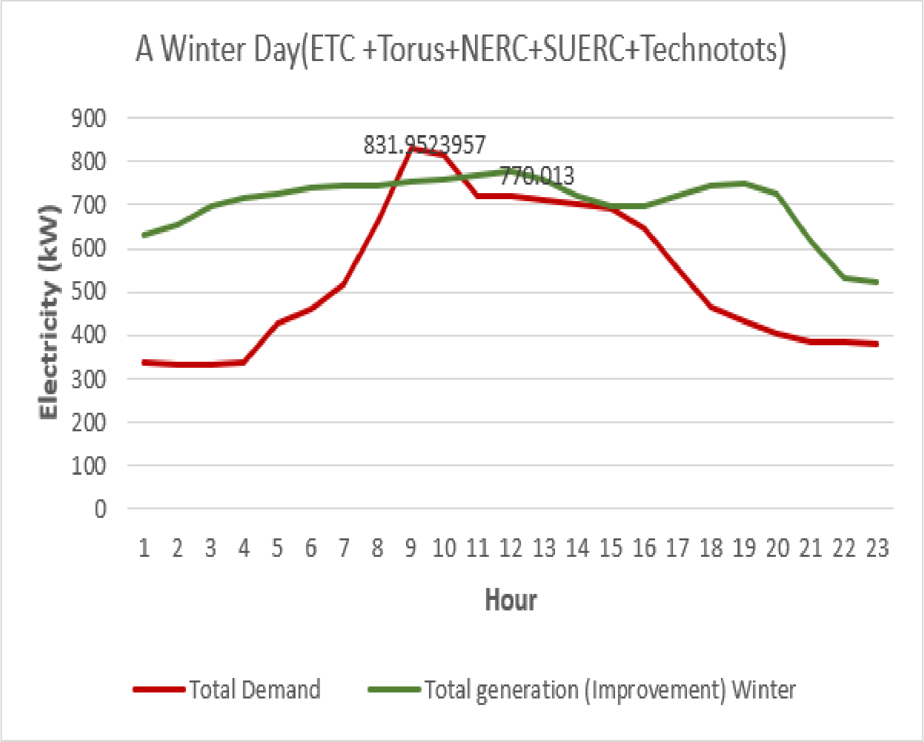

Figure 29:A Summer Day Total Demand and Renewable Profile

The above-mentioned graphs demonstrate the demand profile of buildings ETC, Torus, NERC, SUERC and Technotots with improved generation profiles. The total generation from RES includes 500 kW PV, 800 kW wind turbine and 12 kW small existing wind turbine. The Technotots building is 68 m and SUERC 100 m far from the ETC building [77]. Currently, the Torus building is only connected with the ETC building through a physical wire. However, in future, if all buildings can relate to a virtual wire, the demand of all buildings would have to be met by the power from the generation unit without taking from the grid. The combined maximum demand for summer is 352.6 kW. This can be easily taken from the power of the generation unit of ETC. If every building that is fed from the Rankine transformer connects with the ETC energy pool, the buying expenses of power from the grid will reduce and it can export the remaining power back to the utility market.

Figure 28 shows maximum power from the renewables is 591.51 kW. This time the demand is only around 300 kW whereas considering the export limit, the excess power can sell to the market directly. Apart from this, the implementation of an electric vehicle charging station helps to increase to sell the power directly to the customers. The prosumers will get more benefits from the DER, and it can be used effectively. Figure 29 illustrates the demand during a winter day. Considering a winter day, the maximum electricity produced from renewable energy is 776.6 kW. However, at some point, it shows the maximum demand reaches 831.95 kW which cannot meet by the total generation. This can be solved by taking power from the energy storage system and utilising that during this time. All other times, the power production from the DER of the ETC can meet the demand of all other buildings if they are interconnected. During the night-time, the generation power is 750 kW. The demand during this time is 200 kW less than the renewable profile. This can easily save and use later according to the need. Because of this, the PV and two wind turbines can generate around 600 kW of electricity early in the morning from about 12.00 to 4.00 am. These future possibilities show the capability of the ETC energy pool to meet the demand by its own distributed RES. The graphs illustrate either PV or wind energy is not maximum all the time due to its intermittent behaviour and power disturbances. The SIES 2023 project suggests developments in existing VPP for getting maximum output and the ANM concept can mitigate the network constraints. The instrumentation plays a significant role in measuring the parameters which can monitor and control to either curtail the generator output or other convenient action to mitigate this disturbance.

5.1.3 Limitations

The thesis focuses mostly on the design of the Energy Technology Centre’s distribution network system. Having erected a wind turbine and a photovoltaic (PV) solar panel, ETC can produce a modest amount of electricity. The current export limit is 200 kVA, resulting in network restrictions, particularly voltage limits. SIES 2022 (Smart Integrated Energy Systems) is a project that focuses on low-carbon energy systems that can host and use a substantial amount of RES. Due to a lack of time to do detailed research on the whole project, just the ETC energy pool was investigated for this thesis. Even though the Myreshill facility is an energy pool, the instrumentation design relies on the measurement technique developed specifically for the ETC. Even though the project proposes the benefits of PMU, it has limitations such as lack of observability. The overall power consumption of a building may be determined with the aid of its demand profile. Comparing the demand profile with the renewable profile identifies the potential for greater renewable resource production and how it may be used to meet the building's energy needs. Due to the limited data on the daily power use of the ETC building, the data on daily electricity consumption has been collected from the University of Strathclyde's profile library. The data evaluated for the ETC, NERC, SUERC, Torus, and Technotos was derived from the need for comparable structures. In line with this, the data are inconsistent and inaccurate. By using the renewable ninja software, the coordinates of the place replicate the nearest area of the renewable energy profile. Because this software can not specify ETC coordinates specifically. These are the major difficulties faced during the thesis work.

5.1.4 Future Works

The purpose of the thesis was to study and create a comprehensive instrumentation strategy using ANM at ETC. The dissertation has been successfully finished in terms of designing the local ANM proposal in distribution networks. The thesis also investigated the planning and analysing of the demand profile and renewable profile to determine the future potential for more flexible assets in distribution networks. Nevertheless, the SIES 2023 project has a stake in two energy pools, namely the Myreshill site and the ETC. Considering the time required to work on this thesis, only the ETC energy pool has a comprehensive design. In the future, the sensor and measurement method may be examined and created for the Myreshill location, and pragmatic modelling of SETP can reveal more opportunities. This will contribute to the success of the SIES,2023 project. Insufficient data for displaying the demand profile may be evaluated more accurately with real data in the future. The thesis works need not do more study on the SETP. Future development may consider the potential of constructing additional loads of up to 1.5 MVA at SETP, which is close to the ETC energy pool and thus convenient for connecting the electrical points and using the power from ETC's renewables by installing its control equipment at ETC.

This thesis' sensor measurement, monitoring, and control section focused mostly on IoT-based sensors and PMU. In the future, however, a more sophisticated form of IoT, such as Narrowband (NB-IoT), a wireless sensor with a low-power area network will be able to analyse and provide recommendations. Some of the IED-based smart sensors evaluated with the IEEE 34-bus system can sense short-circuit fault and 80 per cent improvement according to [99]. The current sensor based on GMR also gives more precise measurements [101]. In future, the lack of observability issue can be studied further and suggest a fast-tracking method [103] for PMU. Distribution-level PMU (D-PMU) is advanced and fast dependable [104]. Advanced PMUs, such as the µ-PMU, with an accuracy of angle ±0.01% and amplitude of ±0.05%, might recommend as more cost-effective. The µ-PMU can measure and transmit 120 samples every period, which is twice as many as the PMU [20]. Even though the G100 device illustrates and explain in the previous section, a more detailed study can be considered in future research. To get maximum output from the flexible asset, network restrictions like the voltage, fault, and thermal must be mitigated. The notion of ANM is effective in avoiding thermal restrictions. Based on this, the instruments and sensor technology used in this thesis are more geared toward mitigating thermal constraints. Voltage and fault restrictions are being studied, as well as how to oversee this ANM. In the future, it may be possible to design the instrumentation portion of the distribution network to alleviate three restrictions and implement a more accurate measurement technique to extract the greatest amount of energy from flexible assets. Future studies will also consider a cluster description model for modelling electrical networks and developing a decentralised smart grid to ensure system stability.

5.1.5 General Accomplishments

Considering these results, investigated the limitations and the future possibility of this project. After a detailed review, the design process has been taken by considering a few steps. For the detailed design, the parameters were identified, data collected, and sketched the design. During sketching the architecture, evaluated, revised, and improved the design in each stage. The design has been illustrated by showing the future recommendations of integrating more low carbon technologies at the distribution level of ETC with an ANM controller for achieving maximum output from the integrated flexible assets. This thesis uses an instrumentation strategy in an ANM concept that is also aimed at mitigating network constraints. PMUs can directly detect voltage and current phase values, but SCADA systems use measurements of voltage, active and reactive power, network characteristics, and a reference angle to calculate voltage angles. The suggested schematic model implements PMU with an existing SCADA system. The implementation of an export restricting technique known as G100 as shown in the model to restrict the flow of electricity backwards from the generators. The discussion and results of the comparison of demand profile with renewable profile demonstrated the possibility of more generation of renewable resources. The ESS implementation can store the power when the demand is less than the supply and an Electric vehicle charging station can also use this power.

Due to insufficient data, the suggested instrumentation architecture for the distribution network and demand profile has limitations. For instance, the demand profile graph is depicted by comparing buildings with comparable peak demand. In addition, the notion of active network management is uncommon and not familiar to most technical experts. The mitigation of faults and voltage restrictions using the ANM idea by delaying reinforcement is still under investigation. Although the PMU is one of the most accurate instruments for measuring parameters, it is expensive. The advanced µ-PMU is cost-effective and efficient that PMU can consider in future design at the distribution level. The µ-PMU is an upgraded version of the present PMU, but SCADA is a generic control system architecture, not particular sensors, or measurement units. The fusion of both SCADA and PMU can enhance precision, be effective in an ANM proposal design, and improves the power system estimation. To ensure system stability, future studies will also consider a cluster description model to model electrical networks. The possibilities of the power generated from the DER of the ETC energy pool distributed and used in other buildings such as Torus, NERC, SUERC, and Technotots are also analysed in this thesis work. The ESS can be useful to store the excess power from the flexible assets and prosumers will get direct control by selling to the flexible energy market as Piclo. Future research on the instrumentation of the Myreshill site energy pool is required for the completion of the SIES 2023 project.

6.0 Conclusion

Overall, the thesis work has been completed successfully. Flexible assets in distribution networks can help the UK government to attain net-zero emissions by 2050. The major revelation of this study is to accomplish the goals of network capacity reinforcement deferral and constraint management in distribution networks with a detailed design of instrumentation in an ANM. In this project, one of the energy pools, the ETC energy pool used as a case study. After a detailed literature review, presented a thorough design of the distribution grid level, the sensor and measurement approach of ETC.

The future design has shown 800 kW wind turbine and 500 kW PV implementation at the ETC energy pool. The combined demand of the five buildings is approximately 800 kW which can meet by adding these big wind turbines apart from the existing small 12 kW capacity wind turbine. Throughout the discussion of the sensor measurement technique, both smart sensors and the phasor measurement unit were suggested. It also introduced the G100 an export limiting scheme to control the power flow. It is concluded that PMUs generate synchro phasors concerning a phase angle. Synchro phasors give high-speed and coherent data that cannot be possible with traditional SCADA. The proposed detailed design of sensor, measurement and monitor strategy of distribution networks at ETC helps to investigate and install better instruments for precise measurement, which aids the ANM concept in VPP in obtaining full power output from flexible assets. The additional storage such as battery storage, and thermal storage can help to store excess generation from the flexible assets. Thus, exporting surplus energy can be beneficial to prosumers since it can help them lower their expenses and provide them greater flexibility. The ESS focuses on building a green energy system and employing renewable energy to reduce non-renewable resource dependency and achieve net-zero carbon. Participating in a flexible market like Piclo, where energy export and import are based on supply and demand, may cut costs, and increase advantages to prosumers. Finally, the total capacity based on the generic demand profile and the renewable profile has been analysed. Comparing the demand profile with the renewable profile identifies the potential for greater renewable resource production and how it may be used to meet the building's energy needs. Using the demand profile and renewable profile, experts may estimate how much capacity there will be for more flexible assets in the distribution networks of the future. Integration of DER in distribution networks increases the involvement of prosumers in the utility market and using ANM is an intriguing idea for the realm of distribution to mitigate the network constraints.

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