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Virtual Power Plant Concepts for Ancillary Market – Demonstration, Development, and Validation

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FOREWORD

The journey of my life started thirty years back. I was a six-pound baby by birth and doctors said that it was a difficult delivery. Thus, my struggle in life started with my birth. I was a versatile person even in my childhood. I was good in sports and perfect in my studies. I was the captain of the Cricket and Football team of my school. I still have consecutive medals that I received in all the years of my school.

Not only sports, I used to be part of most of the social events held in my school. I remember the stage play when I was in Fifth standard, and I played the role of Quaid-e-Azam. I performed it so well that my friends started calling me “Baba”. The clapping of audience when I finished and received the award gave me encouragement of being a key part of our society.

Life gets boring without troubles. My life became more interesting when I was in my Eighth standard. My family suffered a great financial loss, and it was after a year that I started to hear comments from my family about my changing of school. It was decided to make me discontinue with my O Levels due to the extreme conditions. I really wanted to acquire quality education. I was filled with motivation, and that time my social circle helped me. I came to know about the tuition academies, giving chance to teenagers to earn money for their studies. I joined one and started taking tuitions. This made my dream of acquiring better education came true.

My dreams in College life added something new. Research is that dream, and it is only the term that I realized at that time, because the interest to investigate was in my instinct since my childhood. Breaking things like Television Remotes and examining the circuitry involved inside was one of my hobbies when I was small. This interest pushed me towards the field of Engineering and specifically the ECE Department. During my Undergraduate, I have been awarded the Bhaimia Scholarship for my BE studies. I have also received award prizes for 3 years for being amongst the top three (CGPA 4.0) in the department.

Combining my dreams and my personality summarizes me as a person, who thinks, discusses, investigates and spreads. My talent and academic experience helps me in thinking and investigating issues, specifically related to my field. My social exposure and personality helps me in discussion and communication, and finally sorting out the problems related to the investigation. By nature, I like to share my knowledge, feelings and experience with others. This is the reason why I am the member of many societies like IEEE, IEEE PES, ICAPM, IEEE IAS, and Facebook bloc. Sometimes I share my opinions orally. Most of the times, I express my views via writing. I was the chief editor of the magazine of my department during Undergraduate. My research paper was also published during early stage at Undergraduate, which is an example of my passion towards research and spreading my knowledge to others.

Fulbright Scholarship provided me the platform for fulfilling my dream of “Research”. I was admitted into NCSU ECE Department. Then, it was the time to perform and to do something what I have been waiting for a long time. My 4.0/4.0 CGPA in the first semester at MS level boomed my confidence, and gave me courage to contact professors in the field of “Power System”. I started working for the FREEDM Systems Center, and was overwhelmed with the research going on in the areas of Smart Grid and Power System. This motivated me a lot, and I decided to devote myself in learning and experiencing the field of Power System.

Thus, I took many of the Power System Courses: Power System Operation and Control (A+), Power System Stability and Control (A), Communication and SCADA Systems for Smart Grid (A+), Smart Electric Power Distribution Systems (AU), Renewable Electric Energy Systems (A+), Power System Switchgear and Protection (A), and Power Electronics (Fall-2015). 4.0/4.0 CGPA at MS makes me more motivated and confident.

My passion brought to me to Italy as a Marie Curie scholar, as a technical specialist expert at a multinational company Enel, and as a researcher at University of Genova. Not only that, I was the part of MEAN4SG consortium – which included the researchers and collaborators from the best universities, research centers and companies of the world.

Now I believe:

“**The backbone of success is passion – hard work, luck and platform are just additives**”

I summarize my PhD phase in Italy with these lines:

“**My life, my journey, and in my intermediate destinations,**
A premature baby to engineer to scholar – all with passion,
My life, my goals, and for my future destinations,
A scholar to living fantasy of Italian communication, research and fashion”

To conclude, I am now a 170-pound man but my struggle continues. The difference is that the struggle, which was started for my life, is now a struggle for my passion and my work.

Disclaimer: The thesis comprises of the material published as part of publications mentioned in Appendix C (publications during PhD).

ABSTRACT

The increased penetration of distributed energy resources and renewables open up issues in power systems as a whole. Chapter 1 discusses these issues, and highlights the literature solutions. The concept of VPP is highlighted, different options are explored, and the use of VPP is motivated. The chapter further discusses different ancillary services, with both technical and market perspectives. It makes a clear demarcation amongst transmission and distribution level VPPs, and their economic and technical aspects. Different components within VPP are also highlighted in this chapter.

The models of VPP, based on SGAM, are presented in Chapter 2, with detailed test cases. The models characterize VPP as an aggregator at TSO, VPP as DER-Aggregator/DERMS at DSO-DMS, and VPP as business case for flexibility to DSO-DMS. It includes the VPP actors, their characteristics, and a compact architecture based on SGAM. It further splits VPP participants in different software: MATLAB/Simulink, DIgSILENT, and LabVIEW for defined test cases. These are further elaborated in detail in the next chapters, and all are discussed with respect to regulatory, technical, and economic aspects.

Chapter 3 co-simulates VPP-DERMS (Distributed Energy Resource Management System as a Virtual Power Plant) based customers' DR through LabVIEW. It develops interface to customers' meters for reactive power visibility, and then develops a HMI and recording tool at VPP controller. The performance of the tool is analyzed in the chapter, which is in fact the modeling of Modbus based customers' interaction for reactive power.

Chapter 4 co-simulates effects of DER on a distribution grid in DIgSILENT. A distribution grid is modelled in DIgSILENT, and then DERs are added to the network. Node voltages and line loading are analyzed in the absence and presence of unplanned DERs. Then the network is seen from two perspectives – flexibility that can be provided to TSO with STATCOM at transmission node, and flexibility that can be provided to DSO with planned DGs at distribution node.

Chapter 5 co-simulates storage model in MATLAB/Simulink. It starts with the techno-economic analysis of potential storage systems, and then to realize the storage model for simulation. The model of selected storage system is implemented in MATLAB/Simulink, and then a explicit service test case is developed within VPP-aggregator to analyze the flexibility margin by storage. Next step is the integration of these co-simulators within different service platform levels.

The objective of Chapter 6 is to develop an interface amongst co-simulators to simulate the VPP chain. At first step, the co-simulators are realized within tags: wind farm tags are created in DIgSILENT, customers' based tags are built in LabVIEW, and storage tags are located inside MATLAB/Simulink. Then communication amongst the co-interfaces is done by the development of Matrikon OPC server and explorer platform. The master platform is implemented in LabVIEW-RT tool.

Then test cases are defined for the validation of platform, which is performed in Chapter 7. Chapter 7 is dedicated to the validation of the formulated VPPs – DERMS, business VPP, and aggregator. DERMS based model is validated within DIgSILENT, by using a portion of the Italian distribution grid. Aggregator based model is validated within DIgSILENT, by using the IEEE 9 bus transmission test model. Business VPP model is validated using IEC 61850 compliant feature of DIgSILENT for the same distribution grid in a translational manner.

The validated VPP is used as an application for power system reliability, which is presented in Chapter 8. It describes the conventional schemes for power system protection, and the issues with DER penetration. It then models a VPP, and verifies its functionality for power system protection.

Chapter 9 concludes the thesis. The thesis comprises of the material published as part of publications mentioned in Appendix C (publications during PhD).

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LIST OF ABBREVIATIONS

AE - Alarm and Events
AGC - Automatic Generation Control
ATM - Asynchronous Transfer Mode
AVR - Automatic Voltage Regulator
CAPEX - Capital Expense
CCGT - Combined Cycle Gas Turbines
DA - Data Access
DER - Distributed Energy Resource
DERMS - Distributed Energy Resource management System
DFIG - Doubly Fed Induction Generators
DG - Distributed Generator
DGS - DIgSILENT Interface for GIS and SCADA
DMS - Distribution Management System
DNO - Distribution Network Operator
DR - Demand Response
DSO - Distribution System Operator
EMS - Energy Management System
EU - European Union
FCR - Frequency Containment Reserve
FERC - Federal Energy Regulatory Commission
FFR - Fast Frequency Response
GIS - Geographic Information System
HDA - Historical Data Access
HMI - Human-Machine Interface
IDMT - Inverse Definite Minimum Time
IED - Intelligent Electronic Device
IP - Internet Protocol
ISO - Independent System Operator
KPI - Key Performance Indicators
LAN - Local Area Network
LV - Low Voltage
LVRT - Low Voltage Ride Through
MPPT - Maximum Power Point Tracking
MV - Medium Voltage
OLTC - On Load Tap Changer
OPC - OLE: Object Linking and Embedding for Process Control
OPEX - Operating Expense
PHIL - Power Hardware in the Loop
POI - Point of Interconnection

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PSS - Power System Stabilizer
PU - Per Unit
RT - Real Time
RTDS – Real time Digital Simulator
RTU - Remote Terminal Unit
SCADA - Supervisory Control and Data Acquisition
SGAM - Smart Grid Architecture Model
SLD - Single Line Diagram
SoC - State of charge
SONET - Synchronous Optical Network
STATCOM - Static Synchronous Compensator
SVC - Synchronous Voltage Condensers
TCP - Transmission Control Protocol
TDMS - Technical Data Management Streaming
TSO - Transmission System Operator
VPP - Virtual Power Plant
WAN - Wide Area Network

Disclaimer: The thesis comprises of the material published as part of publications mentioned in Appendix C (publications during PhD).

Chapter 1: INTRODUCTION

1.1 Evolution in Power Grid

Power system is structured into four blocks: generation, transmission, distribution, and last stage customers. The generators at generating end produce electricity, which goes through transmission system, which is liable to distribute it to distribution grid in the best possible manner. At distribution level, which is designed in radial configuration, electricity is distributed to further end-users. These end-users are real customers in conventional grid, as they are neither producers nor enterprisers. However, the scenario is changing in the modern grid. The structure is seen in Figure 1, which is conventional, and prone to changes.

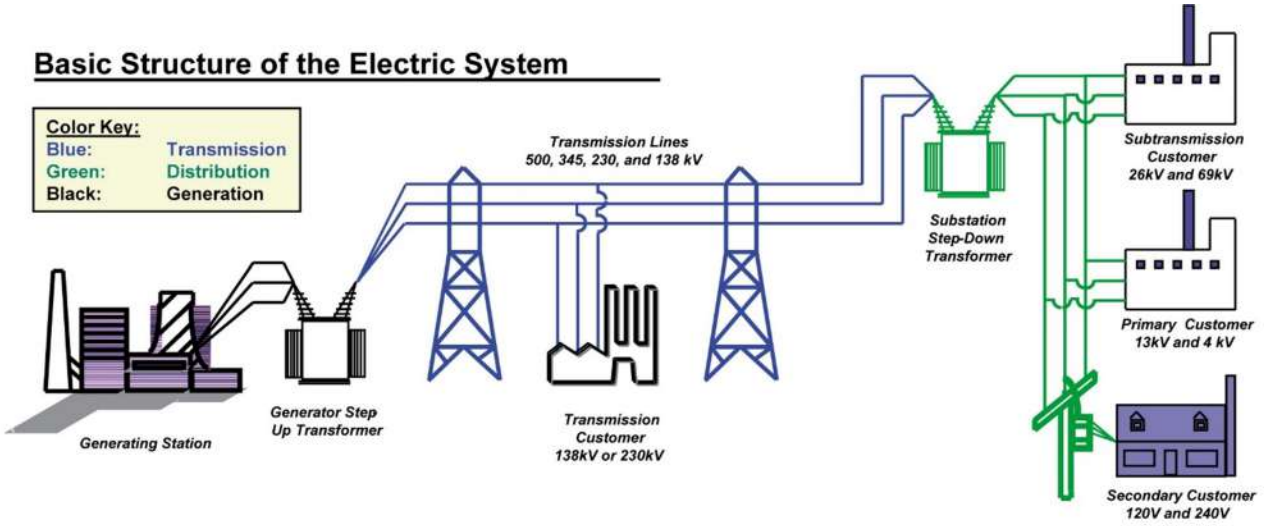

Figure 1: Conventional Power System Structure (from [1])

The changes in modern grid arise from the two major agendas of utility authorities: 1- clean supply of energy, i.e. reduction of CO_2 emissions, and 2- increase the supply, i.e. the efficiency. This motivates the employment of renewable energy resources (predominantly wind and solar), which gives rise to two extensive impediments: 1- These resources are intermittent in nature, and therefore system operators face challenges 2- These resources, when added at the customer level, have reduced visibility to distribution system operators. Keeping in mind that the distribution grid is not designed to incorporate such challenges, the operators and the existing infrastructure are not competent to tackle these add-on variables. These additions create issues on power system reliability, and security, and appeals for the improvements in power grid management.

In the light of addition of these distributed resources at the distribution grid, the overall structure can be viewed in two blocks: 1- G-T-D (Generation-Transmission-Distribution) block, which comprises of interrelated entities, controlled by their respective operators 2- Customer block, which is in fact the turning point for the modern grid. Customer block is affecting G-T-D block, and this requires changes in the current grid infrastructure but is difficult and expensive. Other option is effective communication amongst different system operators, and an effective control of DERs in the grid, and hence the concept of “Smart grid”.

1.2 Towards Smart Management of Grid: Smart Grid

The smarter grid is the one that can handle renewables and distributed energy resources in the best possible way. As the share of renewable energy resources is increasing every year, as [2] mentions that the production mix for renewable vs non-renewable energy production reaches up to 40-60% in Germany in 2018. Reference [3] demonstrates the drastic increase in renewable generation in Italy, around 0.8% in one year from 2018 to 2019, and around 13% in comparison to 2012. It comprises wind, solar, geothermal, hydro, and bio energy based resources. Furthermore, there is a huge investment plan in renewables by developed countries, such as France [4] where the investments are planned for wind and photovoltaic plants in contrary to their conventional nuclear power.

The same trend is followed in USA where the percentage of renewables is around 17% in 2018 [5]. This large diffusion of renewables appeals for a smart distribution management grid. The ultimate goal is to achieve a distribution grid standing on four design pillars of cost, integration, flexibility, and reliability. The design is achievable through techniques like smart meters, better protection system, advanced DMS, and storage. In a compact manner, the smarter the grid implies the broader the involved participants, and the communications amongst them. The smart grid concept complies with SGAM, with involved actors to fit in one of the defined layers as in Figure 2.

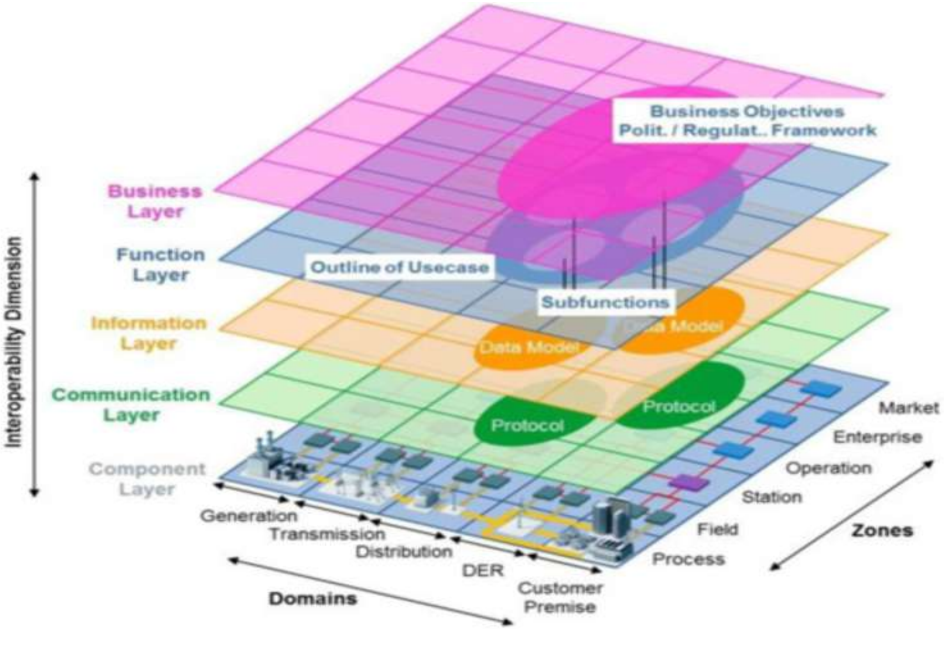

Figure 2: Smart Grid Architecture Model (SGAM) (from [6])

The involved actors should complete the basic cycle from device manufacturer (example: synchronous generators) to customers (example: households); covering the intermediate power plants, system operators, and communication handlers. The chain ensures maximum visibility throughout the power grid, but requires protocols (both network and system levels) and regulations to be followed which varies from grid to grid. The point of innovation is the way these actors are integrated and managed, and one of the techniques is the use of VPP.

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1.3 Virtual Power Plant: Motivation, State of the Art, and Market Mechanism

The concept of VPP is a derived one: it includes the perspective of system operators, stakeholders, and the private third party entities, emerges from micro-grids to mini-grids family and then on a large scale, and aggregates potential participants which were previously either dispersed or not aggregated on a single platform for a medium scale service. Reference [7] defines VPP as the interconnecting point for renewables, storage, and prosumers, with intelligence and control. Reference [8] defines VPP as a power plant, which is operated by loads, storage, and distributed energy resources via EMS. The VPP communication can be central to all the participants, and can be distributed depending on applications. Literature discusses VPP and its applications in a broad manner.

The way VPP aggregator can manage different participants in service market with scheduling is highlighted in [9], and the results are validated for congestion management scenario. Power system based communication standards like IEC 61850 are proposed for VPP business scale integration, as in [10-12], from the point of view of flexibility. Different components within VPP are designed: reference [13] discusses demand response model (without the need to forecast demand), reference [14] presents a flexible demand response method (utilizing prediction), and reference [15] identifies electric vehicle based VPP in coalition with wind generation system.

For a wind-thermal mix generation, a pricing control is presented using VPP model in China [16]. The applications in energy and reserve markets are presented in [17, 23-24], economic dispatch in [18], a test case based on Greek day ahead market is validated in [19], and frequency reserve service in [20]. Another ancillary service to manage voltage loading on a distribution system is explained and examined, on a Greece test system, using VPP in [25]. Literature covers the aspects of TSO-DSO interaction via VPP, as in [21] where a Brixton based VPP is used as an application model. [22] It demonstrates a VPP system on a protection-based test case utilizing the VPP enhanced feature of TSO-DSO interaction. There exists a wide variety of practical implementation of VPP in different countries of the world.

ENERCOC-Enel is a practical VPP in USA, which has the capacity of 157 MW [26-27]. Energy Pool is another VPP aggregator provider in major European countries, i.e. UK, Netherlands, and France etc. A demonstration of their industrial customers' aggregation for frequency restoration service is highlighted in [28]. Another VPP provider is Next Kraftwerke, which aggregates industrial and large-scale customers through storage and distributed renewable assets [29]. It plays the role in most of the European countries, including Germany, France, Belgium, Italy etc. REstore is another DR based aggregator for VPP, which uses Internet of Things in its controller to get a reduced polling interval [30]. It is prevalent in capacity and reserve markets in UK, France, and Germany etc.

1.4 Demand Response: Level 1 Aggregation Mechanism for DMS

DMS manages the distribution grid to check if there are no over generation or congestion scenarios, to design efficient protection system for the grid, and to take effective measures in case of faults or maintenance in the grid. Integration of renewables and distributed energy resources is a challenge for DMS. The resources need to be in a large quantity to qualify as parameter for load flow. This requires balance of production and consumption – a key challenge for the DMS. Therefore, for the aggregation of these intermittent resources, two important requirements are to forecast their production and to create reserves for them. This gives rise to the concepts of demand response, and aggregators [31].

The concept and definition of VPP vary from region to region, and function to function. The technical entity is sometimes referred to as DER aggregator, and as DERMS. DERMS is the extended DMS for the control of distribution system. It can incorporate VPP, DSO, or both (and it will be discussed in the later chapters). There is another perspective of market, which can also be incorporated inside this extended DMS, and a bit of this part is elaborated in this work. The idea is supported in Figure 3, with demarcations between the technical and business features of VPP.

1.5 Storage System: Reserves Market and Aggregation Platform

With the peculiarities of DR, and the need for demand-generation balance, the future solution is the use of energy storage systems. The storage mechanism classifies the specific type of storage technology, for example batteries in case of electrochemical storage. Different types of electrochemical batteries are Lead Acid, Lithium Ion, Nickel Metal Hydride, etc. [33]. Weight, energy density, power density, efficiency, and economics are the points for distinctions. Another electrochemical medium of storage is the fuel cell, which operates with different variations as storage medium, example hydrogen [34]. However, their response time and costs are high in addition to their physical size requirements [35].

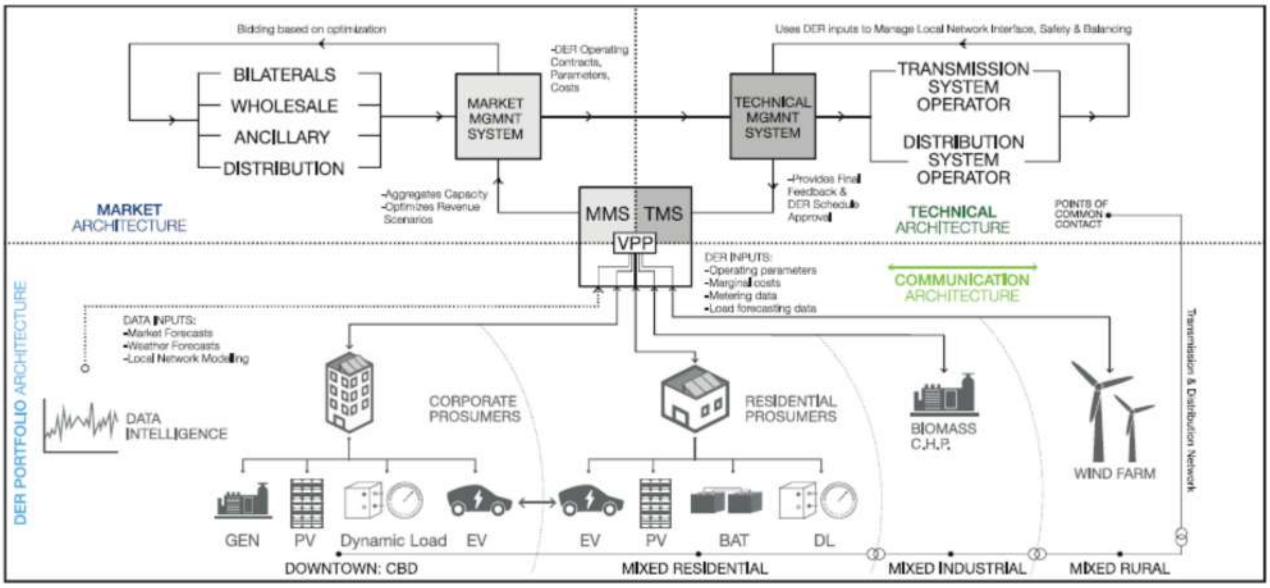

Figure 3: VPP Techno-economic Distinction: DERMS vs Business Model (from [32])

Another storage medium is Pumped Hydro, which exists in developed countries like USA, which can provide up to 3GW, 24 GW-h, at 80% efficiency [36]. However, the Pumped Hydro method is suitable for large scale generating end due to their high power capacity with long discharge duration [37]. As a result, they are prevalent in electricity markets and at generation-end sectors [38-40].

Another potential storage system, which is under discussion to be adapted as a commercially mature entity, is the flywheel energy storage. A practical implementation is demonstrated in [41] for a shipboard, a microgrid, power system used with flywheel technology. Another example is presented in [42], where flywheel is used to store wind power together with network integration. Reference [43] suggests its use for frequency restoration services with the advantage of having low energy density. Apart from the technical characteristics, the sizing and location of storage system is another key parameter to ensure higher efficiency and reliability [44]. To prove the point, WECC standard test model is validated in [45] where storage devices are optimally located and sized to reduce CAPEX and OPEX. In result, storage is now a key business in energy arbitrage, a strong candidate in energy market and ancillary service market [46-48].

1.6 Ancillary Service: Technical Perspective

The role of VPP is to provide flexibility to service operators in terms of ancillary services, i.e. distribution network does not have to depend on DSO for all the service needs, and it has the tendency to resolve local issues before it goes to DSO. This objective motivates the needs to understand the major ancillary services, their technicalities, and the associated mechanism through VPP. From [49], ancillary services are required to ensure reliable operation of power grid. From the point of view of USA, FERC defines ancillary services as the treatments for making the transmission of electricity as smooth as possible [50]. From the point of view of European market model, ancillary services are ornamental for balancing and congestion management through voltage and frequency balances [51]. Therefore, the objective of this work is to ensure voltage and frequency to be within acceptable limits at distribution levels, without disruption to the supply of power. This indicates three services as basis for the test cases: voltage support, frequency support, and power system protection. This includes the basic service of frequency restoration, the additional service of voltage regulation, and the consequential service of power system reliability, i.e. covers the overall spectrum of ancillary services.

Voltage support is required to ensure distribution grid voltage to be within 0.9 – 1.1 per-unit, the conventional MV limits. Reactive power management is the conventional technique to ensure voltage support in a distribution system. Conceptually, capacitive and inductive effects are the two counter mechanisms that inject and extract reactive power from the system. System tends to operate at a specific power factor, and thus tackling this lopsidedness is the objective for this service provider. This disproportion occurs due to four basic reasons: inductive/capacitive ramification of transmission lines, inductive and fluctuating essence of demand, load shedding, and maintenance/failures.

In a conventional system, there are three types of voltage control. The first one is the primary control that occurs at the generating end, automatic in nature, and is provided by AVR. In order to improve further the security of some target nodes, secondary voltage control is used. This automatic voltage control is used in countries like France, Italy etc. The tertiary control is the additional one without automatic provision. However, they are identified as base level and additional voltage services in Europe. Not all the European countries provide the advanced support, like Italy where even the base level service is not remunerated.

Frequency support is required to maintain the grid at a particular frequency, for stable operation. This frequency control is managed by the flow of real power in the grid, and hence the control starts at the power plants. The governor at turbine provides the basic frequency control (primary), i.e. the control referred to as the governor. For large frequency deviations and for better control, AGC is used which is referred to as the secondary control. The integrator influences this control – PID based integrator control - that manages the frequency to adjust the reference/feedback real power. The same control can be provided by real power reserves.

Reactive power management is one of the imperative ancillary services provided by TSO. This reactive power imbalance mainly occurs at transmission levels, and TSO pays generators for managing reactive power. DSO, DER, and DG cannot take part in this provision to TSO due to regulations, specifically in Italy.

The chapter discusses the needs for reactive power management, and comparison of different existing compensation techniques. It talks about the regulatory restrictions, and some proposals for changes, for participation in ancillary market. The chapter then discusses about the use of DER as an aggregated virtual power plant to serve as reactive power compensation technique.

Reactive power exists in AC circuits when voltage and current are not in phase due to inductive or capacitive effects. These effects can be on generation, transmission, and distribution sides of power system. For inductor, voltage leads current, and the reverse is true for capacitor [52]. Thus, the direction of power is reverse for both, and as a convention, it is considered that capacitors produce reactive power, while inductors consume it. For voltage stability, reactive power generation should be equal to reactive power consumption.

Reactive power imbalance can have adverse effects on power systems. For example, decrease of reactive power for a load causes voltage drop. For real power P, the voltage drop causes current to increase through the load, and this can damage the load. If this voltage drop increases further, generators are tripped to ensure safety, and thus the situation becomes worse (with further voltage drop) [53].

Transmission line is the main cause of reactive power mismatch. It has both inductive and capacitive effects, and therefore it can create both increase and decrease in reactive power while the real power is carried along transmission line [54]. Increase in reactive power will cause voltage rise, while decrease will cause voltage drop along the transmission line.

At the distribution level, this reactive power imbalance will take place because of the inductive nature of the majority of the loads. Variation in demand at load side is another parameter for the reactive power effect. Increase in demand causes increase in inductive reactive power at distribution end (or additional reactive power is consumed at the transmission level). Decrease in demand causes increase in capacitive reactive power at distribution end (or additional reactive power is generated at the transmission level).Thus, the voltage stability is at stake at the distribution end too. Failure of generators and transmission lines can increase the demand further, and the above-mentioned effects can take place again.

TSO and DSO play their roles to control this reactive power mismatch. Particularly in Italy, TSO remunerates generators for reactive power provision. Other than that, there may be some penalty charges for DSO or customers for creating additional reactive power mismatch.

At the distribution level, the minor variations in voltage are dealt with VOLT/VAR control (also called as Distribution System Voltage Control). These minor changes during the daily operations may cause both under and over voltage violations. The technologies are OLTC and capacitor banks. The controller manages the taps of both, and checks for voltage limits at nodes. The reactive power provided here is not at the expense of real power, and the only capital cost is the installation of controllers, capacitors, and OLTC.

At the generation level, the primary voltage control is provided by AVR. It is a controller that regulates the terminal voltage of synchronous generator. However, PSS is also used for further improving stability. These controls are sufficient for reactive power (voltage control) at the generating end of power system.

Therefore, the main problem causer is the transmission level, which requires reactive power compensation techniques. The conventional method is to use synchronous generators (at generation side) for reactive power compensation resulting from reactive power imbalance at transmission level. Conventional power plants have synchronous generators to supply/absorb reactive power. The power capability curve of synchronous generator illustrates that a generator can produce (over-excitation), as well as consume (under-excitation) reactive power at the expense of real power.

However, there are some limitations for these synchronous generators in order to provide reactive power. As synchronous generators are designed to produce real power (not reactive power), therefore the loss of real power due to reactive power production is an undesirable. They utilize a significant portion of real power capability. It is thus clear that it is not very efficient to utilize them for the purpose of reactive power. The real power is limited by the size of turbine, and the reactive power has the limitation of the size of synchronous generator. Therefore, increase in reactive power means more investment in terms of increase in ratings of turbine and synchronous generator. There are also other limitations of rotor winding, stator winding, over-excitation, under-excitation etc.

There are other techniques to relax the reactive power requirements for conventional synchronous generators, and different levels of power system have these techniques in place. One of the static techniques is the use of a combination of switched capacitors. They are a source of reactive power to the system. This method is the cheapest amongst reactive power compensation methods, and there is no loss of real power due to reactive power.

However, the reactive power varies with voltage in a square relation (the capacitor equation), and thus the method is only suited for low and medium voltages. For high voltage applications, and the applications where the voltage is a critical phenomenon (like the trip of voltage relays in power system protection domain), the switched capacitor is not a proper option.

Another technique is the use of synchronous condensers. They are synchronous generators, which serve the purpose of compensation of reactive power only, and not the real power. They consume a little portion of real power to provide reactive power capacity. However, for this dynamic technique, the maintenance and conversion costs are high.

SVC is another technique, employing switched capacitors as a part. Consequently, it still has the same issue of non-linear voltage dependency. Another one is the STATCOM, a dynamic technique, with power electronics current controlled devices, in place of voltage-controlled capacitors, and thus the above-mentioned problem is eliminated. The cost here is higher than switched capacitors, but lower than that of synchronous condensers. There is also no loss of real power due to reactive power.

Wind farms are very common in this modern era. They use asynchronous induction machines to convert wind to electricity. Thus, in order to synchronize with the grid, these wind farm generators use power converters (AC-DC-AC). This AC-DC-AC power conversion can provide independent control of reactive power. Again, the reactive power is not dependent on real power for this dynamic technique. However, in order to maintain a continuous power factor and independent control of reactive power, it is required to oversize the converter by 10% of the generator’s rating [55].

Solar panels are also very common these days. They use MPPT, and inverters to convert solar energy into electricity. These inverters can also be used to provide reactive power control. For this dynamic technique, the reactive power is dependent on real power (loss of real power with the production of reactive power). For oversizing of inverters by 10% of generator's capacity, the system can provide 46% reactive power at 100% real power or 110% reactive power at zero real power [55].

The defined wind farm converters have the limitations of terminal voltage; while inverters have the limitations of terminal voltage, real power produced by PV panels, and current rating for the production of reactive power. Another point of interest is the production of reactive power at zero (or very low) wind and solar energy. Companies have already implemented such converters, and literature suggests the same with capability curves for these technologies. However, it requires keeping the plants grid-connected even at no wind and sun.

As seen from [56], there is capability of producing reactive power at zero real power. P and Q are the real power and reactive power respectively in PU at the POI (with 0.95 power factor, at rated output) with different combinations. However, this reactive power provision is not enough as compared to the imbalances, and therefore cannot fully replace the conventional synchronous generators. The comparison is summarized in Table 1.

Table 1. Reactive Power Compensation Techniques

Source of Reactive Power	CAPEX-OPEX (Capital and Operating Costs)	Amount of Reactive Power Provision	Loss of Real Power Efficiency
Synchronous Generator	Very High - High	High	Very Low
Synchronous Condenser	High - High	High	Very Low
STATCOM	Very High - Low	Medium	High
SVC	Very High - Low	Low	Low
Switched Capacitors	Medium - Very Low	Low	Very Low
Inverters (For Already Installed Renewable Resources – Plants)	Medium - Low	Very Low	Low to Very Low

1.7 Ancillary Service: Market Perspective

There are different market strategies for the procurement of ancillary services, depending on the type of service and the regulations. The basic principle of voltage support is through reactive power balance in the grid, in other words – balanced reactive power ensures voltage control. In general, the service can be provided either by generating units, or through advanced techniques like VPP. For comparison studies, every market case is analyzed with the base case of generator-based support. Market can procure the service through bilateral agreements, bidding strategy, or obliged participation service for generators as in Italy. The remuneration can be for maintaining the service, actual utilization of service, and the activation charges for the service.

According to current Italian regulations, any production unit based on intermittent resources cannot participate to services market. In addition, the production units cannot be from the distribution side of power system. These facts restrict the distributed resources and aggregators to participate to the services market [57-58].

Other European countries like Belgium, France, and UK allow these aggregators for participation into the services market, and therefore Italian regulations allow these aggregators to participate as well from 2018 [59-60]. Italy is divided into six geographical zones; the regulations restrict inter-zonal aggregation, and mixed aggregation (loads and generators together) [57-58]. The restriction of regulations creates hurdle as TSO can only get services from generators, and customers only have the option of interaction with their specific DSO. The idea is to allow TSO to get services from these aggregators, and enable customers to offer their services to any market (energy or service) [61].

Keeping in mind the optimistic change in regulations in future, literature suggests that there should be a single market place for balancing and flexibility. TSO-DSO can interact with each other, and increase the observability of each other for efficient utilization of resources and resolution of congestion management for each other. The proposal leads towards mutual reactive power management, where TSO can ask reactive power control from DSO [61-62]. A possible scheme is also discussed in [63], where aggregators can communicate directly with the DER, and aggregators can participate too directly to ancillary market. As a matter of terminologies, DNO, and ISO are used interchangeably for DSO and TSO respectively. These regulatory and technical aspects formulate the concept of thesis.

1.8 Summary of Thesis

The principle of this thesis is explained as:

"For the reactive power support, the conventional support is provided by power plants. The mismanagement occurs due to varying loads (distribution side) and transmission line effects (transmission side), and the concerned actors are DSO and TSO respectively. The support starts with DSO at their local distribution levels, to TSO, which asks for the provision from power plants. The objective is to analyze how VPP architecture can give flexibility to these actors.

The thesis presents reactive power and real power test cases, and then a DERMS for DSO support, aggregator for TSO support, and flexibility scheme for power plants. The test cases are simulated and validated. The results are scaled to other ancillary services and applications"

The thesis is organized in the following chapters: Chapter 2 proposes architecture for DERMS and business model for VPP large-scale aggregator. It includes the VPP actors, their characteristics, and compact architecture based on SGAM. It also develops test cases for reactive power and real power based on DSO requirements, and the technique is presented to split VPP-DERMS participants in different co-simulation software: MATLAB/Simulink, DIgSILENT, and LabVIEW for reactive power and real power test cases. It also develops a business model for DSO and VPP, which covers the aspects of flexibility. The test cases are also discussed from the aggregator perspective, to analyze TSO scenarios.

Chapter 3, 4, and 5 consider these DERMS based co-simulators one after another. Customers based DR is simulated in chapter 3, using LabVIEW Modbus support. The effects of DER on a distribution grid, and the flexibility loads can provide is elaborated in chapter 4 using DIgSILENT. Chapter 5 models a storage system in MATLAB/Simulink for the FCR based support. Chapter 6 develops the interface for these co-simulators using OPC communication via LabVIEW-RT.

Chapter 7 is divided in to three parts: In part one, the DERMS co-simulator interface in chapter 6 is validated using DIgSILENT, In part two, the aggregator platform for TSO-power plants support from chapter 2, is simulated for a reactive power strategy proposal, and validated on IEEE 9 bus system. In part three, the business level IEC 61850 VPP is validated with a distribution grid in DIgSILENT.

Chapter 8 is used to extend the concept to power system protection application.

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Chapter 2: VPP Models for Ancillary Service - Reactive Power

2.1 VPP Model as an Aggregator at TSO

Chapter 1 leaves impression that DERs are very prevalent, and cause significant impacts on power systems. One of the relevant adverse effects is the reactive power mismatch at distribution level, which makes the grid active. Therefore, VOLT/VAR control is the commonly used technique to counter such issue. However, for taking the transmission line effects, and using the analysis for reactive power compensation techniques in previous chapter, the VPP architecture as an aggregator sitting at TSO level is shown in Figure 4.

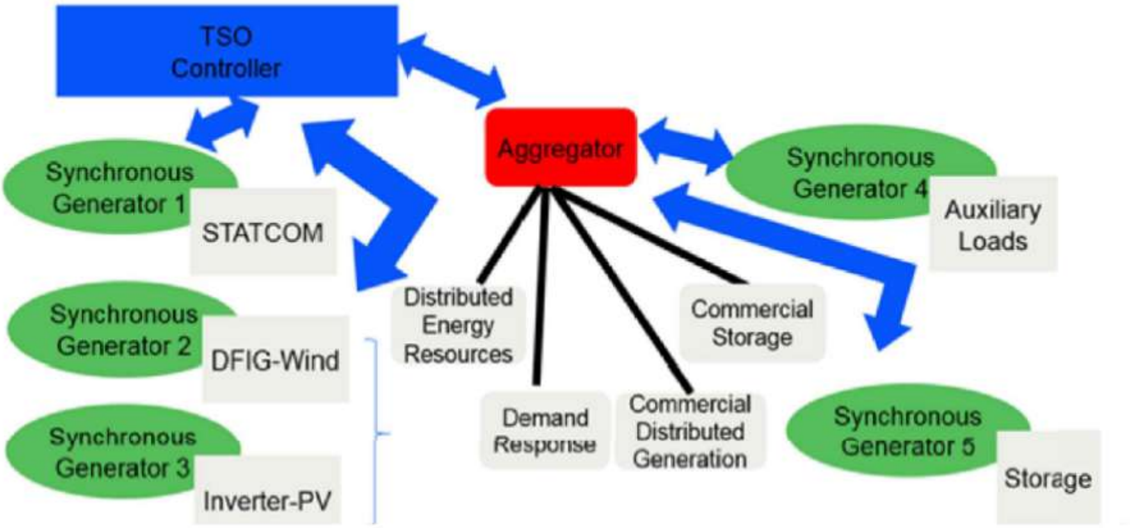

Figure 4: VPP Architecture: Aggregator at TSO Level

The architecture is designed at TSO-power plant interface, in the context of TSO dispatch of reactive power from generators. The scenario gives rise to three options. One is the conventional way of using synchronous generators, together with STATCOMs, for reactive power provision. This combines the benefits of low operating costs (compared with synchronous generators), and no loss of real power for reactive power provision, for conventional generators.

Another way is the use of DFIG based wind plants converters, and solar inverters for reactive power provision, together with synchronous generators. However, as these plants are not designed solely for the purpose of reactive power provision, their capital and operating costs are much lower than the conventional synchronous generators. This combines the benefits of low costs and capability to provide reactive power at zero or very low active power, for conventional generators.

The proposed way is the use of aggregators to participate in the ancillary market provision for TSO, together with the conventional synchronous generators. These aggregators utilize DER and DR at customer end, together with DG, and storage at commercial levels. In fact, the aggregator can generate or consume VAR from generators as auxiliary load (double peaked power plants), and/or storage. This gives relaxation to conventional generators by utilizing the resources at distribution end (and other third party, or generators) by interacting directly with TSO.

TSO in the proposed approach has the opportunity to get reactive power from conventional synchronous generators, with the utilization of STATCOM, DFIG based converters, PV inverters, and aggregators. The controller at TSO can decide the provision of services based on cost, availability, and offered flexibility.

Another way of interpretation of this approach is the improvement in the conventional technique of reactive power provision through conventional coal and combined cycle generating units. STATCOMs can be installed at the generating units to compensate for the shortcomings by synchronous generators. Existing DFIG based wind, and solar plants can be used to provide a component of reactive power provision. In addition, storage and auxiliary loads at conventional plants can be considered as sources of reactive power provision. Flexibility generated by auxiliary loads, connected at conventional power plants, is discussed in Appendix A.

The real and reactive power consumed by auxiliary loads is actually an interpretative burden on conventional generators, and this can further limit the reactive power provision by generators. With double-peaker CCGT, this provision can be made flexible, and it can be utilized as a component in the proposed architecture.

Aggregators have access to customers as demand response, and distributed energy resources. Commercial entities as distributed generators, and storage facilities can also take part in this aggregation. Storage and parasitic loads at generating units can offer flexibility to aggregators, and thus the aggregators have a range of reactive power options from customers, third party entities, and generators. The aggregators can thus offer flexibility to TSO for solving reactive power management issues at TSO, other than asking conventional generators only for the reactive power provision.

Aggregator has built-in intelligence to take decisions based on the inputs from these participants. These decisions are dependent on data, cash flow (cost-benefit analysis), availability of reactive power etc. There will be optimization tools inside the aggregator to serve this purpose. The aggregator then generates a flexibility curve in order to provide services to TSO. This flexibility will depend on the remunerating price, capacity, time of requirement, and the place of required service. The TSO controller can take decisions based on information in Table 2.

Table 2. Flexibility to TSO using Aggregated Reactive Power Techniques

Technique for Reactive Power Aggregation	Associated Costs	Flexibility to TSO
Synchronous generators with STATCOM	High capital costs are required to install STATCOMs at conventional power plants. However, the operating costs are moderate for controllers and maintenance.	Added flexibility to conventional power plants, by producing reactive power without compromising real power production.
Synchronous generators with DFIG based wind- farms, i.e. AC-DC-AC converters OR conventional PV inverters	Capital costs are low considering that the wind farms are already in place, and the costs of converters are only to be considered. The operating costs are moderate for controllers and	Flexibility to be achieved by over-sizing the converters. The margin of flexibility is low when the converters operate at zero or very low real power (no/very less wind, and during night).

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	maintenance.	
Synchronous generators with auxiliary loads	There are no capital costs considering that the double peaked auxiliary combined cycle plants are already in place. Operating costs are the fuel, and maintenance costs.	Flexibility to be achieved by using hot start-up. It is dependent on size of peaked plants.
Synchronous generators with storage	Battery related costs.	Flexibility is dependent on battery sizing.
Aggregators	High capital costs for the installation of DERs, DG, and storage. High capital costs for development of aggregator software platform. The operating costs are for controllers and maintenance.	New era of flexibility, with new business opportunities for all actors of power system.

2.2 VPP Model as DER-Aggregator/DERMS at DSO-DMS

The architecture for VPP for technical service provision at DSO level is shown in Figure 5. The architecture provides a platform for DSO; so that customers, distributed resources, microgrids, and energy storage systems can provide the ancillary services. It is divided into aggregator and sub-aggregator units; where the sub-aggregators can only follow read/write commands. Aggregator also has built-in intelligence to take decisions based on the inputs from these participants. These decisions are dependent on data, cash flow (cost-benefit analysis), availability of energy, etc.

There will be optimization tools inside the aggregator to serve this purpose. Aggregator then interacts with DSO where it provides the services upon requirement. The aggregator then generates a flexibility curve in order to provide services to DSO. This flexibility will depend on the remunerating price, capacity, time of requirement, and the place of required service. The architecture offers advantages both in terms of flexibility (to DSO), as well as increase in the hosting capacity.

Sub-aggregator 1 is the storage system developed and simulated within MATLAB/Simulink. The storage system complies with the capacity requirements, and the relevant KPIs (as described in Chapter 5). The storage system has the potential of both upward and downward reserves, which is available via the state of charge for the storage system.

Sub-aggregator 2 is the customers' demand-response system implemented within LabVIEW, which is capable to monitor the metering data of customers via Modbus protocol. It is assumed that the meters support Modbus communication. It also receives commands from DSO, which serves as control (response) to customers. The aggregator unit is developed using DIgSILENT tool, which includes a medium voltage distribution network, and an interface for controller at DSO management system. Market scenarios for the DSO are created using a tool called PLEXOS.

The next step is the interface between the defined sub-systems. The selected interface is OPC [1], as all the software nodes i.e. DIgSILENT, LabVIEW, and MATLAB/Simulink are compatible with the standard. Matrikon OPC server and explorer are used for the communication with the aggregators and sub-aggregators based clients. Basics of Matrikon OPC is followed from [2]; and LabVIEW data socket programming is used for communication with OPC server as in [3].

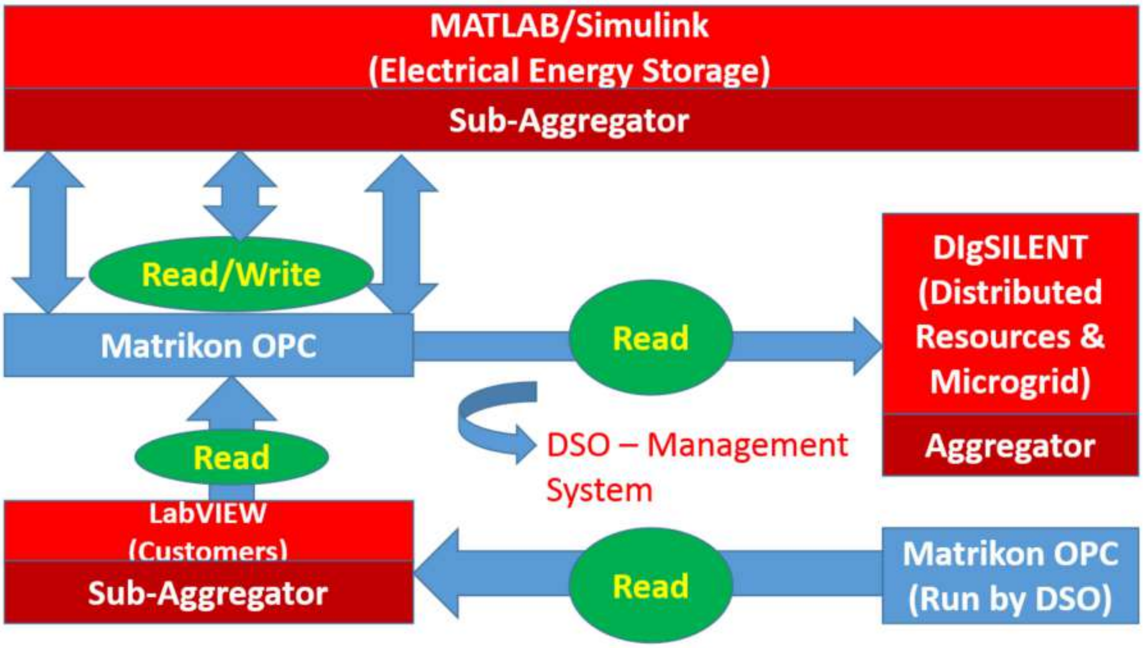

Figure 5: VPP Architecture: DERMS at DMS Level

The distribution network in DIgSILENT mimics the distribution system; where different medium-voltage feeders, low-voltage feeders, and laterals are investigated using power flow and state estimation. Within the feeder, the mixed distributed generation resources are added to experiment the penetration of distributed energy resources. The fact of low visibility of these resources to the DSO remains the same. The selected OPC feeder nodes, for the distribution system, are monitored via the DSO management system. Moreover, these nodes can take OPC read inputs from the OPC server (under the influence of both the sub-aggregators).

With the penetration of distributed resources at the distribution system, the DSO management system becomes aware of any change in power flow and/or state-estimation results (for example, penetration of PV panel varies the reactive power, which ultimately changes the node voltage and line loading) through the OPC alarm. The OPC, run by DSO at PLEXOS, becomes active, and gives OPC commands to the customers' demand-response based sub-aggregator for the possibility of provision of ancillary service. The customers offer the provision according to their capabilities.

Another OPC server reads the commands from the previous sub-aggregator, and gives commands to the micro-grid and storage based sub-aggregator, simulated inside MATLAB/Simulink. The energy storage system manages its state of charge value, depending on the particular ancillary service provision. After adjustment, the MATLAB/Simulink gives read signals to the OPC server, which gives the signals back to the aggregator and DSO management system. After receiving the signals from OPC, DIgSILENT re-performs the power flow calculations, and checks for all the parameters limits. The DSO is aware of the results, and in case of any needs for services, the cycle is repeated.

2.2.1 Benefits of the Architecture to TSO-DSO Interface

The cases where the architecture does not resolve the issues (like congestion etc.), the DSO interacts with TSO for the necessary provisions. Table 3 elaborates the TSO-DSO interactions, and the benefits of the architecture.

Table 3. Benefits of the Proposed Architecture

CONGESTION AND OTHER ISSUES RELATED TO ANCILLARY SERVICES (LOCATION)	**ISSUES RESOLVED BY:**	**OPC SERVER INVOLVED** **VISIBILITY & OBSERVABILITY**
LV LATERAL LV FEEDER	Customers demand-response	OPC(under DSO) Sub-aggregator(Lab-VIEW), Aggregator, and DSO
LV LATERAL LV FEEDER	Micro-grid and/or Energy storage system	OPC(both) Sub-aggregators, Aggregator, and DSO
MV FEEDER	Any sub-aggregator	OPC(relevant) Sub-aggregators (relevant), Aggregator, and DSO
MV FEEDER	Micro-grid	None Aggregator
ANY	TSO	None DSO
POI	Conventional power plants (generators)	None TSO

From Table 3, it is clear that the different sectors, i.e. the aggregators, sub-aggregators, DSO, TSO, and the generators resolve the ancillary issues. Local issues at the distribution level are managed locally under the control of DSO. The responsibility goes to TSO (with the aid of conventional generators) only when the DSO is not able to manage the issues, when the issue is outside of the distribution boundary, or at the POI.

2.3 VPP Model as Business Case for Flexibility to DSO-DMS

The operational model for this VPP is shown in Figure 6, and complies with the framework of SGAM [4]. The VPP incorporates the market aspects of using flexibility to DMS. Literature supports the idea of using IEC 61850 for flexibility as in [5]. The point of innovation here is the use of VPP as an IED. The RTU at distribution substation behaves as a mini-DMS that provides market opportunities to VPP providers. It is mandatory for VPP management system to be interoperable with IEC 61850 standard.

The model includes all benefits of IEC 61850 (such as process bus sharing, easy to expand, and most importantly easy to integrate with VPP). Mainly, it allows flexibility to DSO in terms of both services and energy markets. The idea of flexibility is supported by the fact that the VPP is remotely monitored, and controlled, along with the substation RTU and devices. With the inclusion of VPP as RTU, the observability of DSO RTU, and in turn the DMS is increased.

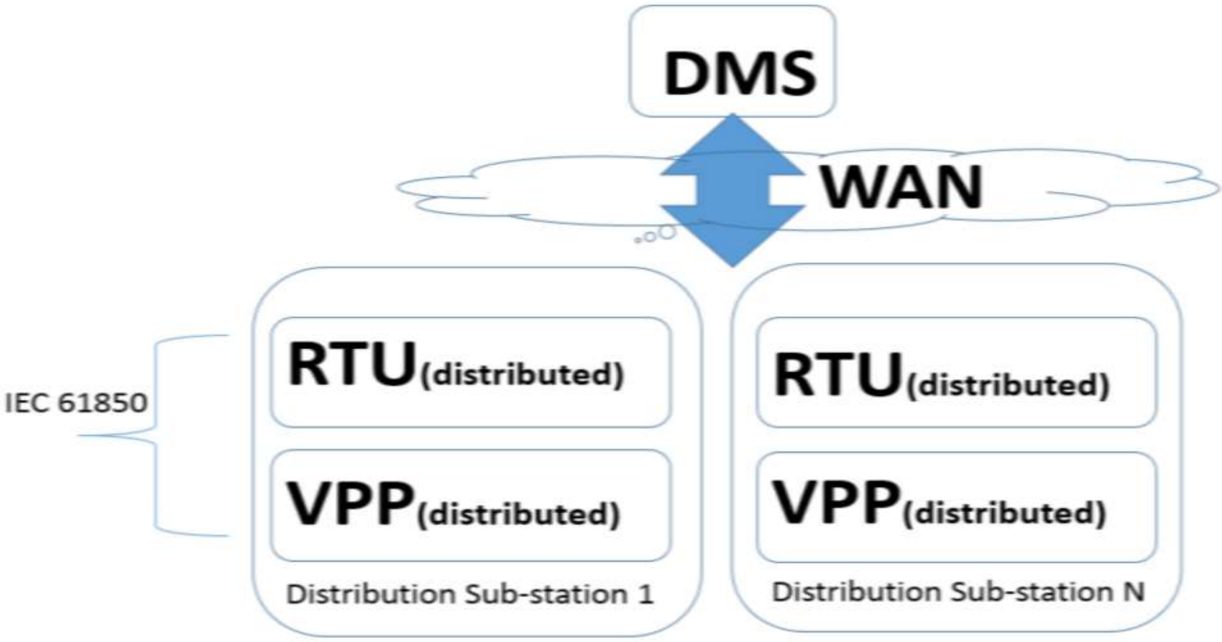

Figure 6: VPP Architecture: Business Model Aspect for Flexibility at DMS Level

The platform has the main advantages of being modular, easily scalable, and easy to integrate with VPP-RTU, all in compliance with [6]. It is important to analyze the technical and regulatory barriers associated with the platform. Main technical barrier is the network security threats with the increase in IEC 61850 traffic, especially with sampled values. The solution is to employ a traffic controller at RTU levels. Next major technical threat is on cyber-security, which becomes vulnerable due to the information sharing with VPP-RTUs, and these VPPs are not protected against cyber-attacks, specifically stealth attacks.

Literature suggests many techniques for the associated cyber risks, however, for VPP as a component IED, it is recommended to use IEC 62443-2-4 based patch management system presented in [7]. The solution may or may not include open data interoperability amongst VPP and DMS. Another barrier is from the regulatory authorities, which restrict VPP or distributed generators to participate directly in DSO market. Ambiguous participation policies for storage, demand response, and aggregators act as another source of barrier. Table 4 lists the barriers that major VPP providers, in major European countries, face as part of BestRES EU project explained in reference [8].

Table 4. Regulatory Barriers of the Proposed Architecture

Country	Regulatory Barriers
United Kingdom	1-High subsidies for DERs 2-DERs cannot participate in ancillary market 3-Lack of standardization for flexibility 4-Primary reserve is a mandatory provision for main generators
Italy	1-Legal barriers in both technical and regulatory aspects 2-Lack of standards for interaction amongst the different actors 3-Data and privacy protection is not well-regulated
France	1-Primary reserve is a mandatory provision for main generators 2-Slow implementation
Portugal	1-Legal barriers in both technical and regulatory aspects 2-No reserve market for wind and PV 3-No existing demand-response.

The solution underlies on the refined roles of DSO, which fits the technical gaps in adapting the platform, and thus becomes evident for potential regulatory changes. Literature proposes variety of these changes, and a lot of DSOs are involved in adapting these changes with potential regulations, as suggested in [8-9].

Main motivation for the model is the involvement of different market players, and hence the trend which the later DSO should follow. The business case for this model can be developed with the utilization of four schemes presented in [10]. The four cases emphasize on different schemes of possible utilization of DERs effectively, in order to participate in ancillary market. Model presented in Figure 6 is compatible with these cases in all aspects. Therefore, all the technical benefits of operational planning, operational functions, and market functions, presented in [10], are also applicable for this model. The model gives novelty in terms of VPP participation for ancillary services with the concepts of using I) IEC 61850 standard II) VPP participation at RTU level III) Market opportunities at RTU level. However, the key points in adaptation of the proposal are:

1- Market opportunities and participation should be allowed to VPP at the level of substations
2- The subsidies for VPP should be reduced. The better is that DSO should provide incentives for adaptation of trend.
3- Regulatory barriers for VPP participation in service market should be removed.
4- The concerns regarding data, privacy, and information management should be regulated. A proper discretion of RTU, DMS, and VPP data for sharing should be done
5- Demand response, storage, and in principle, reserve markets should be prevalent at both MV and LV levels.
6- New policies for IEC 61850 based interoperability of VPP, substation devices, and terminal units should be swift

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Chapter 3: Co-Simulation of Demand-Response in LabVIEW

3.1 VPP Model as Customers' DR

This chapter investigates compensation options for voltage changes through reactive power provision, where customers' demand is a significant actor for these reactive power changes. The chapter discusses the architecture for virtual power plant, and the interaction of customers meters through VPP controller. It then develops the HMI to access the reactive power metering at customers end, and a recording tool for the readings at VPP controller. Chapter 2 provides a VPP-DERMS model, which is also a latest trend towards grid stability, by utilizing the usual storage, customers, distributed generation etc., but with proper management. This concept is explored in [1-2], and further matured in [3-4]. The architecture for the VPP comes from Figure 5, and the relevant portion for this chapter is shown in Figure 7. The VPP controller can access the reactive power profile for all these components that take part in the architecture. However, only the residential and industrial customers, as a subset, are considered in the scope of this chapter. The reactive power consumption for these customers is accessible through the meters of the customers.

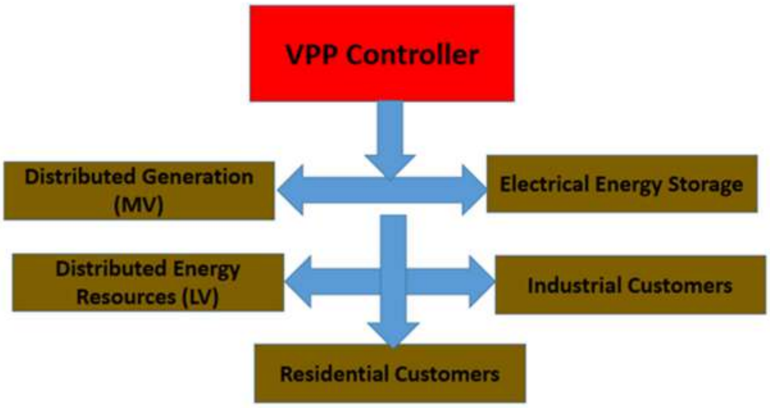


Figure 7: VPP Architecture: Customers' Engagement as DR

3.1.1 INTERFACE TO CUSTOMERS' METERS FOR REACTIVE POWER VISIBILITY

For the participation of customers to the reactive power provision for VPP, the meters should have the capability to support the communication of signals via Modbus [5]. The address to point towards a specific parameter is according to the pattern in Figure 8. The same structure is implemented inside LabVIEW using Create TCP Master block for defining the IP address, Set Unit ID block for setting the Modbus id, and Read Holding Registers for defining the specific parameter of the meter, i.e. the reactive power in the context of this chapter.

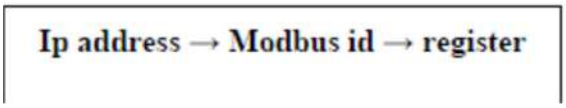

Ip address → Modbus id → register

Figure 8: VPP Customers: Pattern of Address

The structure is shown in Figure 9; however, the values are not indicated for confidentiality purposes. Pink box indicates the IP address, and the box in the middle indicates the Modbus id. The two boxes on the right define the Modbus register and the number of bytes required to acquire the data for the parameter.

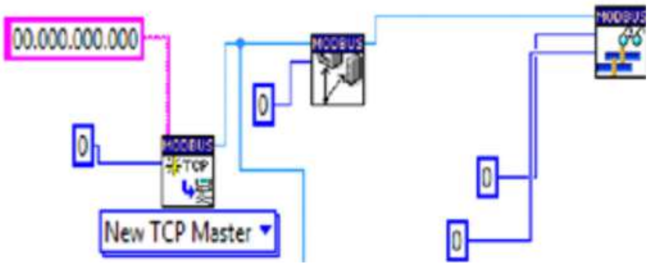


Figure 9: Representation of Meter Data Addressing

Eight customers, four at MV and four at LV nodes, are the sources of investigation in the chapter. The next step is to the acquisition of the reactive power metering data for each of the customers. After that, the step is to store the data in a buffer. LabVIEW offers the functionality of creating an output array via ”Build Array” block, and this array is utilized for the development of buffer for the reactive power readings. The approach is to create a shift register via While loop. In other words, the array receives two inputs which are the reactive power reading on run-time, and the input of while loop, which in turn depends on the output of while loop which is generated through the output of the array.

The buffer can store the reactive power measurements for a single meter. In order to record measurements for all the eight customers, the buffer is extended, and eight shift registers are developed within a single while loop [6]. These shift registers run in parallel, and store the readings for each customer in their respective arrays. For the sake of explanation, the buffer system for the two customers is shown in Figure 10.

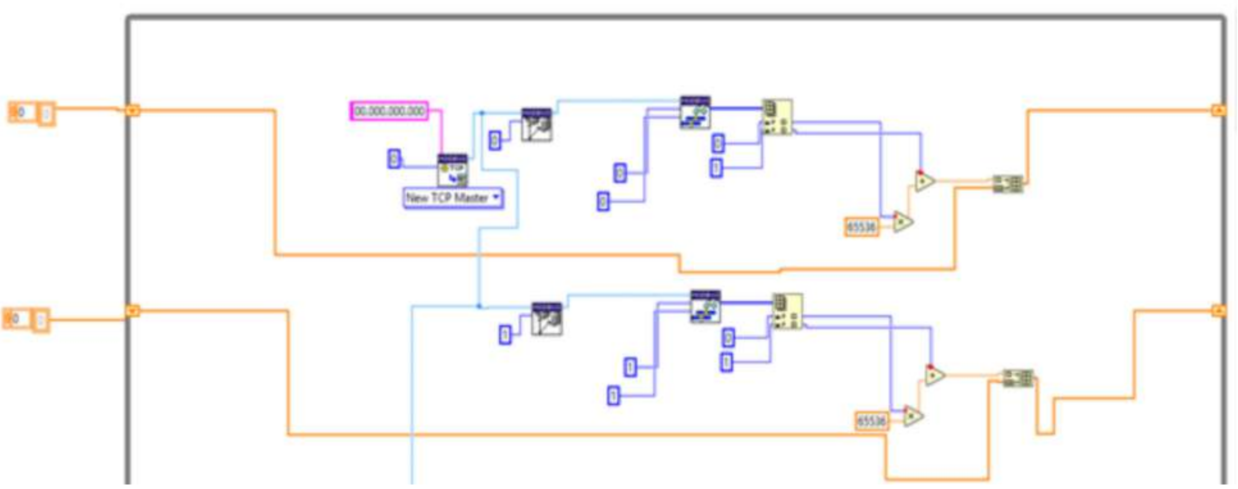
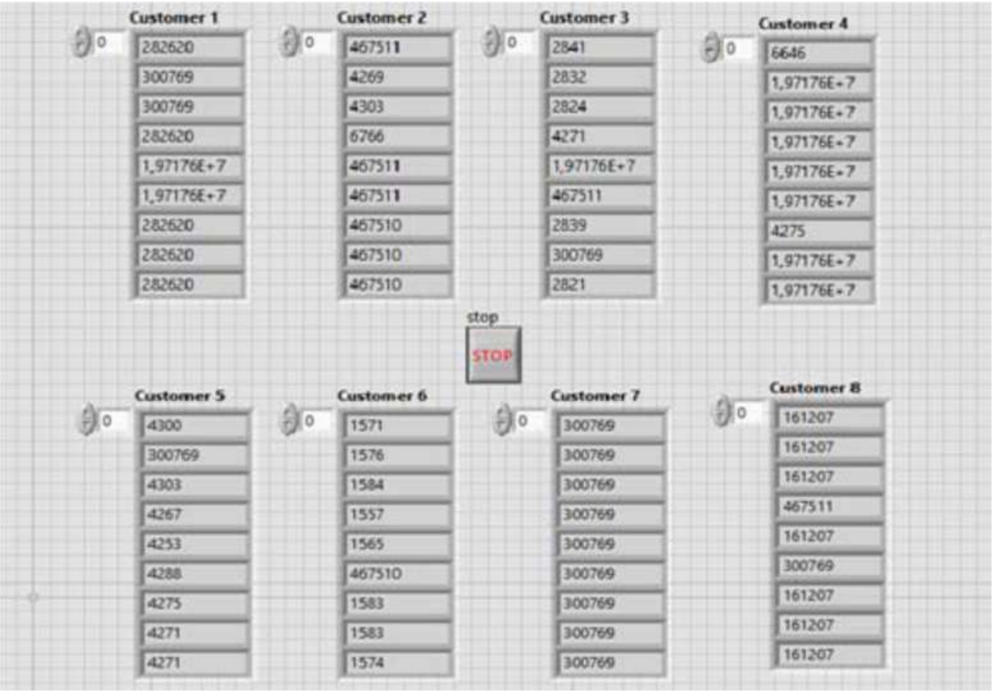


Figure 10: Buffer for Reactive Power Readings

3.1.2 HMI AND RECORDING AT VPP CONTROLLER FOR REACTIVE POWER VISIBILITY

The meters are polled at a rate of 100 milliseconds and the buffers store and display the reactive power consumption for all the customers. The HMI is shown in Figure 11. However, the HMI displays, and then over-writes the measurements. Therefore, a recording tool is required at the control center for the access and use of these measurements at a later stage. One option is to use the option of "Export Data to Excel", but it creates a file for a measurement at each polling instant. Therefore, the problem is the waste of memory to save abundance of files. Another problem is that the measurements only, and not the time-stamps are recorded.



Customer 1	Customer 2	Customer 3	Customer 4	Customer 5	Customer 6	Customer 7	Customer 8
282620	467511	2841	6646	4300	1571	300769	161207
300769	4269	2832	1,97176E+7	300769	1576	300769	161207
300769	4303	2824	1,97176E+7	4303	1584	300769	161207
282620	6766	4271	1,97176E+7	4267	1557	300769	467511
1,97176E+7	467511	1,97176E+7	1,97176E+7	4253	1565	300769	161207
1,97176E+7	467511	467511	1,97176E+7	4288	467510	300769	300769
282620	467510	2839	4275	4275	1583	300769	161207
282620	467510	300769	1,97176E+7	4271	1583	300769	161207
282620	467510	2821	1,97176E+7	4271	1574	300769	161207

Figure 11: HMI for Reactive Power Readings

The technique is to use the block "Write to Measurement File", and set the output of each measurement as a signal to the block [7]. Within the block, the location for the storage of file can be provided. It also supports the option for file append, and thus the measurements are appended with each polling instant, and as a result a single generated file can record all the polling measurements for a single meter end. With the utilization of TDMS functionality, both the data and time can be synchronized, and recorded as signals.

The recording format is shown in Figure 12. It displays the time, date, the reading number, and the measurement value for each measurement. In this particular case, these will be eight files for the eight customers that can record the reactive power measurements for the customers independently.

3.2 Performance Analysis of the Developed Tool

The next step is to analyze the performance of the interface, HMI, and recording unit at different test cases. These test cases represent the demands by system operators and the effective mismatch proportion at both transmission and load levels. These demands may vary as per the time, amount, and the location for the mismatches in reactive power. The test cases are presented in Table 5. The table indicates the three major extremes for the services, and the possibility of support by the presented system. The requirements for adaptability within the tool, and the actions to be taken by the infrastructure are also elaborated.

1	Time	Time*	Untitled
2	06/12/2017 04:40:32,325 PM	0	6465
3	06/12/2017 04:40:37,199 PM	1	2E+07
4	06/12/2017 04:40:42,032 PM	2	2E+07
5	06/12/2017 04:40:45,324 PM	3	4275
6	06/12/2017 04:40:45,617 PM	4	2E+07
7	06/12/2017 04:40:50,511 PM	5	2E+07
8	06/12/2017 04:40:53,085 PM	6	2E+07
9	06/12/2017 04:40:55,943 PM	7	2E+07
10	06/12/2017 04:40:59,273 PM	8	2E+07
11	06/12/2017 04:40:59,607 PM	9	6646

Figure 12: Pattern for Reactive Power Recordings

For case 1, the idea is to poll the system at a more frequent rate. As a result, Modbus communication needs to be fast. It can result in two possible issues: the Modbus master is unable to handle many requests during the high polling period, and the missed data reading propagates the error from one Modbus client to the others (based on other customers). The requirement is to include an error handler, which accepts avoiding a few readings as per the requirements.

The error handler is implemented in LabVIEW, and one unit of each of them is added to each of the Modbus platform for customers. HMI does not support this change due to the limitations of buffered arrays. The recording tool has the tendency to record this large quantity of values in a timely fashion. For case 2, the concept is to check the feasibility of the system at high amount of reactive power requirements. It is the scenario when there is a huge requirement of reactive power due to unexpected tripping, and addition of variable renewable generation resources. The tool requires addition of an increasing counter in order to avoid overwrite and overload issues with buffers.

Table 5. Test Cases for Reactive Power Requirements

Needs	Actions	Support for HMI?	Recording Compatible?
Faster services are required for high system reliability, specifically to deal with faults and contingency issues.	The tool should support reduced polling intervals.	NO	YES
High proportion of reactive power is required. It may be	The tool should support large readings, via mechanism to erase the	YES	YES

during the case the microgrids, unexpected and large addition of distributed energy resources, tripping of any major line and/or generator etc.	previously supported largest value for data logging.		
The requirement is at geographically scattered locations. The scenario may result in case of multi-area systems, and islanding.	The tool should handle a large network range.	YES	NO

For case 3, the requirement is the extended network range, and it may require the Ethernet address variations. The error handler in case 1 can resolve the issue; however, the recording tool does not allow these variations. The architecture in Figure 13 describes the model of the full tool, with indications of the customers, HMI, recording tool, and the two additions of increasing counter and error handler. Other than reactive power, the tool has the capability to record and manage voltages at nodes, active power flow, and the details of the effective loading. It only requires the access of the required port of Modbus, and ultimately the addition of separate buffers to create multiple channels.

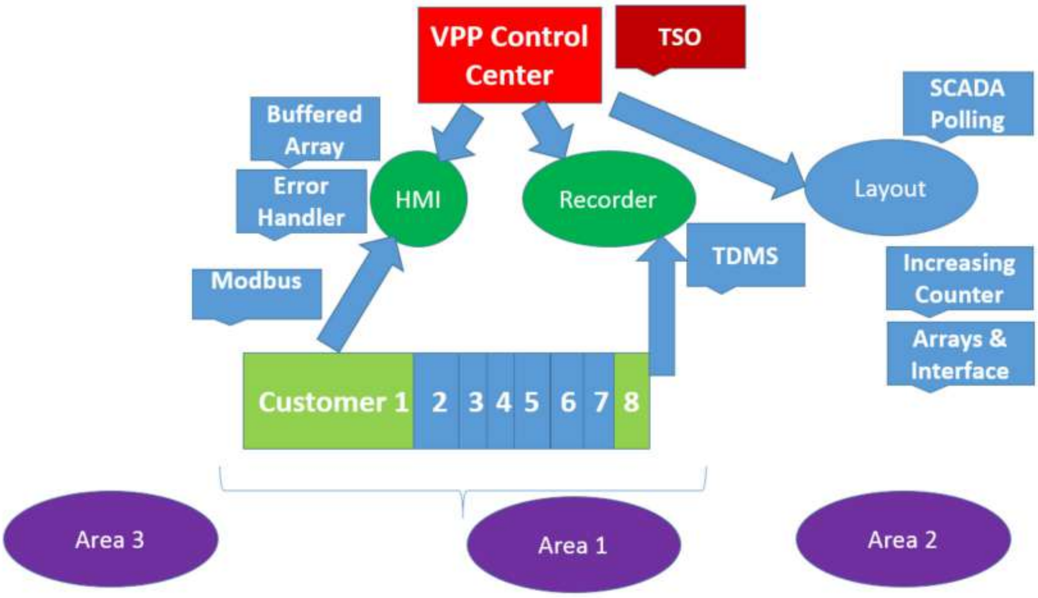


Figure 13: Architecture of the Overall Tool

The idea of the chapter is to employ VPP concept for the provision of reactive power, which can ultimately be used for solving the issues of voltage instability. For the VPP, a centralized tool is required that can keep track of the reactive power flows, and an interactive platform is needed that is used to access the flows and

This project MEAN4SG has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 676042.

to record it for future use. The chapter presented such platform for the aforementioned purposes. The chapter thus presents the architecture, HMI, and the recording tool for the VPP controller. The controller can take care of the reactive power flows to the customers, and thus it can follow a proactive approach for dealing with voltage instability based on reactive power control.

In order to create a more realistic picture of VPP, and as an extended case, the other actors of VPP should be aggregated together with the customers. This will include the energy storage elements, and other distributed generation resources, which will give not only the flexibility to VPP controller, but will also provide the involvement of different actors of power system in the provision of voltage stability, and thus it will create a better market opportunity. Chapters 4-5 are dedicated for these steps.

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Chapter 4: Co-Simulation of DER effects on a distribution grid in DIgSILENT

4.1 Modeling of the Distribution Grid in DIgSILENT

The objective of this chapter is to analyze the effects of DER as imbalance of the reactive power at the distribution side of the power system occurs. These mismatches cause the violations of the voltage limits at the distribution nodes, which affect all sectors of the power system in terms of line loading and voltage at different nodes of the system. The chapter illustrates the effects of these DERs on the node voltages of a medium-voltage distribution grid. The grid is modelled in DIgSILENT; the static load flow analysis and the quasi-dynamic analysis for the network are performed to analyze the voltage loading of the grid (before and after the inclusion of dedicated DER).

A published Italian distribution network is used, which is the part of the dissemination of the project called ATLANTIDE as in [1-4]. The SLD of the grid is shown in Figure 14. The network has 103 nodes, and 7 feeders that serve the MV loads. The feeders are further connected to the LV loads via load transformers.

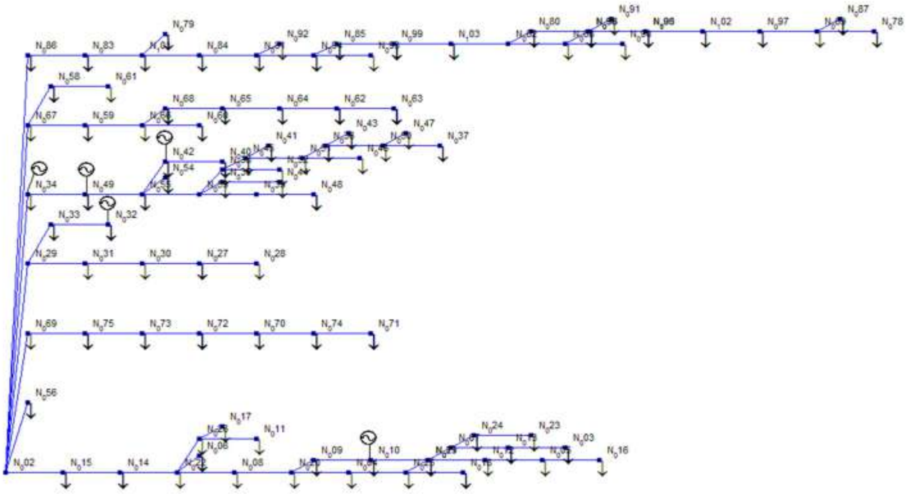

Figure 14: Distribution Network from [1-4]

There are 190 loads in total. The distribution transformer serves the MV end at 20kV level, which is stepped down from 150kV at HV transmission end. This transmission system is under the control of TSO, which has the visibility to both generators and primary substations. This is as per the Italian power system structure as in [5-6]. The nominal rating of apparent power by generator, and the active and reactive power ratings are parts of the grid data.

The project ATLANTIDE as in [1-4] discusses the overall details of the network, which include the topology, voltage levels, profiles of distributed energy resources etc. The effects of the high penetration of distributed energy resources on the Italian grid are well discussed in the project, and all these details are skipped in this chapter.

However, the idea presented in the chapter is to model the distribution system and then select a representative feeder, and some nodes to carry out the analysis for voltage loading, the effects of wind and solar penetration, and the cascaded impacts. The idea is to use DGS, the facility of DIgSILENT, to create the excel file with the representation of the network. The excel file is then imported into DIgSILENT using the DGS import facility. The procedure to create the excel file is discussed in [7-9]. Other relevant details are in [10-12]. The general and the object tables are created, and the parametric values of the network are converted into the format supported by DGS.

One of the major object tables is ElmLne, which is used to define the data for lines and cables. Per length values of the positive, negative, and zero sequence resistances, capacitances, and inductances are described in TypLne, along with the rated current and voltage of each type of line. Some of the line sections are also created using the ElmLnesec object table [6-11].

The loads are defined in the object table called ElmLod. Next step is to define the buses and nodes using ElmTerm, where the nominal line-to-line voltage of the nodes are mentioned. With the iUsage field in the object, the nodes of this distribution system are indicated as either bus bar, junction, or internal node [6-11].

The external grid feeding from 150kV end and the distributed generators are explicitly mentioned in object table called ElmXnet, with the potential to indicate operating real power, reactive power, voltage, and torque angle. Other object files include the StaCubic, StaSwitch, and ElmShnt, which define the shunts, breakers, and switch details [6-11].

The remaining component is the distribution transformer, which is defined using ElmTr2 and TypTr2 object tables. In this way, the excel file can indicate DIgSILENT of how each of the components are connected to each of the terminals. The graphical coordinates of the terminals are mentioned in the object file called IntGrf [6-11].

After exporting the excel file into DIgSILENT, a .PFD file is generated which allows to edit the data for the network using the Network Model Manager. The manager gives access to all the components, types of components, and the terminals, where all the parameters of basic data, load flow, and other operations can be edited. This is the place where the transformers at the loads are also defined.

The step now is to define the area, feeders, and zones so that the grid is represented in a standard way. Within an area, seven feeders are defined for a particular defined zone. The feeders are marked with different colors in order to make the simulations in a friendlier version. The feeders and grid are well represented in DIgSILENT. The graphical representation for this network is shown in Figure 15.

The network is now ready with all the required parameters, with SLD of one representative feeder generated from graphical network in DIgSILENT in Figure 16, and thus the next step is to perform the load flow analysis. It requires defining the PQ, PV, and slack buses. All the loads are defined as PQ buses (with the ratings already mentioned in the network manager), and the external grid is considered as slack bus (ignoring the distributed generators). The load-scaling factor is set to 100% now for all the loads. The load flow is run, and the Newton-Raphson algorithm is converged with three iterations. The software generates a load-flow calculation report, as seen in Figure 17.

To analyze the behavior of grid, it is not sufficient to perform load analysis for a static time instant. It is therefore necessary to perform the load flow for a period, and to see the behavior of voltage at nodes, and loading of lines throughout that period. This is in fact the motivation towards the quasi-dynamic analysis, so

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that the grid behavior can be analyzed through graphs. The step towards this is to define a particular parameter of loads for the window period.

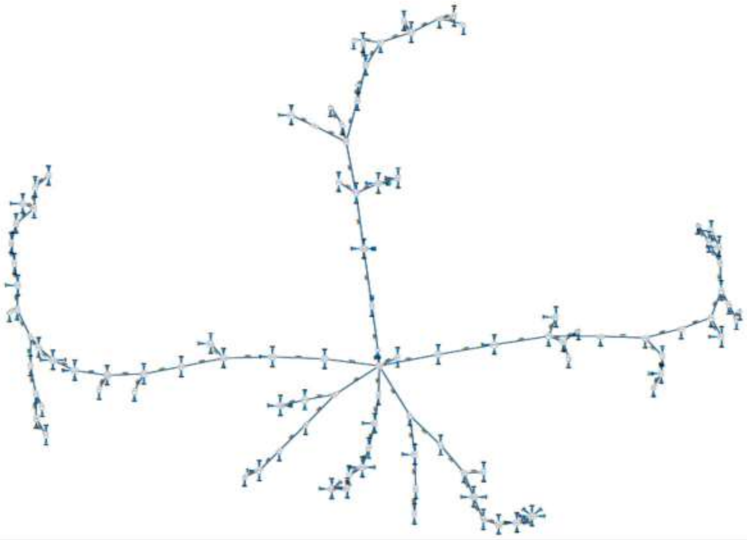

Figure 15: Graphical representation of the Network

The scaling factor of loads is a parameter that is chosen for the purpose, and the data is defined for a particular day, with increments of 1 hour. Guidelines for the load scaling are taken from [13-14]. The loads are categorized as aggregators, residential-LV, industrial-MV 1, industrial-MV 2, and industrial-MV 3. These loads are representatives of the loads connected to the distribution network.

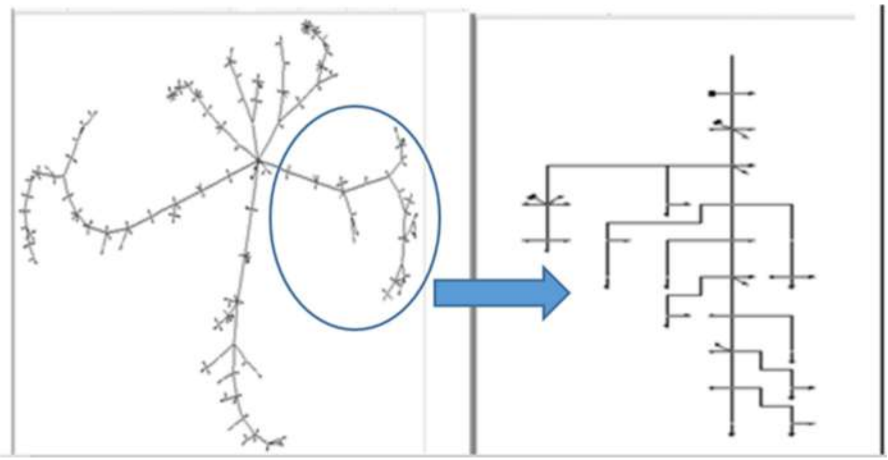

Figure 16: Graphical representation of the representative feeder of the network

The vectors are created for this parameter characteristic of scaling factor by creating ChaVec object table in the excel file. The loads are characterized according to their types by creating ChaRef object table, where each of the load is mapped to one of the types as in ChaVec.

The mapping is done according to Table 6. Table 7 indicates the load numbering with reference to the sequence of nodes.The idea is to create a mixed aggregation and demand response scenario, and the loads

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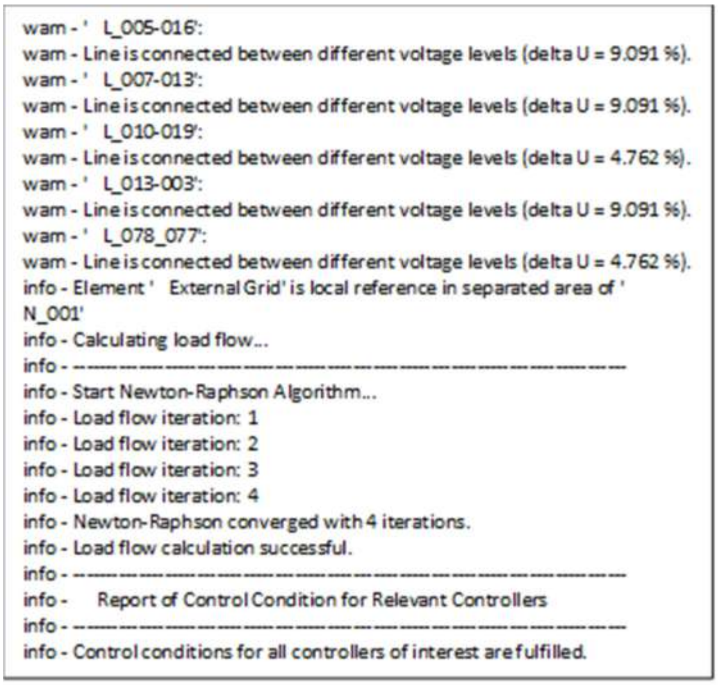
are connected in a complex fashion in order to create a better picture for simulations. A 24-hour time scale is created with a window size of 1 hour, using an object table called TriTime. The excel file is now ready with all the parameters for quasi-dynamic simulations, and it is imported to .PFD file of the DIgSILENT. The scaling values for the types of loads are generated in a table for 24-hour scale, and the values for each hour are fed. The software can generate a curve for these discrete values, so that a quasi-dynamic picture of simulation is developed. A well- approximated load-curve is generated for aggregator, and the hermite approximation is used for the creation of curve.



```
wam - '  L_005-016':
wam - Line is connected between different voltage levels (delta U = 9.091 %).
wam - '  L_007-013':
wam - Line is connected between different voltage levels (delta U = 9.091 %).
wam - '  L_010-019':
wam - Line is connected between different voltage levels (delta U = 4.762 %).
wam - '  L_013-003':
wam - Line is connected between different voltage levels (delta U = 9.091 %).
wam - '  L_078_077':
wam - Line is connected between different voltage levels (delta U = 4.762 %).
info - Element '   External Grid' is local reference in separated area of '
N_001'
info - Calculating load flow...
info - -------------------------------------------------------------------
info - Start Newton-Raphson Algorithm...
info - Load flow iteration: 1
info - Load flow iteration: 2
info - Load flow iteration: 3
info - Load flow iteration: 4
info - Newton-Raphson converged with 4 iterations.
info - Load flow calculation successful.
info - -------------------------------------------------------------------
info -     Report of Control Condition for Relevant Controllers
info - -------------------------------------------------------------------
info - Control conditions for all controllers of interest are fulfilled.
```

Figure 17: Load Flow Analysis

The quasi-dynamic simulations are performed now, and the software requires the time duration and step size for the simulations. In the context of this chapter, the time interval is a full day of 7/4/2017, with a 1-minute step size. For better precision, 1-second step-size can be used too; however, it takes a lot of time for the simulations to proceed. The software is capable of producing report based on loading ranges (maximum and minimum in percentage) of components, and the voltage ranges (maximum and minimum in per unit) of nodes. The graphs for behavior of these components and nodes can also be visualized through the software.

Table 6. Classification of Load Types

ChaVec(type of loads)	ChaRef(reference of loads)
Aggregator	5-8, 10-12, 14-15, 19-21, 24-29, 31-36, 38-39, 42-45, 47-49, 51, 60, 63-64,67, 70, 72, 77, 81-83, 87, 89-96, 101,103-104, 107-108, 111-114, 118-124,126-138, 140, 142, 144-148, 154-155,161-167, 172-173, 179-180, 185-186,189-190
Residential	1-4, 9, 16-18, 23, 30, 37, 52-59, 61,65-66, 68-69, 71, 73-74, 78-80, 84-86, 88, 97-100, 105-106, 110, 115-116,139, 141, 149, 152-153, 156-159, 168-171, 174-178,

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	181, 183-184, 187-188
Industrial 1	40
Industrial 2	22, 50, 62, 75, 117, 125
Industrial 3	13, 41, 46, 76, 102, 109, 143, 160, 182

Table 7. Node-Load Mapping

Node Number	Load Number
3, 6, 9, 10, 13, 14, 15,18, 21, 24, 27, 32, 33,36, 37, 40, 41, 42, 43,45, 48, 49, 54, 55, 56,57, 58, 59, 60, 62, 63,64, 65, 68, 70, 71, 72, 73,74, 75, 76, 77, 78, 79, 80,81, 83, 84, 85, 86, 87, 94,97, 98, 99, 100, 101, 102,103. (One node to multiple loads mapping)	1-3, 6-8, 10-11, 12-13,16-18, 19-21, 22-23, 26-28, 31-32, 35-36, 39-41,45-47, 48-49, 52-53, 54-55, 57-59, 60-61, 62-64,65-66, 68-69, 72-74, 75-77,81-82, 83-84, 85-86,87-88, 89-91, 92-93, 94-95, 97-100, 101-107, 108-109, 110-111, 114-117, 119-120, 121-125, 126-129, 130-131, 132-134, 135-137, 138-139, 140-141, 142-143, 144-146, 147-148, 149-150, 151-153, 154-155, 156-158, 159-160, 161-163, 170-171, 174-175, 176-178, 179-182, 183-184, 185-186, 187-188, 189-190
4, 5, 8, 11, 12, 16, 17, 19,20, 22, 23, 25, 26, 28, 30, 1, 34, 35, 38, 44, 46, 47,50, 51, 52, 61, 66, 67, 69,88, 89, 90, 91, 92, 93, 95,96. (One node to one load mapping)	4, 5, 9, 14, 15, 24, 25, 29,30, 33, 34, 37, 38, 42, 43,44, 50, 51, 56, 67, 70, 71,78, 79, 80, 96, 112, 113,118, 164, 165, 166, 167,168, 169, 172, 173

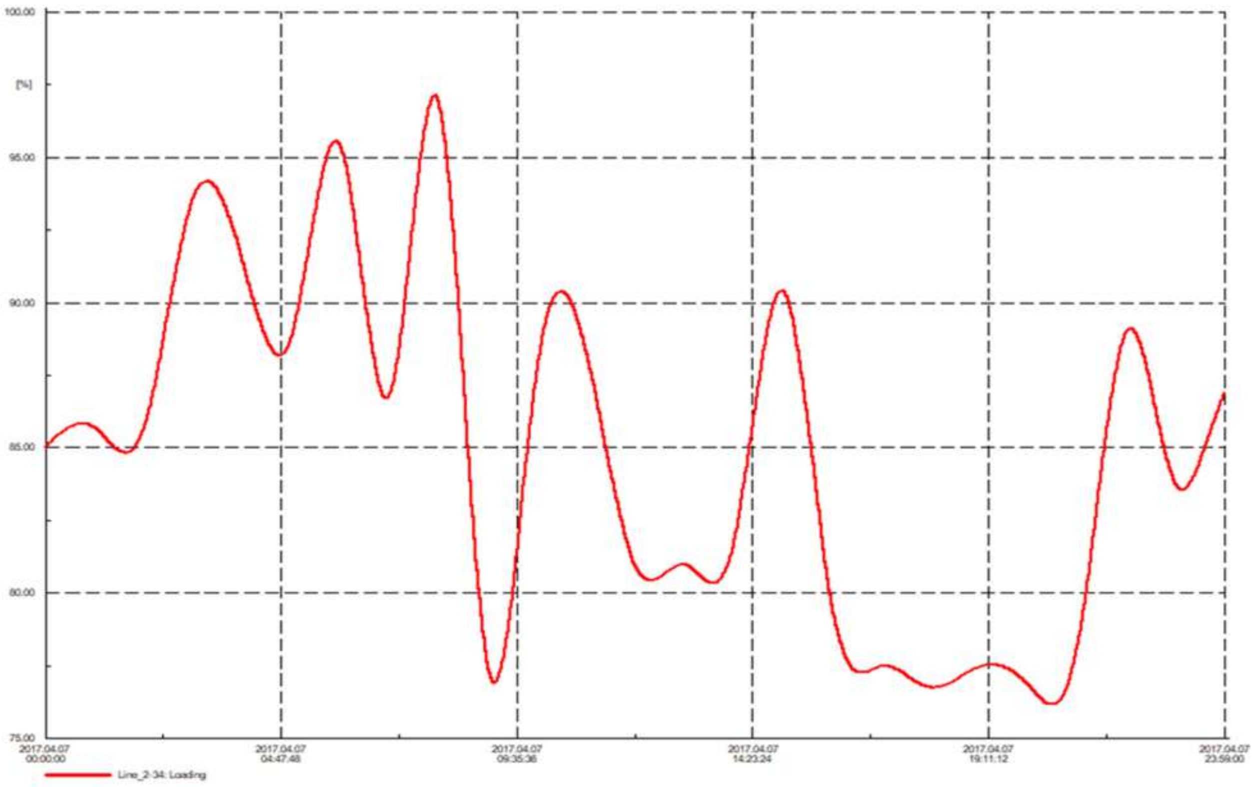

Figure 18: Loading for Line 2-34

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Line 2-34 is the one with maximum loading of 97.122%, as seen in Figure 18, and it complies that none of the lines is overloaded. The next step is to check for the voltage loading of the distribution grid, such that none of the nodes undergoes under-voltage and over-voltage violations. The voltage is assumed acceptable within the limits of 0.95 per-unit to 1.05 per-unit. The usual medium voltage range of 90%-110% is little under-estimated as the DERs are not simulated in a widespread manner. Lower range is used for more pessimistic bounds. Nodes 2 and 56 experience the maximum voltage of 1.022 per-unit, and node 37 experiences the minimum voltage of 0.97 per-unit. The voltage profiles for the two selected nodes, i.e. 2 and 37, are shown in Figures 19 and 20 respectively. Thus, there are no issues of line over-loading and voltage range violations for the selected grid.

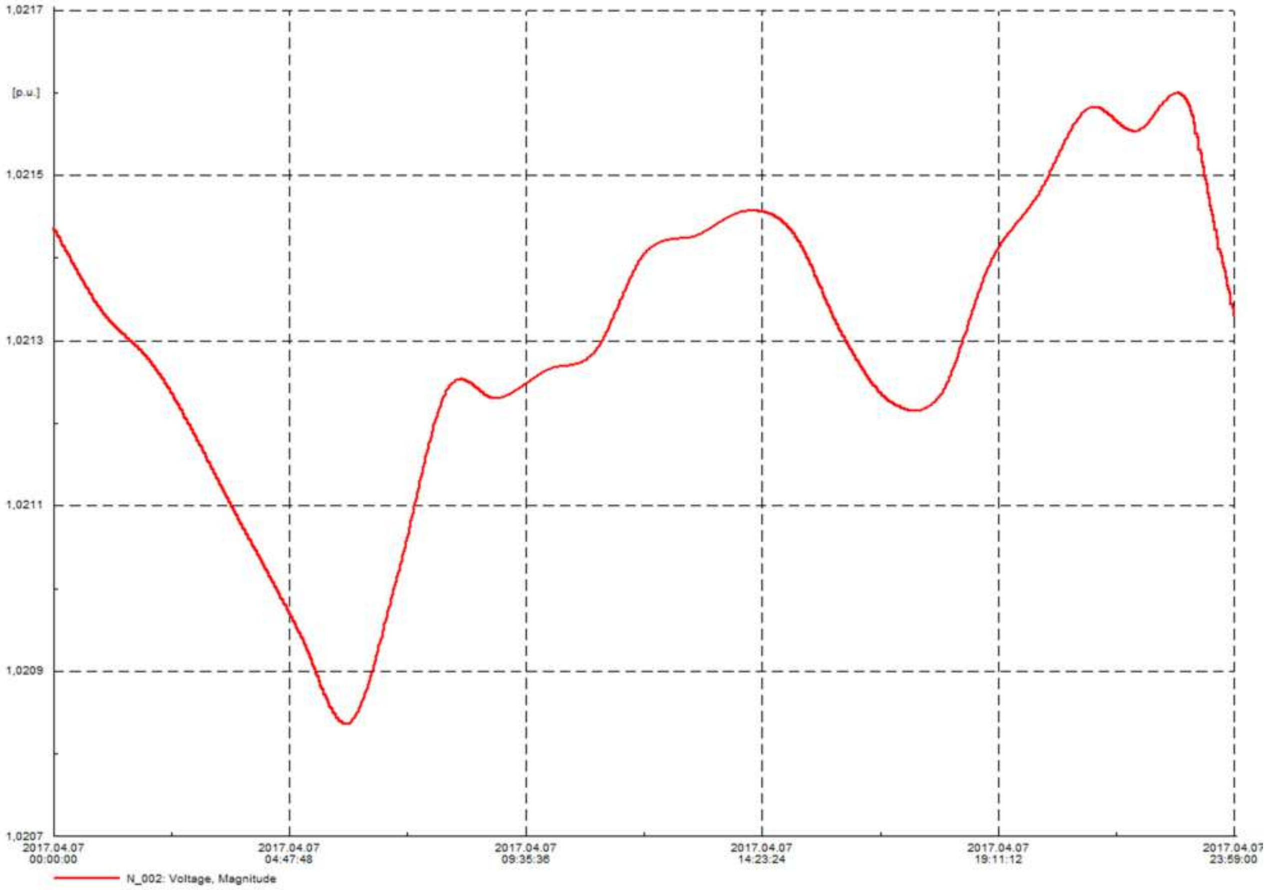

Figure 19: Node 2 Voltage in PU

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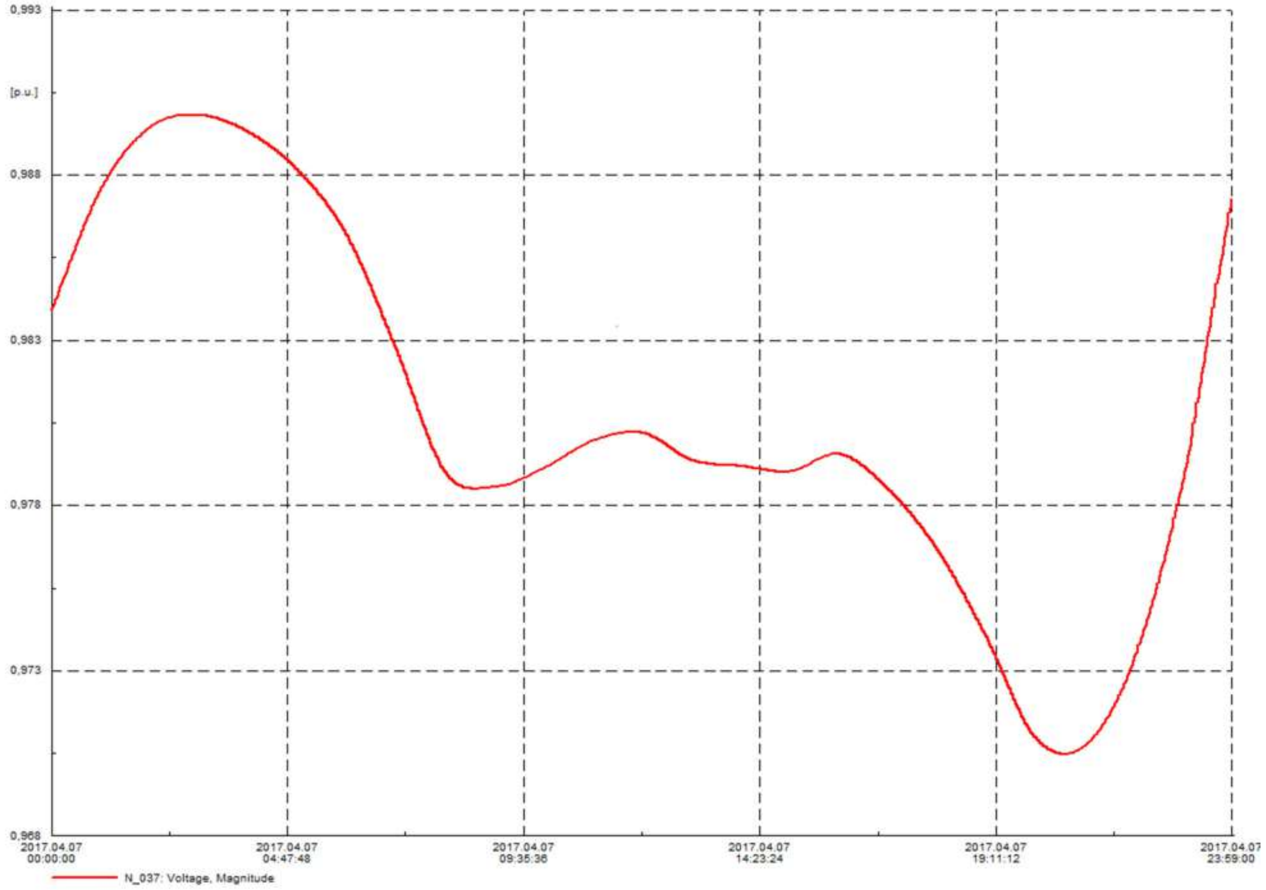

Figure 20: Node 37 Voltage in PU

4.2 Addition of DER in the Network

The next step is the addition of distributed resources at some of the selected nodes. It helps to analyse the impacts on the overall stability of the grid. The selected nodes are 9, 36, 44, and 63 with the inclusion of hydro distributed generation, combined cycle distributed generation, wind distributed resource, and solar distributed resource respectively. The inclusion of wind and solar above demonstrate the combined effects of wind plants and solar plants on the low voltage nodes for the MV nodes 44 and 63 respectively.

For the quasi-dynamic analysis, the factor of scaling is taken to be the reactive power, which is defined in the same way as the scaling factor for loads in the previous case. This scaling is the representation of the overall impact on the reactive power for the particular node. The four types of the generations are described in the object table ElmXnet, and the vectors for the scaling are created in the ChaVec object table. All the other parameters and representations remain the same.

The quasi-dynamic analysis is performed for the same day, and the results for voltage at nodes, and the line loading are analyzed. None of the lines violates the loading conditions, which is in accordance with the previous conditions too. However, three nodes violate the over-voltage conditions, and there are eight nodes, which are very close to the high-voltage threshold. The results are shown in Table 8, with indications of the maximum encountered voltage by the specified nodes. There are no under-voltage violations.

4.3 Flexibility to TSO by the Addition of STATCOMs

4.3.1 Modelling STATCOMs

Next step is the addition of STATCOMs in the grid, to analyze the way they can add flexibility to the grid in terms of reactive power provision. The aggregation criteria in chapter 2 states it as the expensive solution. However, the option of STATCOM is considered in the context of the chapter because it has a higher capability with readiness, but at the expense of high costs. The criteria for aggregation is explained in Figure 21, where loads and storage are not considered to avoid conflicts with what expressed in chapters 3 and 5 respectively.

Table 8. Demonstration for Over-voltage Violations

Node Numbers	Maximum Voltages in PU
10, 19, and 9(overvoltage)	1.056, 1.056, and 1.052.
32, 33, 20, 8, 4, 29, 25, and 18(close to overvoltage)	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, 1.041, and 1.040.

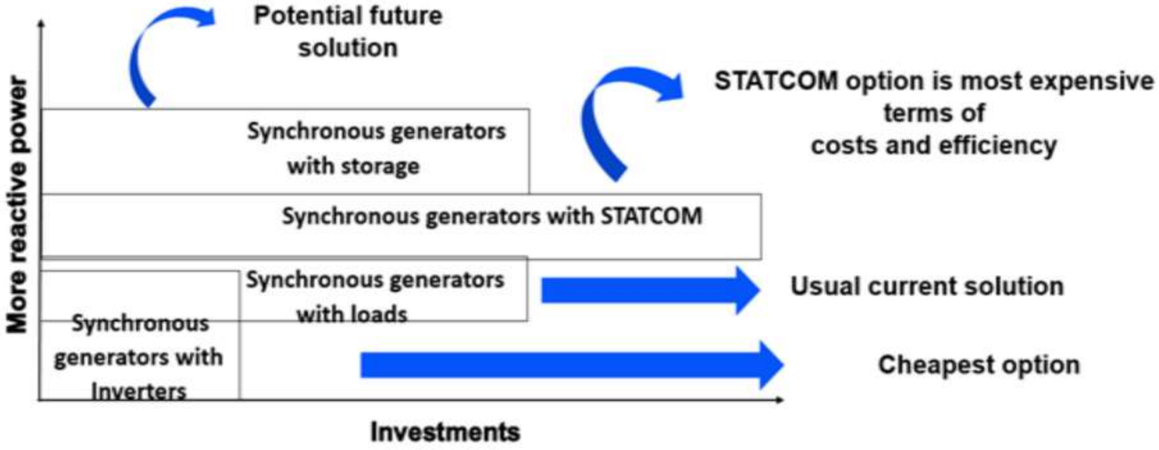

Figure 21: Criteria for Aggregation Solution

Addition of STATCOM at the generating end (high voltage end) can give relaxation to conventional combined cycle and coal-fired power plants. This section demonstrates the flexibility that a STATCOM at high-voltage end can provide. A test case is established in DIgSILENT, which includes the electric output end of a coal-fired power plant, and a high voltage cable that connects the electrical output end of the power plant to the point of interconnection. Details of the power plant are out of the scope of the thesis, however [15-16] is followed for the calculation of losses during the proceeding simulations. The variations in voltage (i.e. the reactive power) are incorporated by TSO, and thus the TSO- controller at the point of interconnection provides the reactive power mismatches.

The STATCOM model is taken from [17], which has the capability of 20 MVAR. The reactive power provision is provided through a controller that is in accordance with the power-electronics based components. The

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STATCOM is connected to the secondary side of the transformer to assure the voltage compatibility, and the primary side is supplied to the point of interconnection for reactive power provision. Table 9 shows the results of scenarios created with respect to the variations set by the TSO controller.

Table 9. Demonstration for Over-voltage Violations

VAR variations by TSO	Reactive Power Provision by Power Plant	Reactive Power Provision by STATCOM
Increase of 20 MVAR	Supply of 1.36 MVAR	Supply of 18.64 MVAR
Increase of 25 MVAR	Supply of 10.78 MVAR	Supply of 14.21 MVAR
Increase of 35 MVAR	Supply of 16.38 MVAR	Supply of 18.61 MVAR
Decrease of 20 MVAR	Consumption of 1.90 MVAR	Consumption of 21.90 MVAR
Decrease of 20 MVAR	Consumption of 3.11 MVAR	Consumption of 21.88 MVAR
Decrease of 20 MVAR	Consumption of 13.14 MVAR	Consumption of 21.85 MVAR

The flexibility STATCOM can generate to the conventional synchronous generators can be viewed in a different perspective. From the conventional point of view, distributed resources cause reactive power mismatches (hence voltage instability) at the MV node. TSO asks for conventional coal and CCGT plants for the compensation, where STATCOM can generate flexibility in terms of reactive power provision. From another perspective of transmission operator, these STATCOMs can be installed at the distributed generation nodes, where stability can be achieved directly with less remuneration from the power plants.

4.3.2 Addition of STATCOMs

The STATCOMs with provision of 2 MVAR are installed at the nodes 9, 36, 44, and 63 where the distributed generators are present. All the other conditions remain the same and the quasi-dynamic analysis are performed. The results are shown in Table 10. It is obvious that the addition of STATCOMs reduce the over-voltage from 1.056 per-unit to 1.052 per-unit at node 10. At other nodes also, the effect is visible, and there are only two nodes (i.e. 10 and 19) now with over-voltages. There is no overloading of lines, and no under-voltage violations.

Table 10. Voltage after 2 MVAR STATCOMs

Node Numbers	Maximum Voltages in per-unit without 2 MVAR STATCOM	Maximum Voltages in per-unit with 2 MVAR STATCOM
10, 19, and 9 over-voltage	1.056, 1.056, and 1.052	1.052, 1.052, and 1.048.
32, 33, 20, 8, 4, 29, 25, and 18 close to over-voltage	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, 1.041, and 1.040	1.046, 1.045, 1.040, 1.039, 1.039, 1.040, 1.038, and 1.037

As per the VQ curve and the study in [18-19], the appropriate ratings of STATCOMs are used, and the curve provides the maximum stability at a value of 1.5 MVAR. The results are shown in the Table 11. There is no overloading of lines, and no under-voltage violations. Table 11 indicates that the grid now has no voltage violations.

Table 11. Voltage after 1.5 MVAR STATCOMs

Node Numbers	Maximum Voltages in per-unit without 2 MVAR STATCOM	Maximum Voltages in per-unit with 2 MVAR STATCOM
10, 19, and 9 over-voltage	1.056, 1.056, and 1.052	1.047, 1.047, and 1.044.
32, 33, 20, 8, 4, 29, 25, and 18 close to over-voltage	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, 1.041, and 1.040	1.043, 1.042, 1.038, 1.037, 1.036, 1.038, 1.036, and 1.035

4.4 Flexibility to DSO by the Addition of Distributed Generators

The DGs are modelled within DIgSILENT, at nodes 9, 10, and 19, to analyze the effects on voltage loading. The types of DGs are wind, hydro, and PV with their generation profiles in Figures 22, 23, and 24 respectively. The impacts on node voltages with and without DGs are represented in Figures 25-30. Table 2 indicates the comparison of the node voltages with and without the respective DGs.

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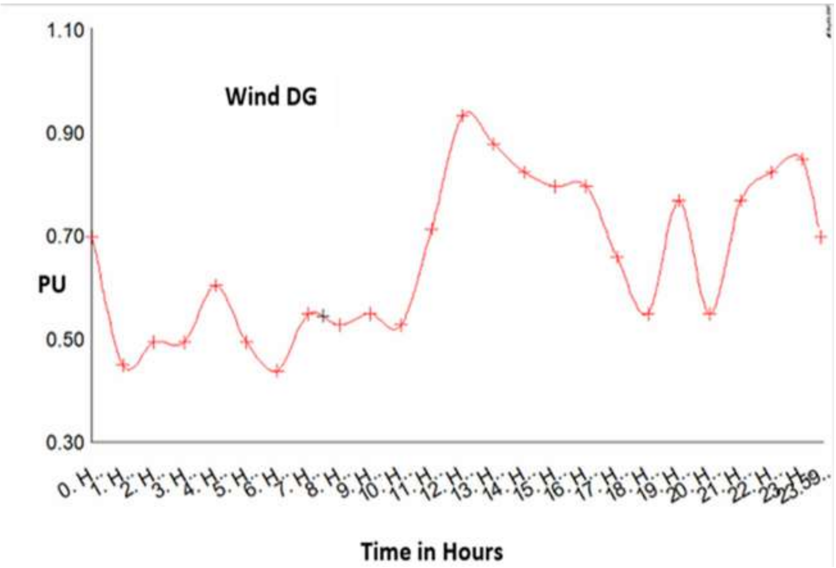

Figure 22: DG Profile for 24 Hours: Wind

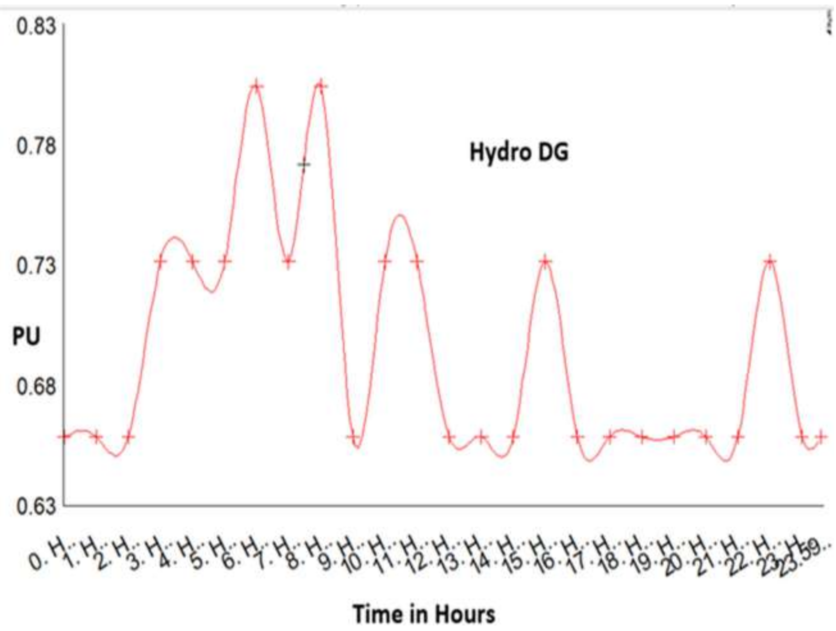

Figure 23: DG Profile for 24 Hours: Hydro

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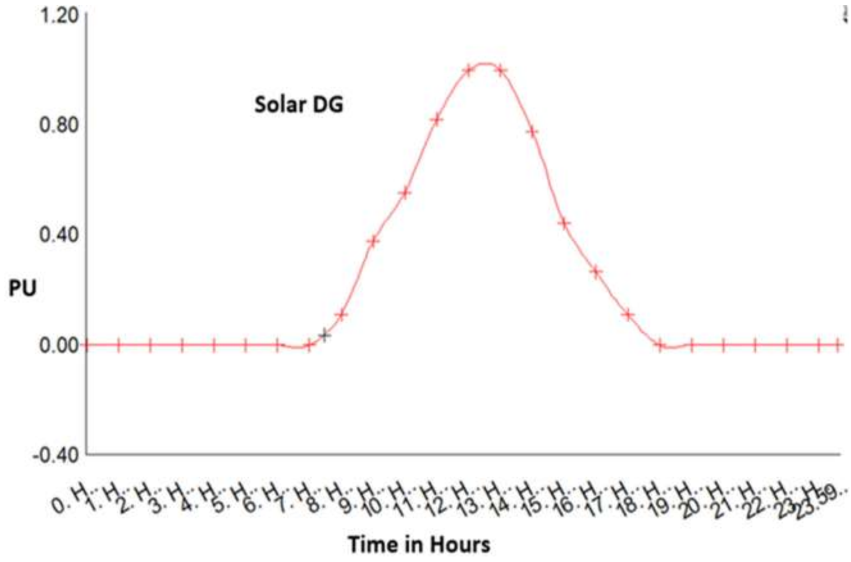

Figure 24: DG Profile for 24 Hours: PV

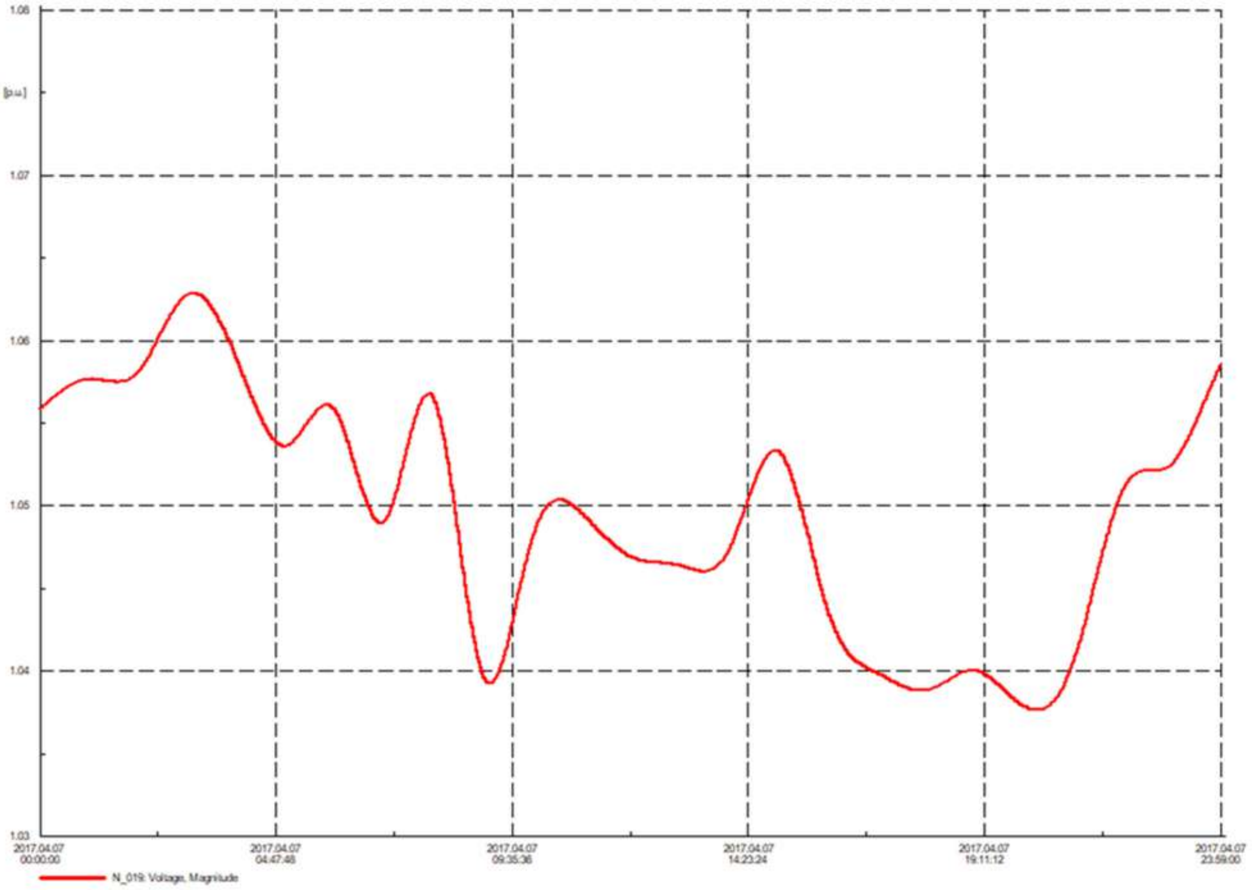

Figure 25: Voltage Loading at Node 19: Without PV

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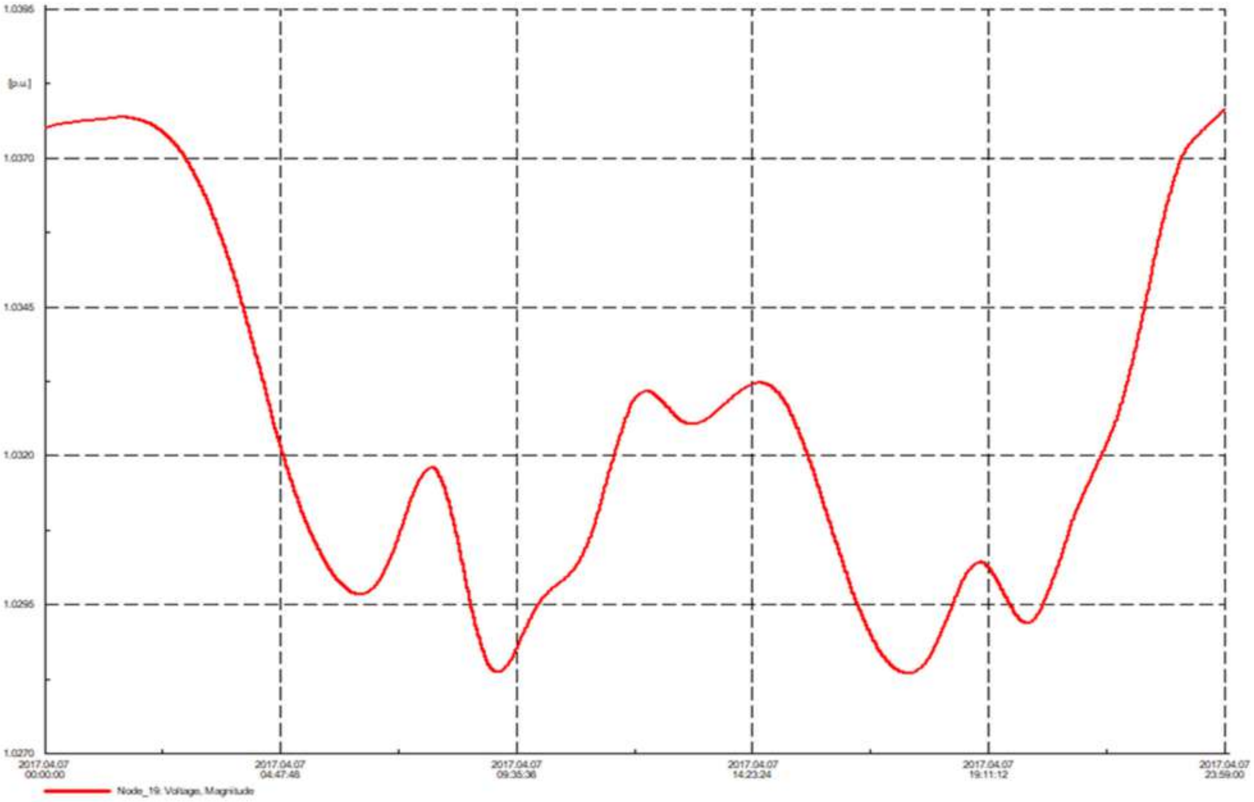

Figure 26: Voltage Loading at Node 19: With PV as DG

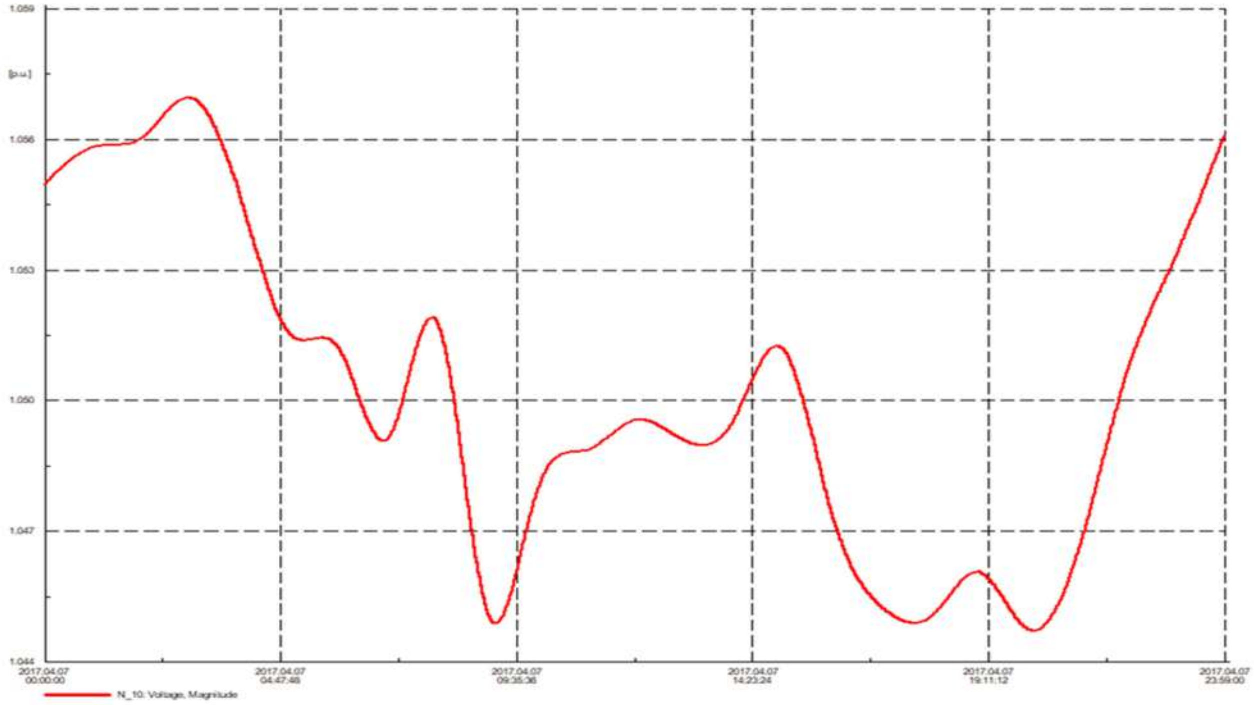

Figure 27: Voltage Loading at Node 10: Without Hydro

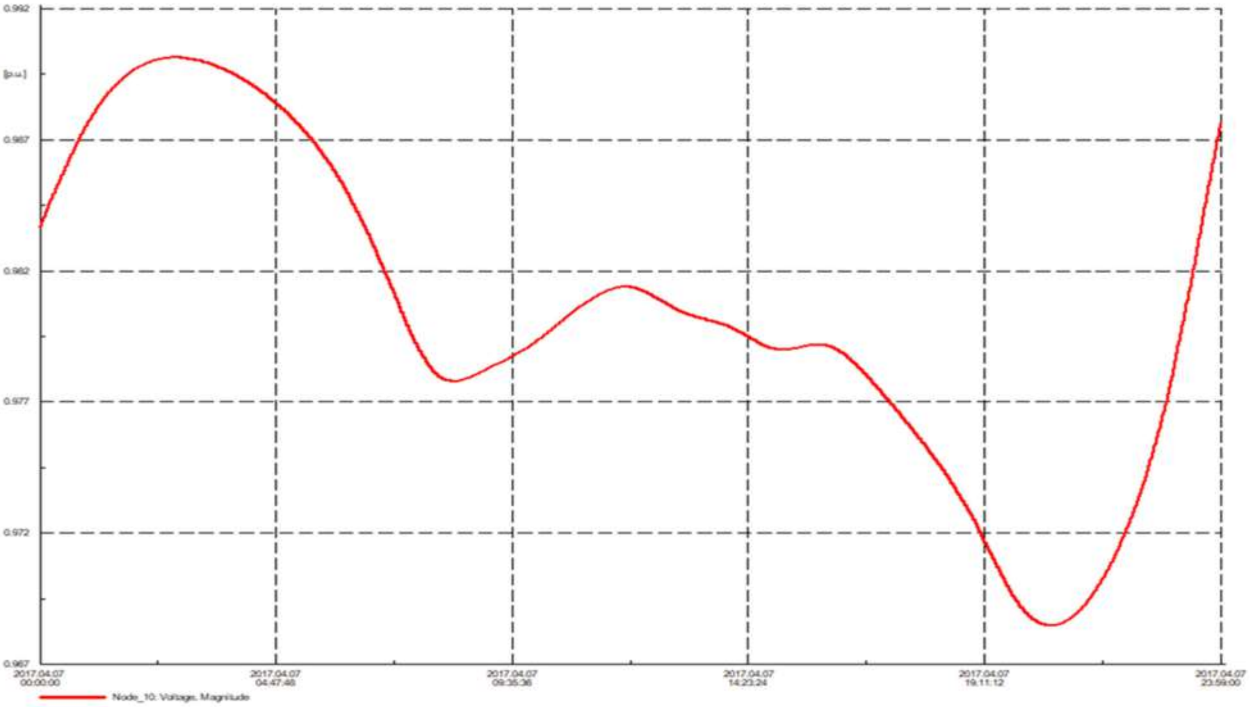

Figure 28: Voltage Loading at Node 10: With Hydro DG

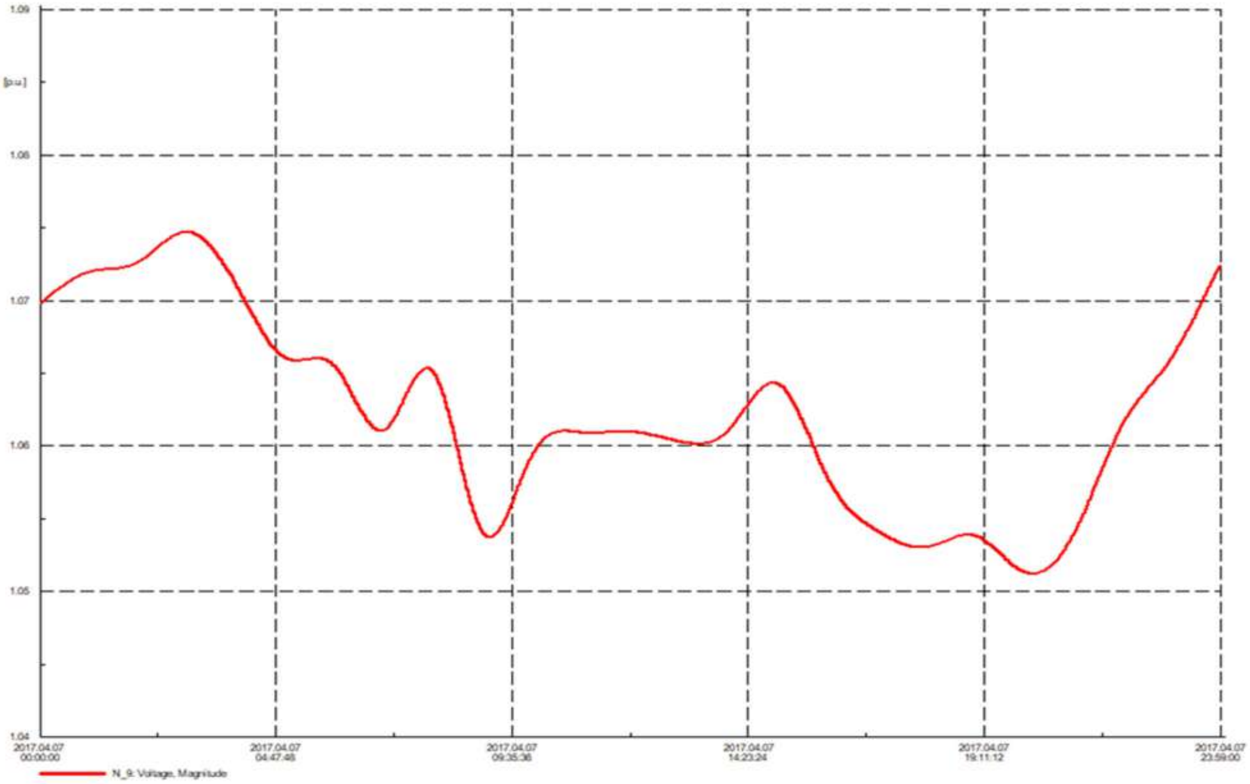

Figure 29: Voltage Loading at Node 9: Without Wind

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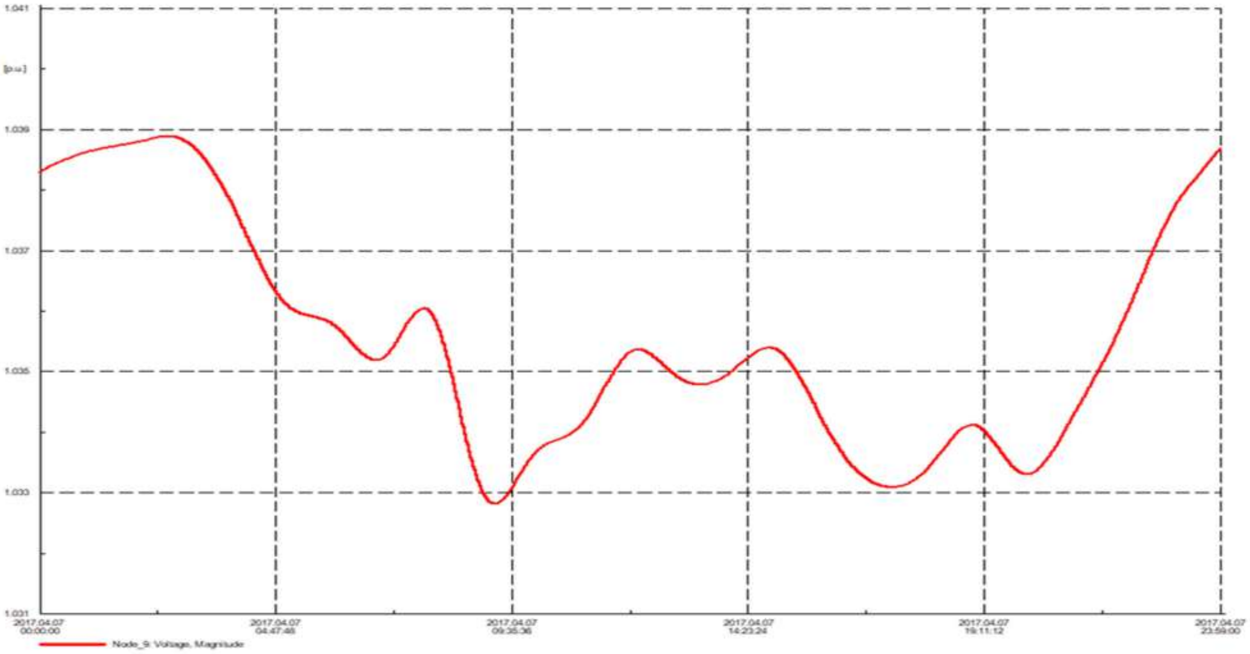

Figure 30: Voltage Loading at Node 9: With Wind DG

Table 12. Node Voltage after Planned DGs

Node Numbers	Maximum Voltage in per-unit(Before DG)	Maximum Voltage in per-unit(After DG)
10	1.056	0.986.
9	1.056	1.0388.
19	1.052	1.0376.

DERs impact the grid in both positive and negative ways. The chapter discusses the negative impact on the voltage of a chosen distributed grid, due to the influence of these distributed resources. The selected grid is defined and modelled in DIgSILENT. The static and the quasi-dynamic analysis are performed, and the results indicate no voltage violations without taking into account the distributed resources.

The distributed resources are modelled using DIgSILENT, and are added to the nodes of the distribution grid. The quasi-dynamic analysis indicates the issues of voltage violations at some of the nodes after the influence of these distributed resources in the grid. The chapter then suggests the management of voltage limits by the provision of reactive power, using STATCOM. The STATCOM is modelled within DIgSILENT, and the flexibility to TSO for the provision of reactive power is discussed. The STATCOMs are then added to the nodes prone to over-voltage, and then the quasi-dynamic analysis is repeated. The results suggest that the addition of STATCOMs improve the transmission-end grid in terms of voltage violations.

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The chapter then suggests the management of voltage limits by the planned addition of DGs. Three types of DGs are modelled within DIgSILENT, and then added to the nodes with over-voltage. Then the quasi-dynamic analysis is repeated. The results suggest that the planned addition of DGs improve the distribution-end grid in terms of voltage violations. It emphasizes the flexibility to DSO for the provision of reactive power, with DGs. The results indicates the flexibility to DSO by the addition of DGs, and flexibility to TSO by the addition of STATCOM.

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Chapter 5: Co-Simulation of Storage Model in MATLAB/Simulink

5.1 Techno-Economic Analysis of Potential Storage Systems

This chapter is dedicated to use storage system to support system operators for services. The type of service is frequency restoration, and in order to create market for FFR, the primary response has to be fast enough. This requires techniques with fast response for better compensation of real power reserves. The compensation can be provided through conventional, and VPP based techniques; and the analysis is shown in Table 13 [1-2]. The new actors employ inverter-based techniques for the service with emphasis on response to service request, service restoration time, and economics for low/high provision. The table shows that storage system is best suited in terms of better flexibility, adequacy, and response time. Next step is to compare potential storage technologies for the frequency service.

Table 13. Potential Service Providers

Technique Name	Key points
Synchronous Generator	High amount of provision at high costs. High activation time of 5-6 seconds. Provision can be as long as the machine is in operation.
VPP based battery storage system	High amount of provision with better flexibility than SG. Only point is absence of grid inertia Faster than SG; battery discharges at a faster rate. 200 m-sec response time. Low activation time[2]
VPP based wind farm	High (but investments are required to build doubly fed induction generators plant). Grid inertia provided by supplementary control loop. Activation in 12 seconds. Intermittent without storage Suitable for small scale [1].

Literature suggests a variety of electrical storage options in various forms, and the distinctions are made according to applications. For the provision of FFR, the parameters of interest include response time, discharge duration, rated power, and the maturity level of technology. From a long list of potential technologies, four are chosen (which are mentioned below) on technical grounds and for further economic analysis. The choice covers all maturity levels of technology, and suitable parameters range for this application [3].

The first one is flywheel, with response time in seconds; up to 15 minutes discharge duration, and commercial availability. Next commercial solution is advanced Li-ion with better response time and discharge duration. Lead acid is chosen as mature, and flow batteries mechanism is considered as developing option. The selection is based on analysis in [3]. Further selection amongst these four depends on capital/operating costs, and the procurement application. Next section is dedicated to economic analysis amongst these four technologies, and then to analyze the performance of the selected one w.r.t base conventional technique in section II.

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These four storage technologies are economically compared using ES-Select tool [4]. Investment cost vs discharge duration analysis is presented in Figure 31. For each of the four technologies, the discharge duration and the investment costs are compared at rated efficiency. Three rated efficiency values (w.r.t 100 MW) are used: 50%, 75%, and 80% respectively. In order to create a better visualization with the technical analysis in previous section, the graph displaying efficiency-discharge duration is shown in Figure 32.

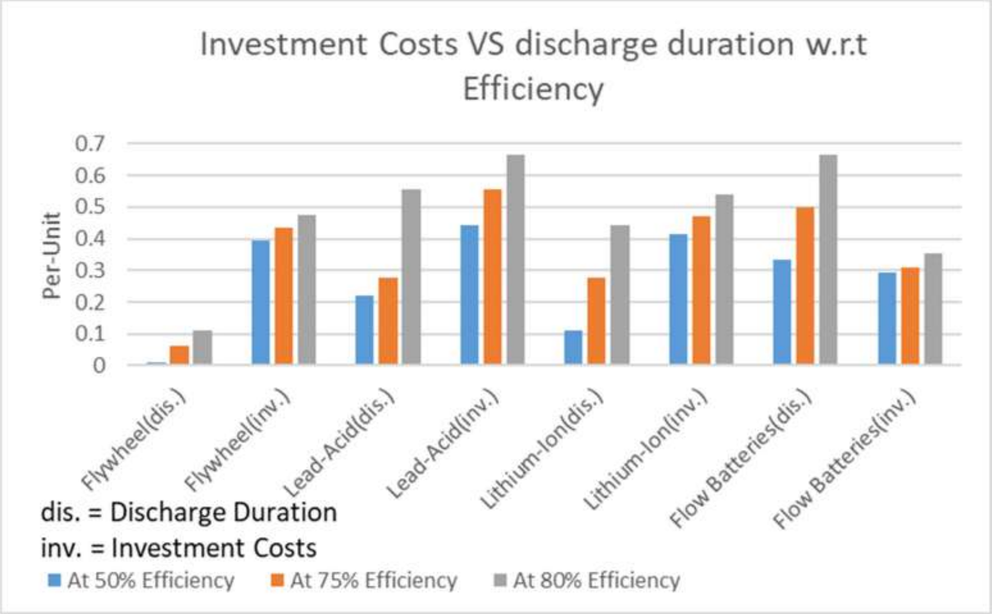


Figure 31: Discharge duration VS investment for battery options

From the analysis of Figures 31-32, it is visible that flow batteries require the least capital investment and provide the best discharge duration. The analysis is further supported by the results from ES-Select tool, as in Figures 33-34. However, the technology is not mature enough and the efficiency is the least amongst the selected options. Lithium-ion is the average in capital costs and discharge duration, but it provides the best efficiency with the commercial level maturity. Lead acid is the most expensive investment, but is better in energy efficiency and maturity level. Flywheel is an emerging technique with limitations on discharge duration, so it can only serve a limited period. VPP integrated model is shown in Figure 35.

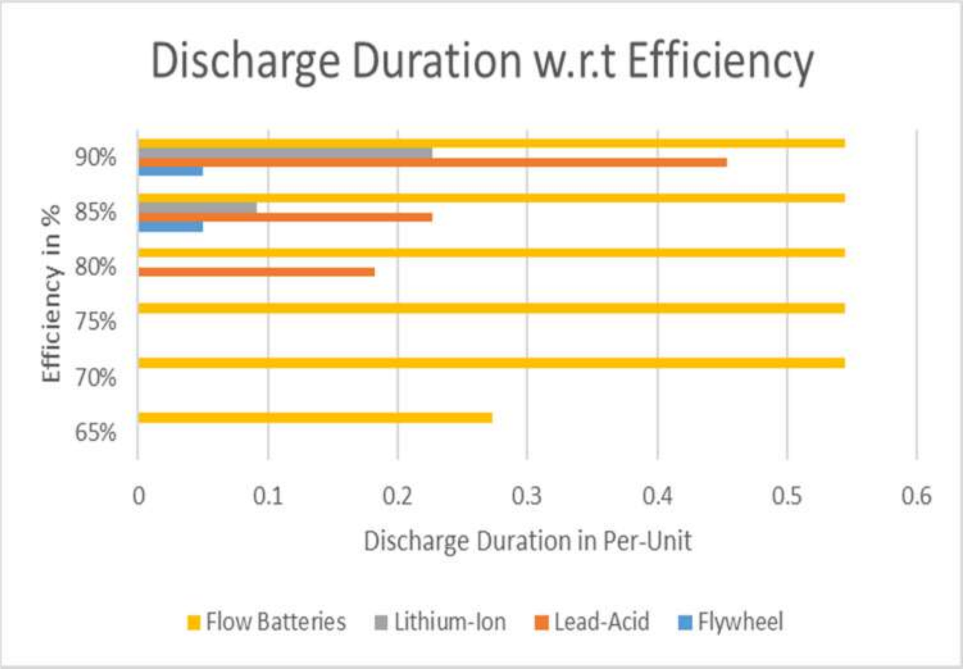
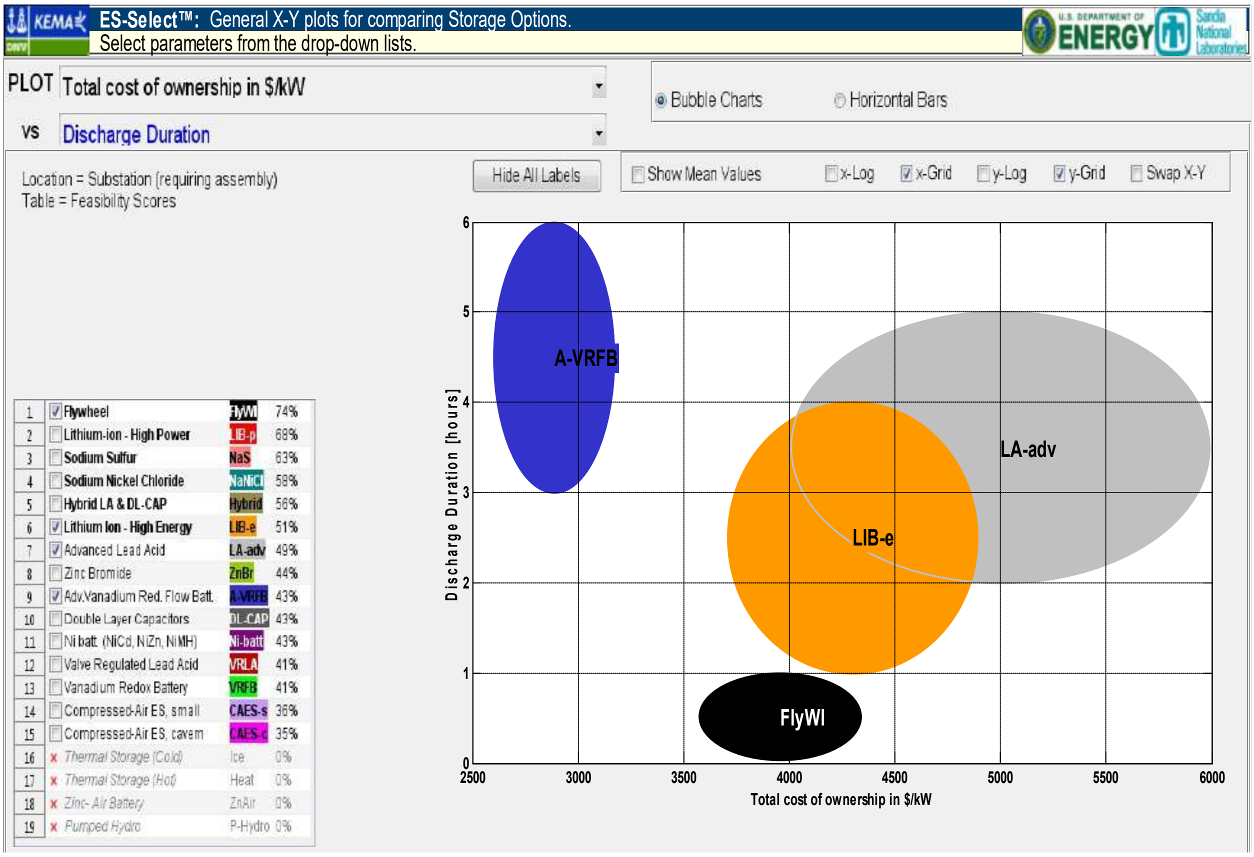


Figure 32: Energy Efficiency VS Discharge Duration for Battery Options



PLOT Total cost of ownership in $/kW
VS Discharge Duration

● Bubble Charts ○ Horizontal Bars

☐ Show Mean Values ☐ x-Log ☑ x-Grid ☐ y-Log ☑ y-Grid ☐ Swap X-Y

Location = Substation (requiring assembly)
Table = Feasibility Scores

1	☑ Flywheel	FlyWl	74%
2	☐ Lithium-ion - High Power	LIB-p	68%
3	☐ Sodium Sulfur	NaS	63%
4	☐ Sodium Nickel Chloride	NaNiCl	58%
5	☐ Hybrid LA & DL-CAP	Hybrid	56%
6	☑ Lithium Ion - High Energy	LIB-e	51%
7	☑ Advanced Lead Acid	LA-adv	49%
8	☐ Zinc Bromide	ZnBr	44%
9	☑ Adv.Vanadium Red. Flow Batt.	A-VRFB	43%
10	☐ Double Layer Capacitors	DL-CAP	43%
11	☐ Ni batt (NiCd, NiZn, NiMH)	Ni-batt	43%
12	☐ Valve Regulated Lead Acid	VRLA	41%
13	☐ Vanadium Redox Battery	VRFB	41%
14	☐ Compressed-Air ES, small	CAES-s	36%
15	☐ Compressed-Air ES, cavern	CAES-c	35%
16	☒ *Thermal Storage (Cold)*	Ice	0%
17	☒ *Thermal Storage (Hot)*	Heat	0%
18	☒ *Zinc- Air Battery*	ZnAir	0%
19	☒ *Pumped Hydro*	P-Hydro	0%

in

Figure 33: Discharge Duration VS Investment for Battery Options – ES Select Tool

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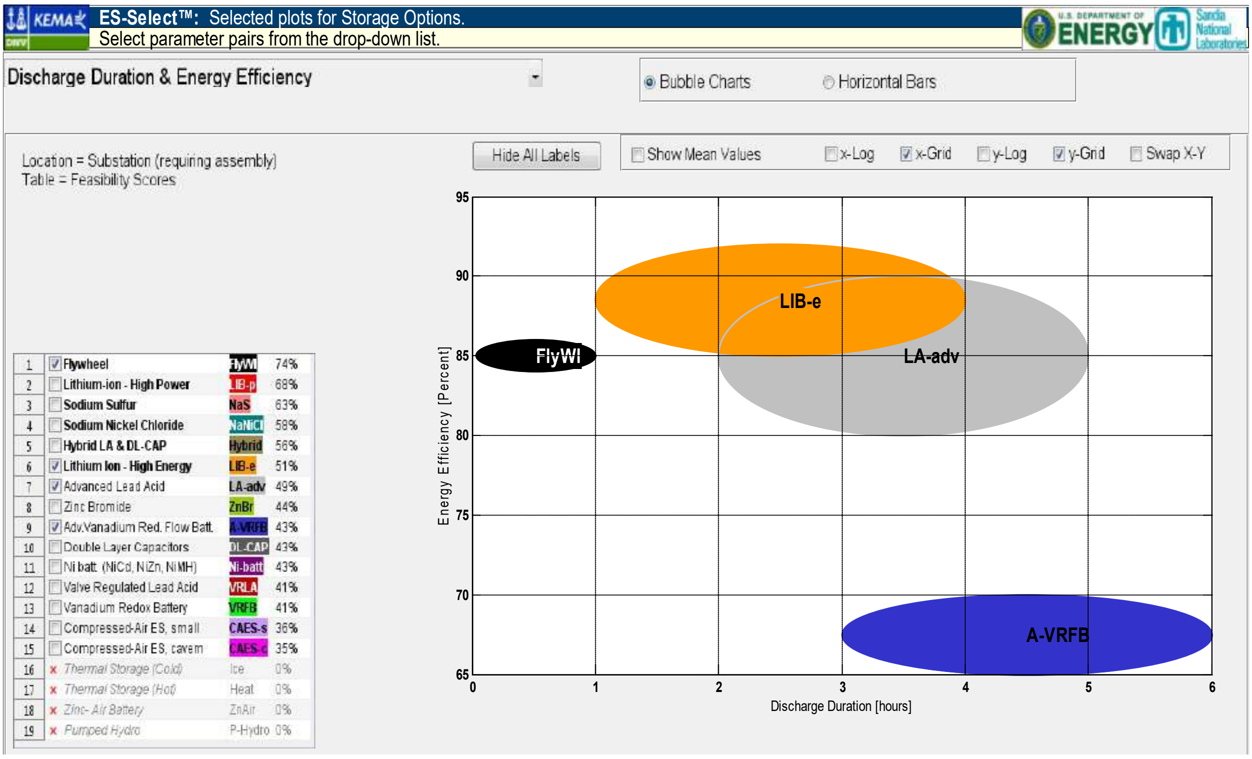

ES-Select™: Selected plots for Storage Options.
Select parameter pairs from the drop-down list.

Discharge Duration & Energy Efficiency

● Bubble Charts ○ Horizontal Bars

Location = Substation (requiring assembly)
Table = Feasibility Scores

1	☑ Flywheel	FlyWl	74%
2	☐ Lithium-ion - High Power	LIB-p	68%
3	☐ Sodium Sulfur	NaS	63%
4	☐ Sodium Nickel Chloride	NaNiCl	58%
5	☐ Hybrid LA & DL-CAP	Hybrid	56%
6	☑ Lithium Ion - High Energy	LIB-e	51%
7	☑ Advanced Lead Acid	LA-adv	49%
8	☐ Zinc Bromide	ZnBr	44%
9	☑ Adv.Vanadium Red. Flow Batt.	A-VRFB	43%
10	☐ Double Layer Capacitors	DL-CAP	43%
11	☐ Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	43%
12	☐ Valve Regulated Lead Acid	VRLA	41%
13	☐ Vanadium Redox Battery	VRFB	41%
14	☐ Compressed-Air ES, small	CAES-s	36%
15	☐ Compressed-Air ES, cavern	CAES-c	35%
16	✗ *Thermal Storage (Cold)*	Ice	0%
17	✗ *Thermal Storage (Hot)*	Heat	0%
18	✗ *Zinc- Air Battery*	ZnAir	0%
19	✗ *Pumped Hydro*	P-Hydro	0%

Hide All Labels ☐ Show Mean Values ☐ x-Log ☑ x-Grid ☐ y-Log ☑ y-Grid ☐ Swap X-Y

Figure 34: Energy Efficiency VS Discharge Duration for Battery Options – ES Select Tool

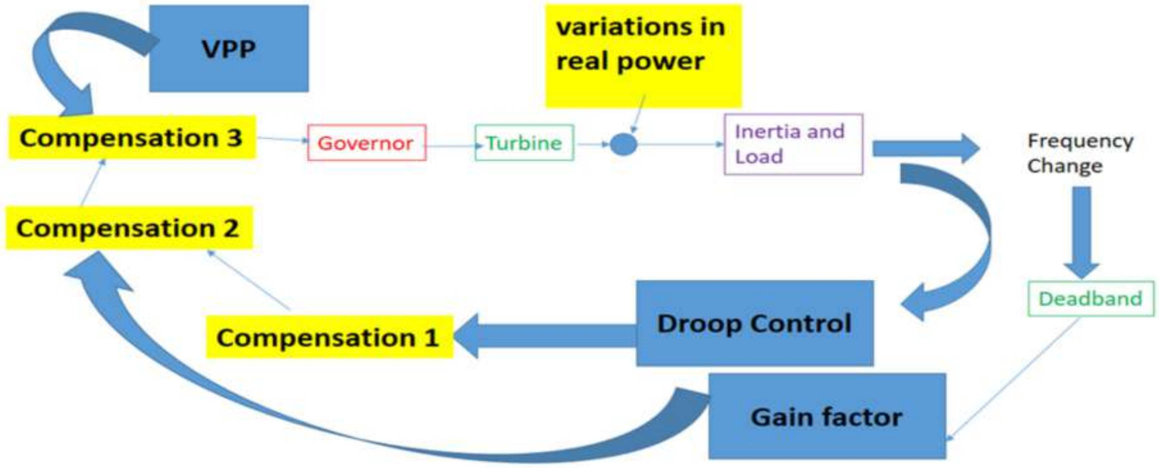

Figure 35: Frequency control integrated technique – with VPP ([5])

Next step is to perform the techno-economic analysis on a single scale, to decide the best regions of operation for each selected technology. The analysis is performed in PU, with the following base values: 5000$ for investment, 5 hours for discharge duration, and 100% for efficiency. The rated power is assumed 100 MW to comply with base case, and the results are shown in Figure 36. The results can be analyzed starting from efficiency, which can be divided into two zones: High efficiency zone, and reduced efficiency zone. For the high efficiency zone, the competition is amongst flywheel, lithium-ion, and lead-acid. Within this zone, the most expensive option is lead-acid, but with the best discharge duration.

In order to reduce the investments, there is a point of comparison amongst flywheel and Lithium-ion. For a given cost, flywheel provides less discharge duration than Lithium-ion. Therefore, flywheel is discarded from this zone. For the reduced efficiency zone, flow battery is the best option with the best discharge duration, and least investment. This leads to three competitors, i.e. lead-acid, lithium-ion, and flow batteries amongst two different application zones. The analysis is shown in Table 14.

Table 14. Application Zones VS. Potential Service Providers

Zone of Operation	Prioritized Options	Merits
High Efficiency	Lead-acid and Lithium-ion	Trade-off amongst costs, and discharge duration, with best efficiency
Reduced Efficiency	Flow batteries	Best discharge duration, and least cost requirements, but with compromised efficiency

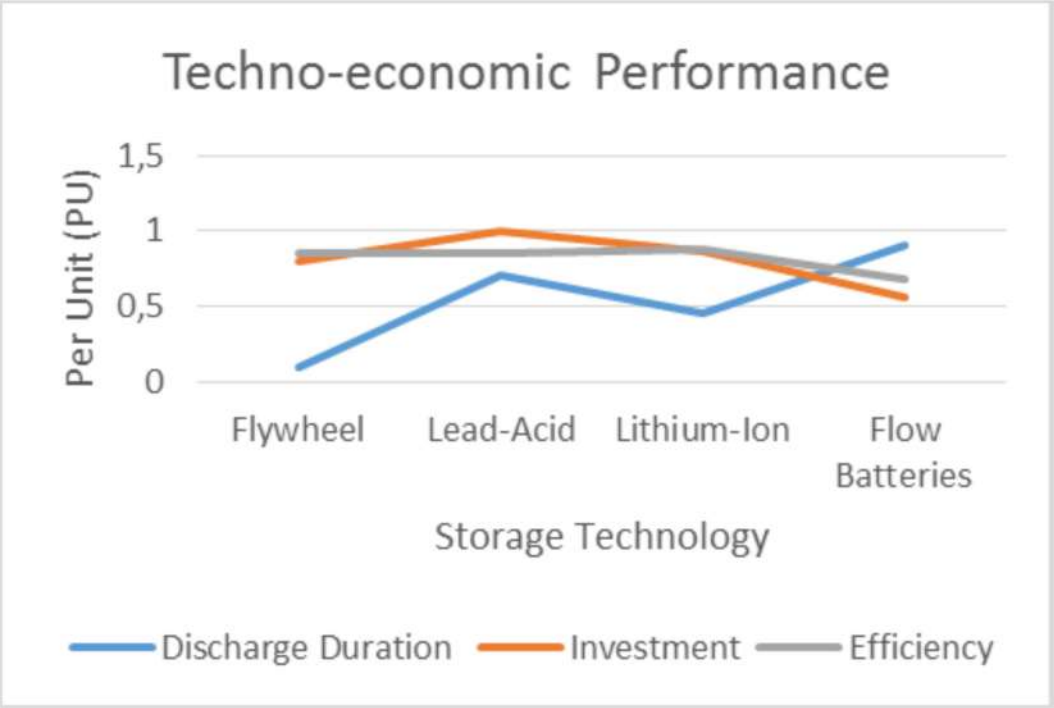

Figure 36: Combined Performance of Battery Options

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For FFR, the requirement is high efficiency, so the comparison remains amongst lead-acid and lithium-ion. For the service provision, aggregation for both these technologies is used. Next step is to compare the performance of aggregated storage option with three cases: mixed aggregation, 60-40% aggregation, and 70-30% aggregation mix.

The results are shown in Figure 36, which shows that the aggregation, as a package, is always better than the base cases. TSO can request the service in any such forms, it can be the fast service for which efficiency is considered in Figure 37. For long service duration; discharge duration is given importance, and for reduced costs (at high flexibility), aggregation trade-off can be visualized.

These aggregation criteria are representative of the technology, and the use of service. It also depends upon the specific service requirement from TSO.

5.2 Modeling of Storage System in MATLAB/Simulink

For the analysis of VPP in the context of this chapter, the model of VPP is taken from [6]. The equivalent model for Lithium ion battery is based on the characteristics of self-healing, as shown in Figure 38 (taken from [6]).

The battery, targeting 1 MW loads, is placed at the LV end of the grid. The operating point open-circuit voltage from [6] is 3.48 Volts, which can stand for a period of 1 hour. Therefore, the Watt-hour rating for storage system would be 1 MW-h. Consider that the inverter can operate with 85% efficiency; the safe Watt-hour rating for storage system would be 1.18 MW-h, the battery capacity would be 339 k-Ah. The next step is the identification of battery manufacturer, and the number of battery sets in series and parallel.

The selected Lithium ion battery has the nominal capacity of 100 Ah, and complies with the calculated values of maximum depth of discharge, discharge rate factor, and rated capacities. It leads to 3390 sets of batteries in parallel and 35 sets in series. All the battery related calculations are based on theory and analysis in [7].

The battery is charged using a PV panel, with demonstrations of renewable-storage integration in [8-9], in section 1, and the 1MW loads are added with the representative customers in section 2. An example of the behavior of battery system during the charging phase (0 to 1.4 time instants), discharging phase (1.4 to 2.8 time instants), and during no-operation periods are shown in Figure 39.

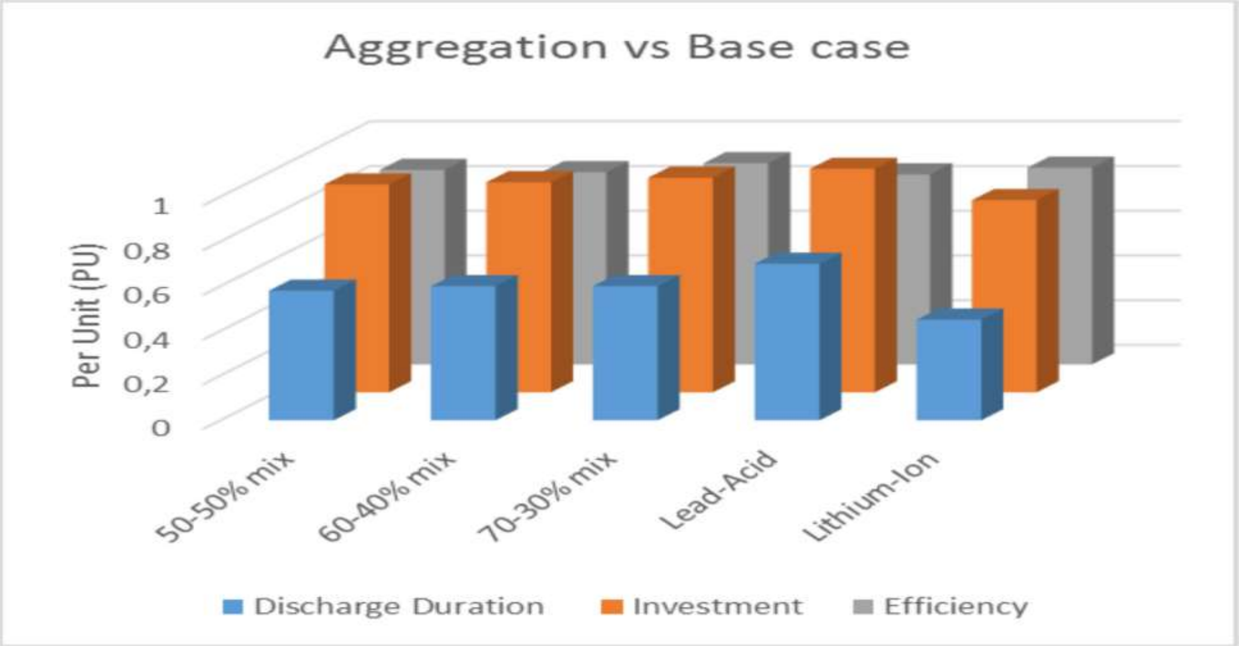

Figure 37: Aggregation Performance of Battery Options

5.3 Analysis of Service Provision with the Selected Storage under VPP

Next step is to analyze the performance of this storage system for FFR, as service to TSO. The system in Figure 35 is implemented with compensation 1 – Governor, compensation 2 – extended dead band, and compensation 3 – VPP. The system is implemented in MATLAB/Simulink. First, Primary frequency control is provided by governor control at turbine, where the frequency is dependent on rotor angular speed. The details are provided in [10], with the equivalent representation of control in figure 1 adapted from [10]. All values of turbine time constant, governor time constant, and inertia constant H [1] are taken from [10].

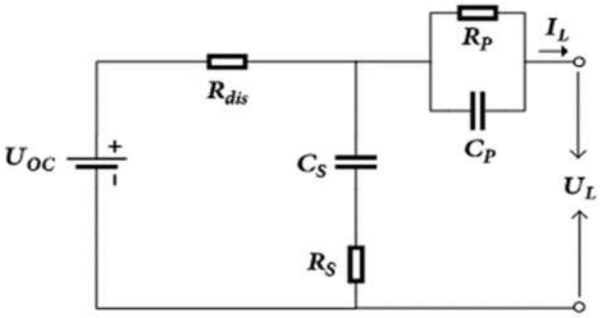

Figure 38: Equivalent Model for Lithium Ion Battery (from [6])

The compensation factor is deduced from [5], which occurs from the fact that the frequency variations are high enough, and thus the swing equation mechanical and electrical powers are never equal in the swing equation. The model for this compensation power is taken from [5], which introduces a gain factor K

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incorporating the frequency changes and the dead band. The modified system diagram is shown in Figure 35. From [5], large dead band is used to reduce procurement cost, following all the requirements of nadir frequency and FCR timings (settling time, and restoration time).

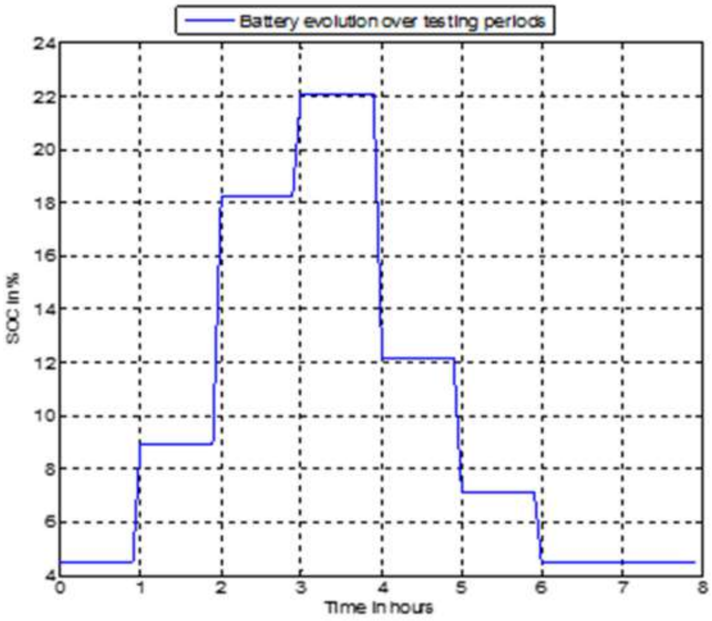

Figure 39: Battery Evolution over Testing Periods

For the rated power, the system is operated at a rated frequency. In other words, the frequency change is zero when there is no variation at the loads. Then, the load is varied from 1% to 10% of rated power (with step size of 1%), and the frequency change is observed. The point of disruption is noted, at that particular load level. The gain factor is applied with the real power reserves to adjust the frequency change within the required dead band [5]. The time for the service is noted. The system is implemented in MATLAB/Simulink, with Governor Time constant = 0.11 seconds, Turbine time constant = 0.40 seconds, Droop = 6%, extended dead band = 80 mHZ,

All loads have 100 MW rated power. With no compensation, the frequency is not settled at all as in Figure 40. With the governor control, the frequency is settled for 30 seconds, but the dead band is very close as in Figure 41. The dead band is further secured by compensation 2 in Figure 42. With the use of storage system as VPP in Figure 43, the response has a better dead band margin with the requisites.

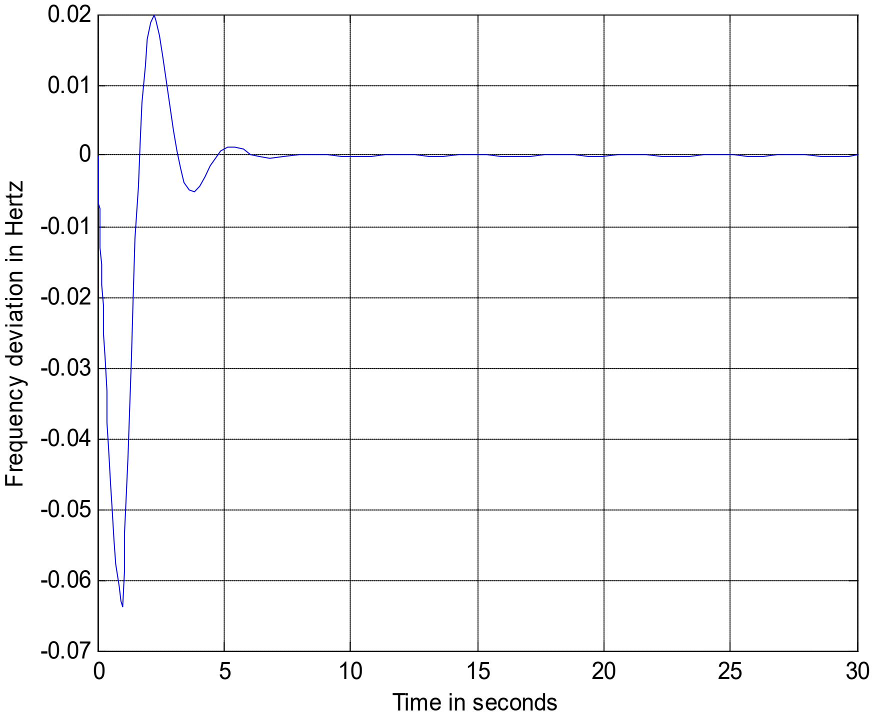

Figure 40: Frequency Response – No Compensation

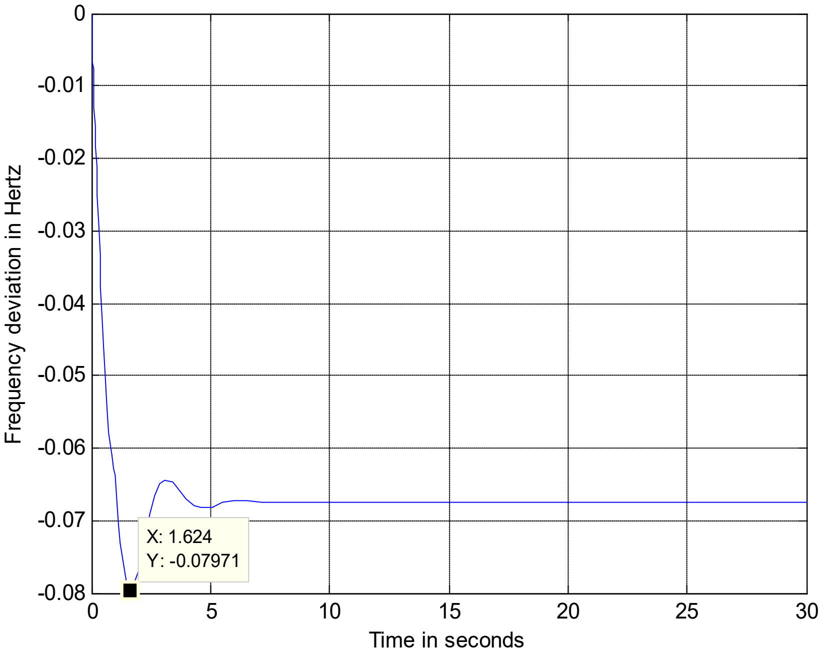

Figure 41: Frequency Response – Compensation 1

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From references [12-13]; there are three types of frequency reserves: FCR, FRR in automatic (secondary) and manual (tertiary) modes, and RR. TSO, in general (excluding some European countries), remunerates the providers for FCR with a 30 seconds activation time [14-15]. These real power reserves that are used for FCR need to be very fast in response, and thus the participants for this service are bound to ensure the use of relevant technologies only [11]. Due to these characteristics requirements; battery energy storage is thus a literature mostly discussed solution as in [16].

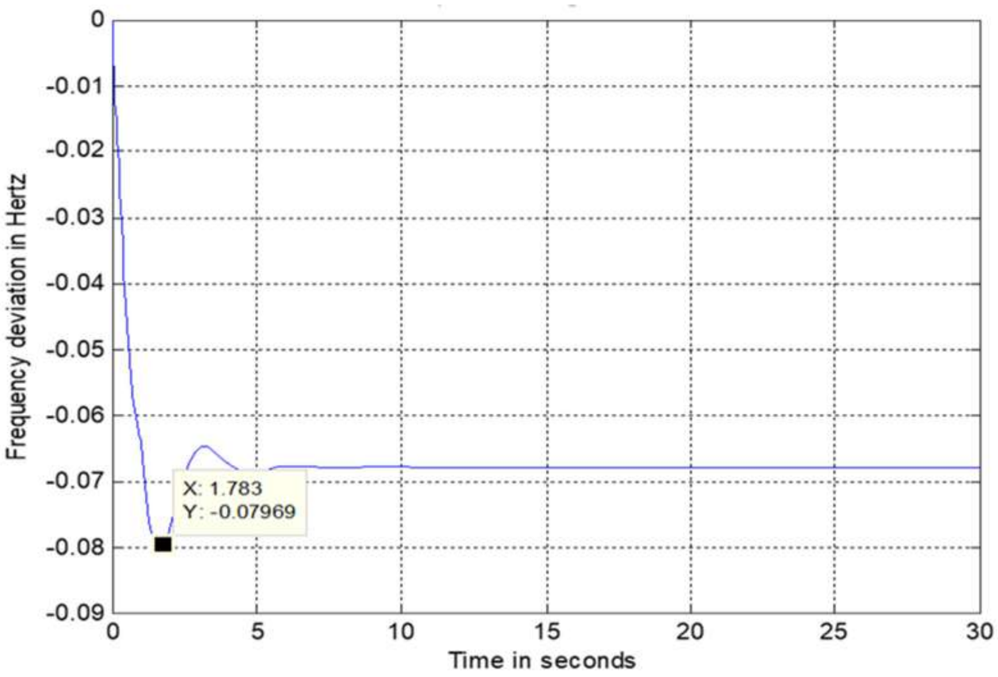

Figure 42: Frequency Response – Compensation 1&2

The secondary reserves have a time limit of 7.5 minutes with a centralized control from TSO as in [17]. Different TSO of different countries may have different time limits, and different remuneration strategies. In the context of this chapter, Italy is used as the reference country, and the primary reserves are only discussed. For the Italian system, FCR has to be sustained within 30 seconds, and secondary reserves in 4 minutes. However, with the large frequency deviations, FCR has to reach the settling frequency within 10 seconds [18]. With the new service providers in the market, another important service is Fast Frequency Response (FFR) for which TSO remunerates for restoration within 2 seconds [19]. Nadir frequency is assumed to be 100 mHz (0.2% with reference to 50 Hz), as a pessimistic bound for further analysis [20].

Frequency regulation is one of the basic objectives in ancillary market, which involves different stages and multiple participants. There exists different techniques for this service, where the points of demarcation are the time of service, and the regulatory requirements. The chapter discusses primary frequency regulation, w.r.t Italian regulations, which is provided by conventional power plants upon TSO requests. The chapter demonstrates conventional technique with its limitations, and proposes use of Virtual Power Plant (VPP) for the service provision. The use of storage is motivated, and technical/economic comparison amongst potential storage techniques is done.

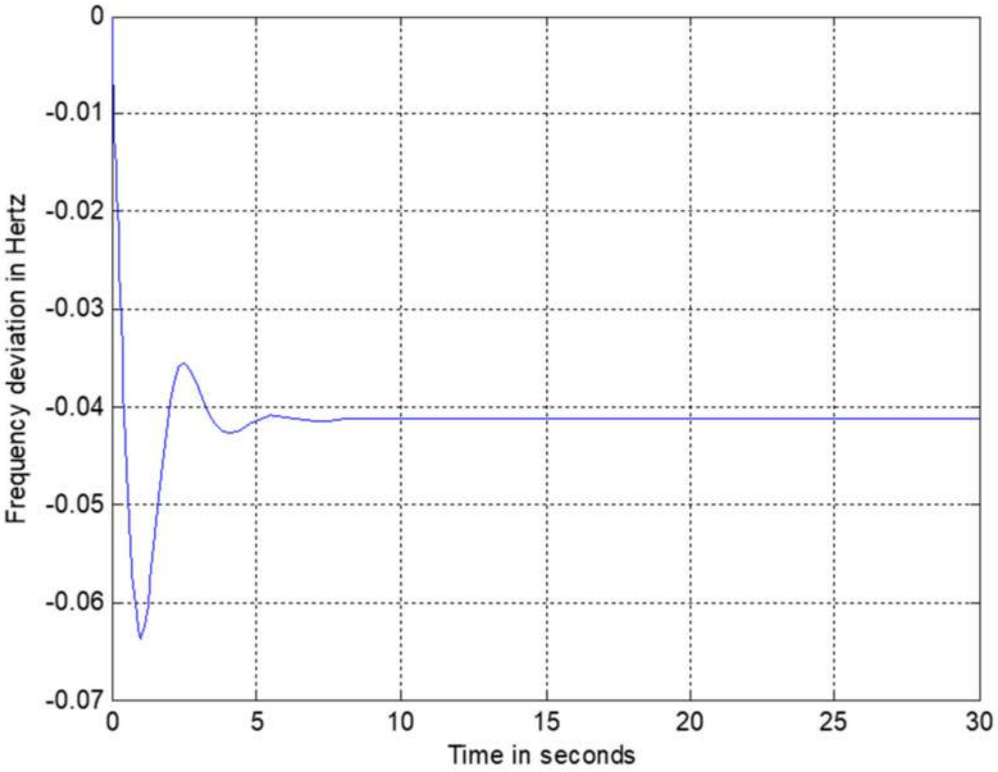

Figure 43: Frequency Response – Compensation 1, 2, & 3

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Chapter 6: Interface amongst co-simulators to simulate VPP chain

6.1 Description of the Interface

This chapter aims to develop a distribution level aggregator platform for DSO support, with Integration of storage, demand response, and renewables. The support is primarily the flexibility to operator, and in particular, DSO for distribution grid. The chapter suggests the use of distribution level aggregators to serve as sub-DSO (JDSO). These aggregators utilize three main components: Electrical energy storage system, customers demand response, and the renewable resources (PV and wind). These aggregators utilize a platform where all these actors can participate. DSO-JDSOs interaction is possible through the platform, and the local problems at distribution can be resolved before it goes to TSO. Chapter presents and simulates the platform, develop test cases, and validate the model.

There are a variety of aggregator platform providers with demarcations on software, services, and technology level. Literature further suggests plenty of aggregator platforms, with various protocols, and schemes; use of each protocol at each level is justified in its respective application. The existing platforms include dynamic participation of different actors in a bidirectional manner. This leads to issues of high costs (with respect to infrastructure and high network traffic), regulatory barriers (as the market needs to be incorporated within the platform, and it varies for different trading regulations), and data handling (it can lead to data privacy issues, requirement of pro-active customers, and a huge human resource). In this chapter, the aggregators can only access the run-time service availability of participants, and can procure for service only upon requirement, which requires implementation of different components. The focus here is on the HMI and toolbox, participants, integration, and validation.

The HMI and the toolbox is implemented in LabVIEW real-time, and this is the source of interaction amongst JDSO control box (JDSO-B, i.e., Junior DSO) and DSO. Within JDSO- B, the access is provided to local JDSO customers, storage providers, and the wind-solar participants. Implementation of this platform is done through LabVIEW RT based OPC— socket programming. The chapter proposes a pilot scheme for the three providers, and implements them on LabVIEW, MATLAB/Simulink, and DIgSILENT, respectively. All the three actors communicate to JSDO-B through their respective Matrikon based OPC server. Then, a test case is presented to form basis to experimentally simulate the platform.

6.1.1 Implementation of the Sub-Interface - Wind Farm in DIgSILENT

A 20 MW wind farm is used, which consists of four wind turbines. Each wind turbine has a nominal apparent power rating and power factor based on [1]. The model is taken from [2], with both MPPT and LVRT supports [3-4]. The model is implemented in DIgSILENT; and the power output for a 24-hour test day is noted, with a polling rate of 10 seconds. The generation profile is shown in Figure 44, and the real power output for 24 hours (at an interval of 2 hours) is recorded in Table 15. For later calculations, the PU values are used with a base value of 20 MW. Intermittency in real power is clearly visible from Figure 44.

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Table 15. Real Power Output for 24 Hours - Wind

Time (Hours)	Real Power Generated in MW
0	17.3
2	15.2
4	16.1
6	14.7
8	15.4
10	15.2
12	19.2
14	18.3
16	18.0
18	15.4
20	15.2
22	18.1
24	16.8

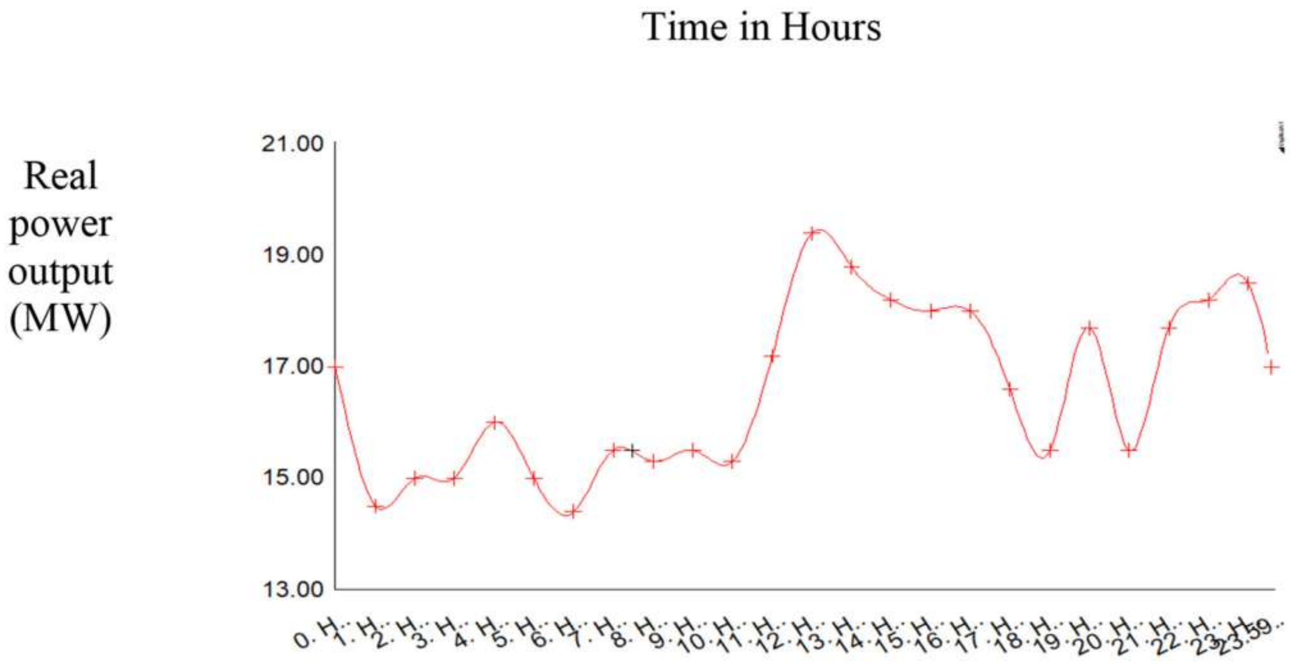

Figure 44: Generation Profile – Wind

6.1.2 Implementation of the Sub-Interface - Customers' Participation in LabVIEW

The idea is extracted from Chapter 3, where customers contribute towards ancillary service with the support of presented monitoring and recording tools. The customers participate using the Modbus protocol, where the interaction is amongst the meters and VPP controller. Modbus is used as the meters are compliant with Modbus automatic reading scheme. Details of Modbus communication, addressing, and

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communication pattern are already discussed in chapter 3, as in [5-6]. In this specific chapter, there are four customers, which have the capabilities to provide real power reserves via demand-response [7-8]. These customers have meters, which are Modbus-compatible [9], and communicate towards the VPP controller in a unidirectional manner.

Four types of customers are residential, commercial, aggregated, and residual. Residential customers are at LV node, while the remaining ones are on MV. For the polling of customer metering information, the Modbus-TCP specific addressing scheme is used [10]. The structure is implemented inside LabVIEW using Create TCP Master block for defining the IP address, Set Unit ID block for setting the Modbus id, and Read Holding Registers for defining the specific parameter of the meter, i.e. the real power in the context of this chapter [10]. The structure is already described in detail in Chapter 3.

Generation profiles for these four types of customers, for a 24-hour test sample, are shown in Figure 45. Table 16 shows the real power output, at some specific time instants, for the different types of customers.

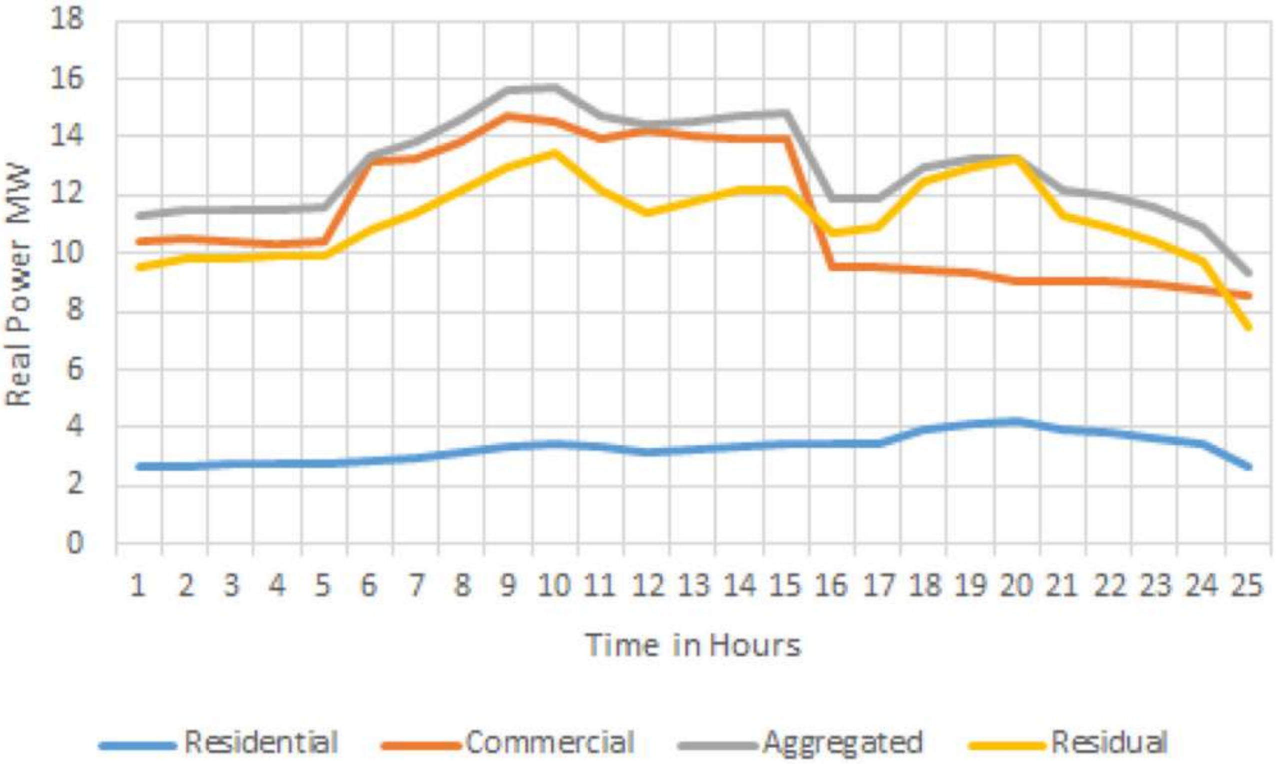

Figure 45: Generation Profiles – Customers

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Table 16. Real Power Output for 24 Hours - Customers

Time (Hours)	Customer Type	Real Power Generated in MW
0	Residential	2.65
2	Residential	2.74
4	Residential	2.76
6	Residential	2.97
8	Commercial	14.77
10	Commercial	13.91
12	Commercial	14.01
14	Aggregated	14.78
16	Aggregated	11.92
18	Aggregated	13.22
20	Residual	11.26
22	Residual	10.42
24	Residual	7.48

6.1.3 Implementation of the Sub-Interface - Storage System in MATLAB/Simulink

With the widespread penetration of renewable energy resources, which are not only intermittent but also additives under the existing grid, the idea of storage is the literature best solution to cope with these unplanned changes [11-13]. Under the umbrella of energy storage, use of battery is the first priority, and the most common and conventional battery technology is based on Lithium-ion cells [14]. The model is taken from Chapter 5, where all the relevant details are mentioned. The SoC values, at some specific time instants, for the extracted battery system (from Chapter 5) are shown in Table 17. Next step is to describe the interface between the three service providers.

Table 17. SoC Output for 24 Hours – Storage (from Chapter 5)

Time (Hours)	Storage Phase	SoC Value in %
0	Charging Start	4.5
1	Charging	8.9
2	Charging	18.2
3	Discharging Start	22.1
4	Discharging	12.2
5	Discharging	7.1
6	Discharging End	4.5

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6.2 Communication amongst the Interface

6.2.1 Development of Matrikon OPC Server and Explorer Platform

Storage, customers, and renewable resources have their individual capabilities within their particular management systems. In order to provide inter-zonal monitoring and control capabilities, these three zones need to communicate with one another. For this purpose, OPC communication mechanism is used [15-17]. Service providers (DIgSILENT, MATLAB/Simulink, and LabVIEW) and the control platform (LabVIEW RT) are all compatible with OPC standard [18-21]. The developed co-interface platform is shown in Figure 46.

JDSO can read the real-time tags of real power reserves at DIgSILENT based wind farm, real power reserves at LabVIEW based customers, and SoC values at MATLAB/Simulink based Li-ion storage system. Reactive power is also an important parameter to view, but the significance in the context of this chapter is low due to two reasons:

1- For LV and MV, the real power characteristics are more similar to distribution level voltages, as compared to reactive power.
2- Use of storage system is battery based.

However, the platform includes both real and reactive powers for future potential extensions. For homogeneity reasons, SoC values are mapped to real power (from percentage to per-unit to actual) by reversing the conversion in [22]. Next step is the definition of tags that can be monitored and configured via OPC Explorer.

There are six tags created overall; tag 1 describes the real power generated by wind farm at its output node, tag 2 describes the real power generated by customers' demand-response with flags indicating the types of customers, tag 3 gives the effective real power values by Lithium storage, while the remaining tags are created for J-DSO. For J-DSO, three tags represent the real power, reactive power, and the circuit breaker status with flags identifying the individual participants and their aggregation. The communication between J-DSO and DSO-DMS can be through LAN (Ethernet) or WAN – (ATM or SONET) [23].

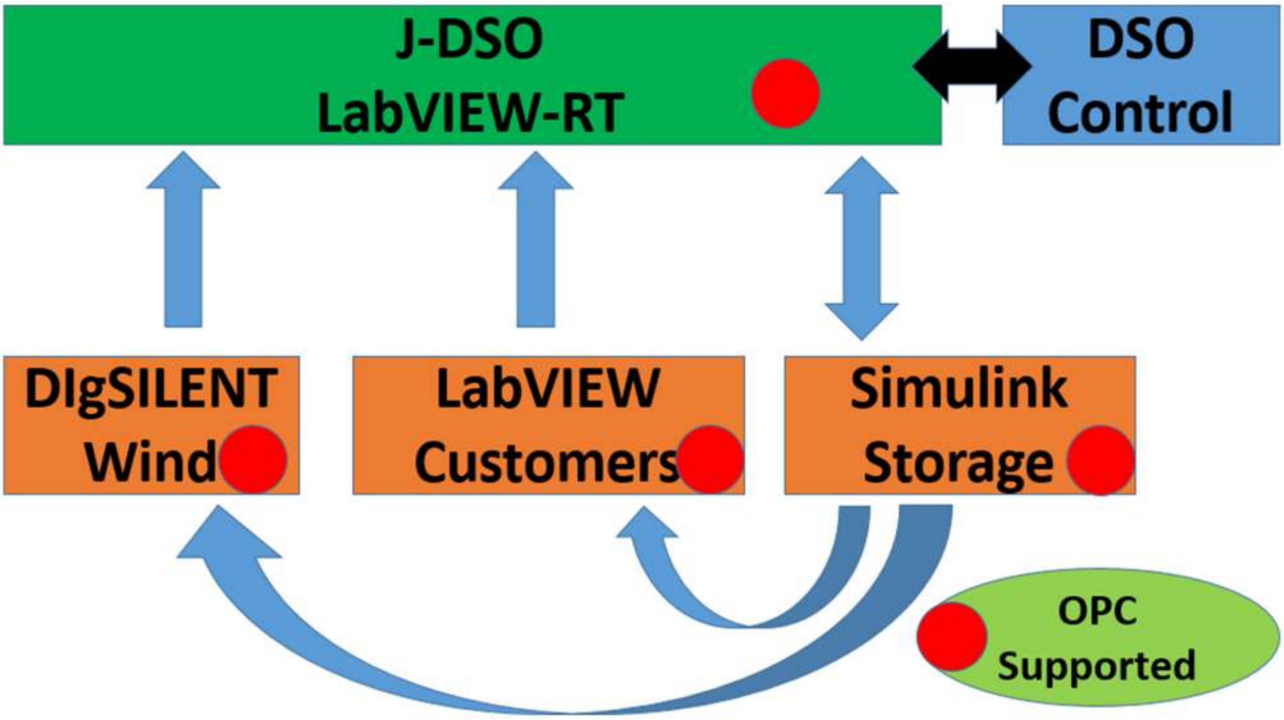


Figure 46: Co-Interface Platform

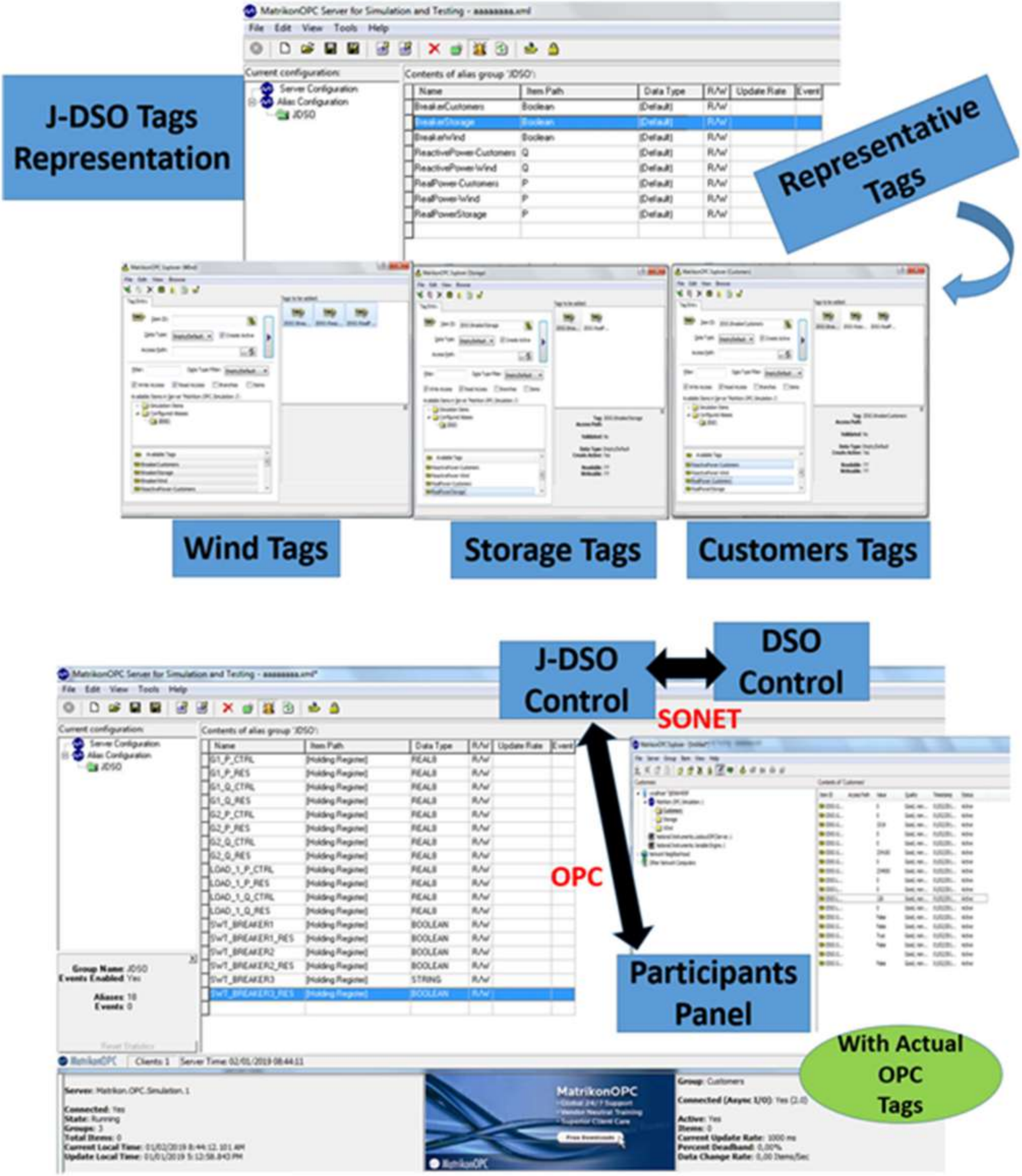
It works on server/client configuration. The servers extract the information/data from industrial devices, and then these servers communicate with the clients. These clients can be software like MATLAB/Simulink, DIgSILENT etc. The interesting part is that clients can order information/and send data to the servers, and the approach is basically client-driven. There are different types of OPC, for which the more relevant ones are DA, AE, and HDA. For the context of current study, OPC-DA is the point of focus. DA includes data, timestamp, and quality (sort of data validity flag) [24-25]. The OPC server, clients, and explorer based platform, with all OPC tags, are shown in Figure 47.

6.2.2 Implementation of LabVIEW-RT Platform

There are different ways through which LabVIEW can communicate with an OPC server. It is possible through data sockets with a LabVIEW real-time module, LabVIEW DSC module etc. It depends on capability in terms of UA, and other features. The point of focus here is the data sockets based LabVIEW communication with a LabVIEW real- time module. It breaks it into two parts [24-25]:

1- Implementing a data socket platform in LabVIEW which can read from OPC server [26-27]
2- Connecting it with real-time module, so that the ports communicate with each other for the three clients here [21, 28].

It can take the OPC server URL, in a specified format as in [24-25, 27], and take tags to be displayed one at a time [21, 26, 28]. With the data logging support of LabVIEW RT, OPC data items can be accessed through URL in the specified format of OPC-Machine identification-Server location-Tag selection [21, 26-28]. The developed interface is shown in Figure 48.



Name	Item Path	Data Type	R/W	Update Rate	Event
BreakerCustomers	Boolean	(Default)	R/W		
BreakerStorage	Boolean	(Default)	R/W		
BreakerWind	Boolean	(Default)	R/W		
ReactivePowerCustomers	Q	(Default)	R/W		
ReactivePowerWind	Q	(Default)	R/W		
RealPowerCustomers	P	(Default)	R/W		
RealPowerWind	P	(Default)	R/W		
RealPowerStorage	P	(Default)	R/W		

Name	Item Path	Data Type	R/W	Update Rate	Event
G1_P_CTRL	[Holding Register]	REAL8	R/W		
G1_P_RES	[Holding Register]	REAL8	R/W		
G1_Q_CTRL	[Holding Register]	REAL8	R/W		
G1_Q_RES	[Holding Register]	REAL8	R/W		
G2_P_CTRL	[Holding Register]	REAL8	R/W		
G2_P_RES	[Holding Register]	REAL8	R/W		
G2_Q_CTRL	[Holding Register]	REAL8	R/W		
G2_Q_RES	[Holding Register]	REAL8	R/W		
LOAD_1_P_CTRL	[Holding Register]	REAL8	R/W		
LOAD_1_P_RES	[Holding Register]	REAL8	R/W		
LOAD_1_Q_CTRL	[Holding Register]	REAL8	R/W		
LOAD_1_Q_RES	[Holding Register]	REAL8	R/W		
SWT_BREAKER1	[Holding Register]	BOOLEAN	R/W		
SWT_BREAKER1_RES	[Holding Register]	BOOLEAN	R/W		
SWT_BREAKER2	[Holding Register]	BOOLEAN	R/W		
SWT_BREAKER2_RES	[Holding Register]	BOOLEAN	R/W		
SWT_BREAKER3	[Holding Register]	STRING	R/W		
SWT_BREAKER3_RES	[Holding Register]	BOOLEAN	R/W		

Group Name: JDSO
Events Enabled: Yes
Aliases: 18
Events: 0

Clients: 1
Server Time: 02/01/2019 08:44:11

Server: Matrikon.OPC.Simulation.1
Connected: Yes
State: Running
Groups: 3
Total Items: 0
Current Local Time: 01/02/2019 8:44:12.101 AM
Update Local Time: 01/01/2019 5:12:58.843 PM

Group: Customers
Connected (Async I/O): Yes (2.0)
Active: Yes
Items: 0
Current Update Rate: 1000 ms
Percent Deadband: 0,00%
Data Change Rate: 0,00 Items/Sec

Figure 47: OPC Server-Clients-Explorer Platform

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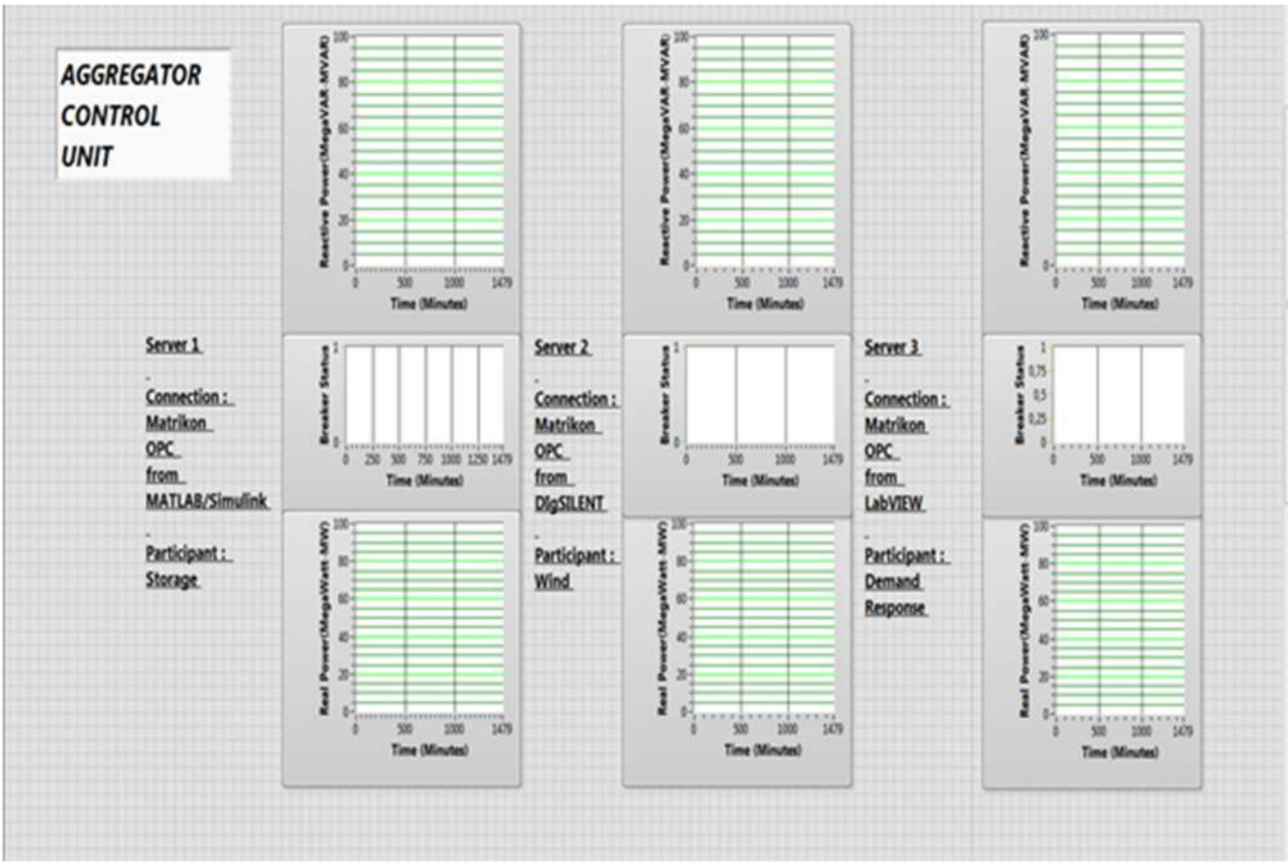

Figure 48: J-DSO Platform

6.3 Demonstration of Test Cases for Validation of Platform

Next step is the description of test cases for the support of DSO in provision of ancillary services, and managing local issues with flexibility from VPP based J-DSO. These test cases will be validated in the next chapter. The concept of test cases is extracted from [29], with added details from [5, 30].

6.3.1 Test Case 1: Over voltage issue at distribution substation buses

At time = 2 hours, DSO suffers over-voltage issues at one of its distribution substation. DSO procures service from J-DSO for real and reactive power, and then J-DSO manages the offers from three providers. Based on its analysis, J-DSO then provides the service to DSO for voltage support.

6.3.2 Test Case 2: Congestion issue due to overloading at distribution substation buses

At time = 8 hours, DSO suffers congestion issues at one of its distribution substation. DSO procures service from J-DSO for real power, and then J-DSO manages the offers from three providers. Based on its analysis, J-DSO then provides the service to DSO for congestion relief. Next chapter simulates the two test cases, and compares it with separate DIgSILENT based analysis for validation of the platform.

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Chapter 7: Validation of the Formulated VPPs – DERMS, Business VPP, and Aggregator

7.1 Validation of the VPP - DERMS

For the 24-hour profile of the contributions by renewables, customers, and storage systems in Chapter 6, the following steps are taken for the start of validation process:

1- The distribution grid from Chapter 4 is used, from Figure 14, with all the relevant modeling details there.
2- Load profile is created for the network for a 24-hour time; with 1-hour intervals. Dynamic behavior is then modelled using the Hermite approximation facility under DigSILENT.
3- Generation profiles (storage, customers, and wind), from Chapter 6, are added to the primary node (just after transformer low voltage end). The node is named as N-test.

These steps create the validation platform for the two test cases presented in the previous chapter. Next step is to represent over-voltage and over-load conditions in the presented network. For the ease of analysis, the checkpoint is considered N-test only. In other words, overload and over-voltage due to any reasons are reflected, restored, and analyzed at N-test only. The distribution network follows IEC 61850 standard, and hence the data is exchanged as sampled values using process bus.

For the over-voltage, the concept is extracted from [1], which considers that lightning strikes are a major source of over-voltage. The concept is used only for simulation purposes; however, it has no implications in actual grids. In other words, a fault at ground level is created on a neighboring node (Node 7 here). Overloading is created by increasing real power by 150% in neighboring nodes (Node 23 and 57 here). The results, based on Table 18, are recorded and observed.

Table 18. Validation Table for Analysis

Number.	Details of Analysis	Rationale
1	N-test voltage, without any disturbance and participants	To check initial conditions
2	N-test voltage, after over-voltage issue	Test case 1 initialization
3	N-test voltage, after over-voltage issue, and aggregation of three participants – DIgSILENT analysis only (Figure 49)	Test case 1 results with DIgSILENT analysis
4	N-test voltage, after over-voltage issue, and aggregation of three participants – JDSO analysis only (Figure 50)	Tags from OPC at Explorer are plotted in DIgSILENT. A single node is added and plotted. Test case 1 results with proposed platform

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5	N-test real power, after congestion issue	Test case 2 initialization
6	N-test real power, after congestion issue, and aggregation of three participants – DIgSILENT analysis only (Figure 51)	Test case 2 results with DIgSILENT analysis
7	N-test real power, after congestion issue, and aggregation of three participants – JDSO analysis only (Figure 52)	Tags from OPC at Explorer are plotted in DIgSILENT. A single node is added and plotted. Test case 2 results with proposed platform

Figure 49 shows the PU voltage at node 2 (the test node) with DIgSILENT based simulations.

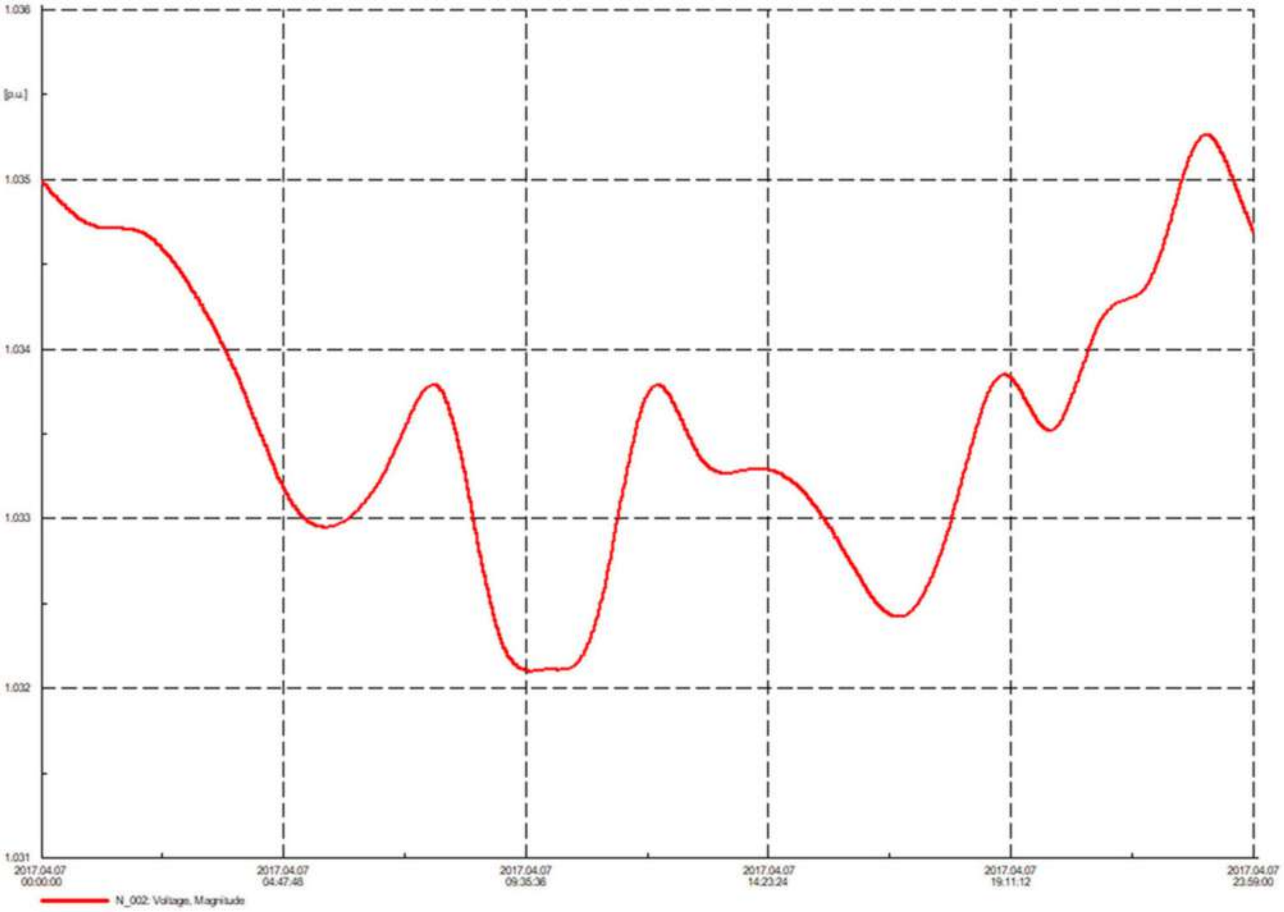

Figure 49: Test Case 1 – With DIgSILENT

The profile complies with voltage loading criterion, and hence there are no technical issues within the network. Figure 50 shows the same analysis results with the use of platform, and there are minor variations for the following reasons:

1- Pauses in receiving contributions from customers due to Modbus delays. These delays increase with the increase in customers. The delay is negligible in case of just a single customer
2- Tags are rounded up to two decimal places, and hence vary with DIgSILENT actual data values.
3- Tags are sampled at a rate of 0.5/sec.

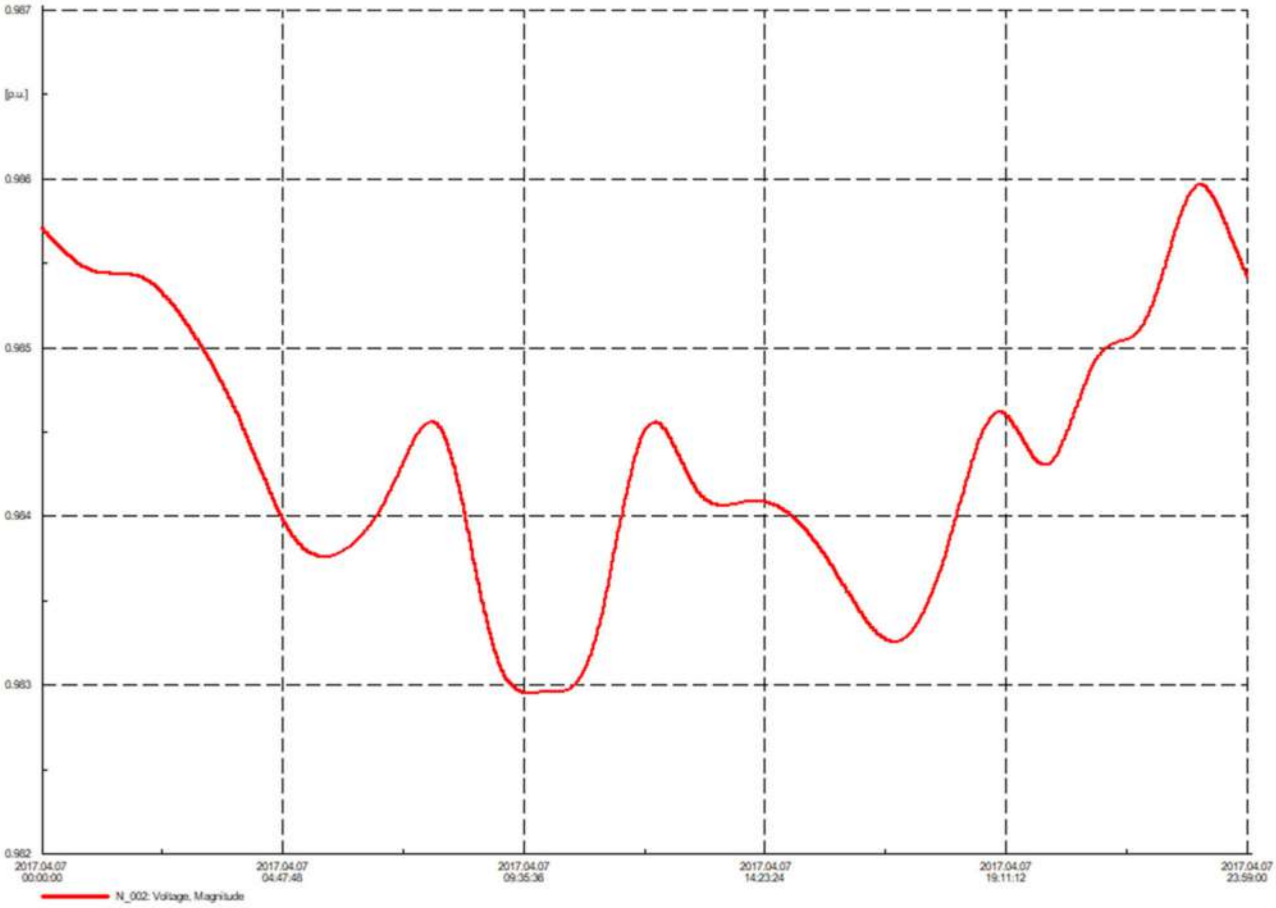

Figure 50: Test Case 1 – With J-DSO

4- Delay in validity check of tag flags.
5- Generation of representative tags by DIgSILENT and MATLAB/Simulink takes a little pause.
6- Delays in reading the data sockets
7- Error with hermite representation for creating quasi-dynamic profile in DIgSILENT analysis
8- Errors in conversion of values from SoC to real power for storage system.

Figure 51 shows the loading on lines associated with node 2 (the test node), in percentage, with DIgSILENT based simulations. Figure 52 shows the same analysis results with the use of platform. There are no congestion issues in the network. There are minor variations due to the same reasons as described above.

For the distribution grid in DIgSILENT, it is observed that there are no over-voltage and over-load conditions. The grid is then disturbed with over-voltage and over loading, and then the issue is resolved with two techniques:

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1- VPP with separate controls for their participants, and the centralized proposed platform
2- With the simulations of participants under DIgSILENT

Since the focus of this thesis is on platform, therefore, the plots for only the platform related comparisons are provided. Figures 49-52 validate the performance of the proposed platform, with minor variations due to communication delays and tags rounding errors. The chapter incorporates the use of VPP and its participants at DSO level, with a tool that can serve as sub-terminal between DSO and VPP actors at distribution level. The tool is validated with DIgSILENT, using DSO based test cases and a test bed Italian distribution network. Chapter 8 further includes validation within a real-time tool with PHIL capabilities, i.e. OPAL-RT.

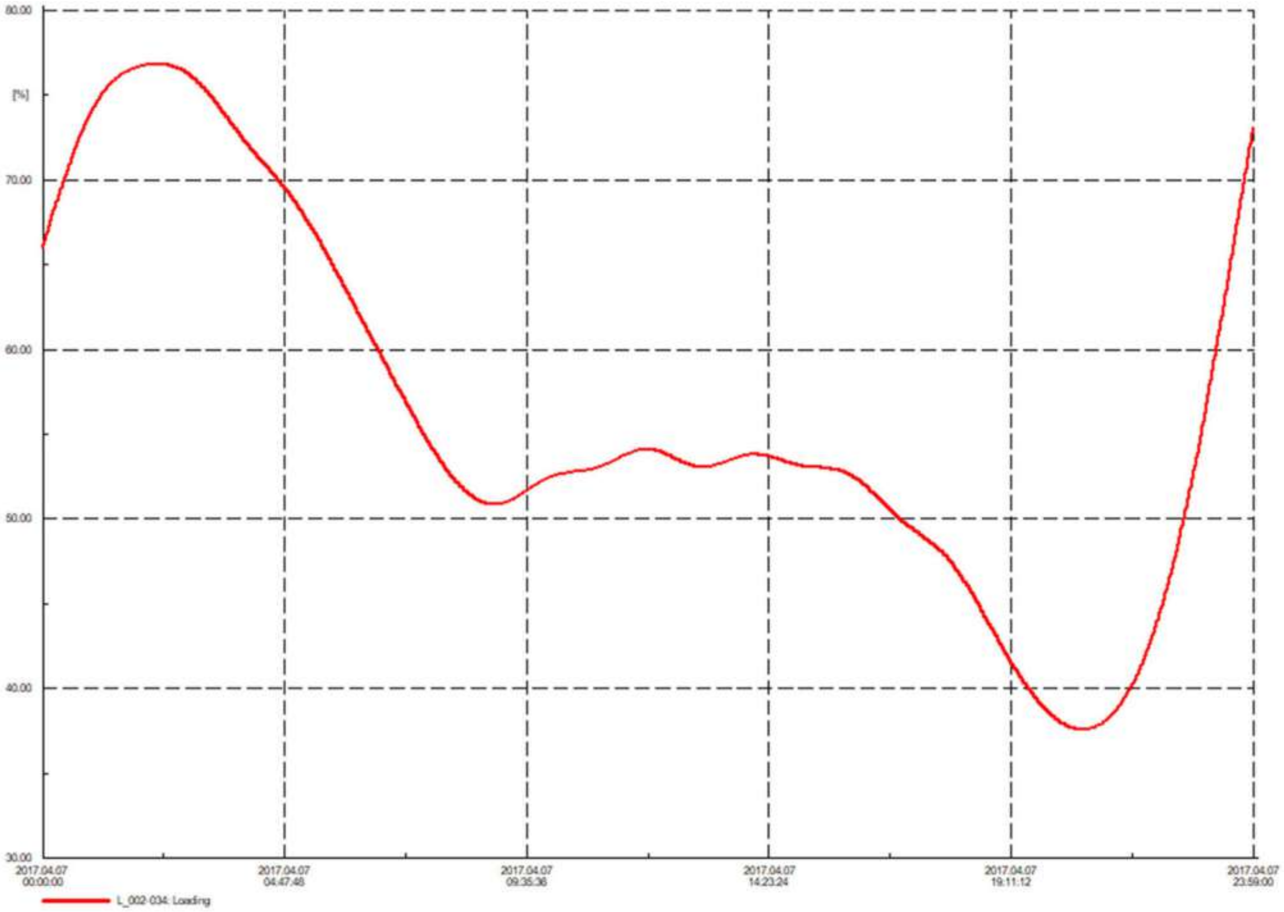

Figure 51: Test Case 2 – With DIgSILENT

7.2 Validation of the VPP - Aggregator

The VPP-Aggregator model in chapter 2 is used, as shown in Figure 4. For the validation, a sub-set of the platform is used for reactive power support, see Figure 53. The strategy is designed for the platform, and the platform is validated. From the analysis in Chapters 1-2, it is derived that each technique for reactive power has trade-off in its performance, and therefore the chapter is devoted to propose a coordinated strategy.

The strategy should follow the requests of TSO in the best possible way. TSO procures the service of reactive power from conventional generation units for the following reasons:

1- Quick service is required in case of contingencies and urgencies.
2- Huge amount is required in case of huge deviations.
3- More efficiency is required to justify better use of resources.

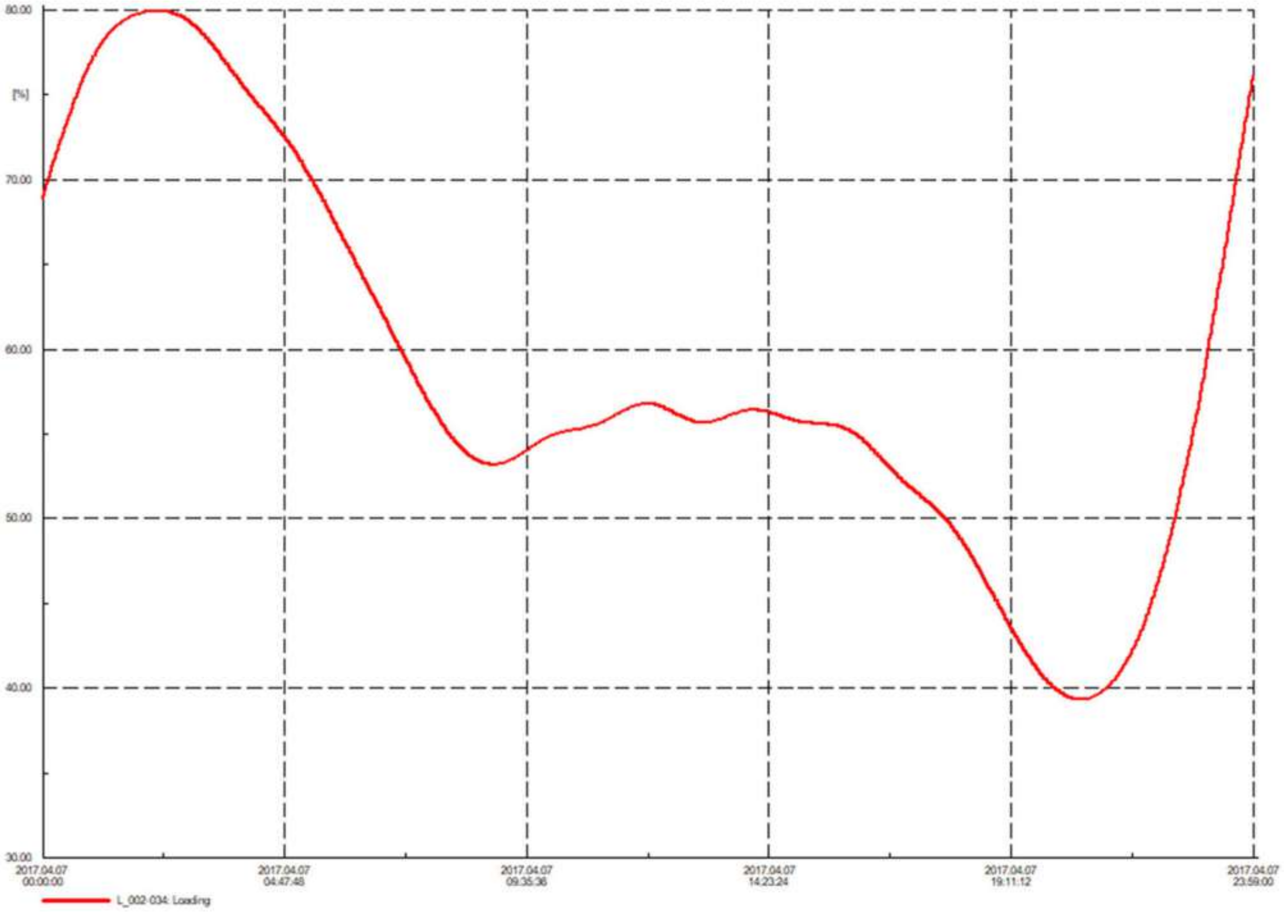

Figure 52: Test Case 2 – With J-DSO

TSO therefore requires a strategy that meets the VAR (unit of reactive power) requirements in best possible way. The strategy initiates with these two points to support the service with low losses, high amounts, and quick restoration:

1- Use of SG for normal conditions, with addition of synchronous condensers for high steady state reactive power requirements.
2- Addition of STATCOMs for fast provision.

This initialization leads to four different cases: Normal conditions with SG, use of additional SG only for any reactive power needs, addition of synchronous condensers for more provision, and addition of STATCOM for better transient response.

The initialization of the strategy is explained in Figure 54, with elaboration of TSO requirements. The arrows with yellow indicate the type of service from power plants, requested by TSO. In response to these requests, the control center at power plants can take service from red arrow (SG as mandatory provision for low losses), green arrow (Synchronous Condenser for huge amounts), and blue arrow (STATCOM for fast response).

TSO decides for this provision through the flexibility curve generated at their controllers. The plot in Figure 55 characterizes the strategy-curve, which comes from the following aspects:

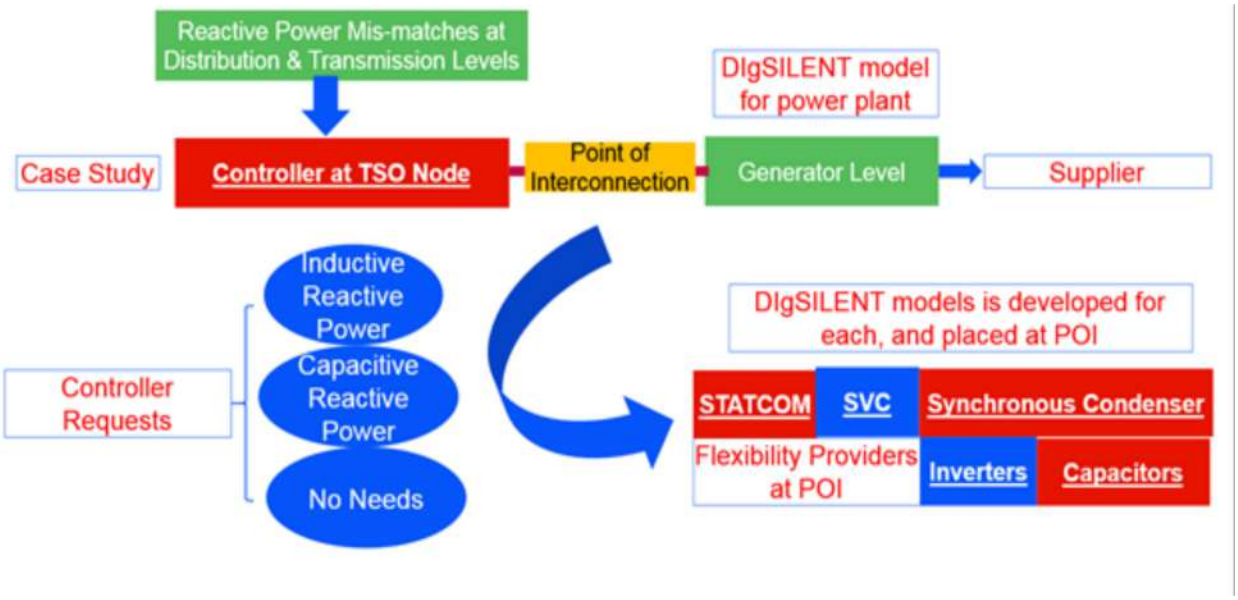

Figure 53: Validation Platform for Aggregator

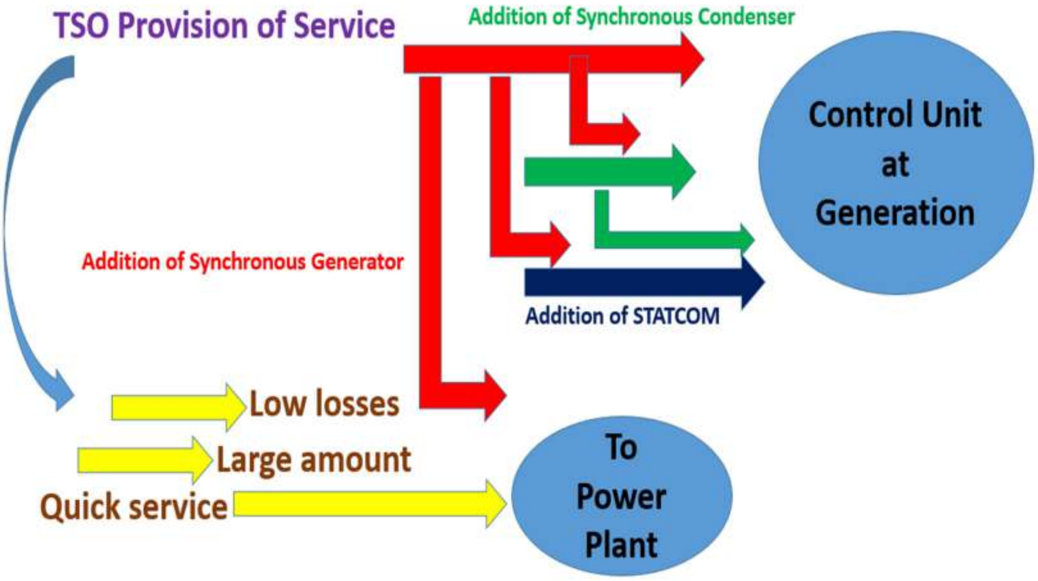

Figure 54: TSO needs VS. Approach of controller

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1- Use of capacitor banks is eliminated because reactive power depends on square of voltage, and hence it is not suitable for high and medium voltage applications.
2- SVC is eliminated due to the voltage non-linear dependency too, and the associated high costs for the investment.
3- Inverters are skipped too due to the very low provision of reactive power.
4- Synchronous generators and synchronous condensers are the best in terms of steady state response.
5- STATCOM performs best for transient cases.

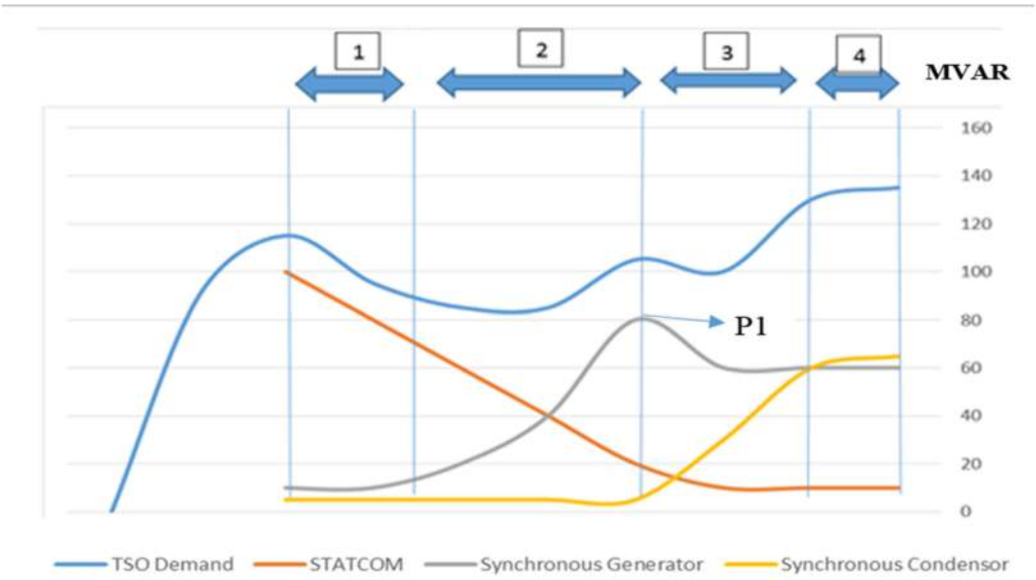

Figure 55: Proposal for Aggregation Strategy

The strategy is mapped with four regions of operation. Region 1 is to guarantee fast response in transient conditions with STATCOM. Region 2 incorporates more use of synchronous generators in order to reduce the operating losses. Region 3 incorporates more use of synchronous condenser in order to reduce the capital costs, and to give more flexibility to power plants. Region 4 is the use of all these techniques to satisfy the TSO requirements in an optimal manner.

Region 4 is the prospective one to be used in the future. It allocates the added flexibility with regard to advantages of high service provision in both transient and steady states, with most favorable costs and efficiency. Each one of these regions is visible to both generators and TSO (with a controller-based interface at power plant). All these regions need to be validated in order to endorse the feasibility of the presented mechanism. Figure 56 explains the adapted flow in a better way. Figure 57 describes the benefits of the proposed strategy in terms of speed of response (time taken to arrive maximum provision of SG, named as P1, vs time taken by STATCOM only for the same provision), flexibility (reactive power demand by TSO vs provision by SG only at P1), and associated capital and operating costs (taken from Chapter 2). All the comparisons are based on base value of one. The chapter further describes the test cases, and the testbed for this validation.

The test system includes electrical interface of a power plant, under the supervision of TSO at POI with conventional generators and representative transmission network. At the electrical output end of power plant, a step-down transformer is used at POI. The compensation devices are added at the lower voltage end of transformer to comply with their operational ratings.

The IEEE 9 bus system in Figure 58 is used as the reference transmission network, to demonstrate the management of the reactive power mismatches with reference to demand and transmission lines. The reference IEEE model is taken from [2-3], and the DIgSILENT implementation is taken from [4]. Load A is selected as the source of load variations, and line 8-9 as the representative transmission line. Generator 3 is selected as the representative coal-fired power plant, where the reactive power compensation devices are installed.

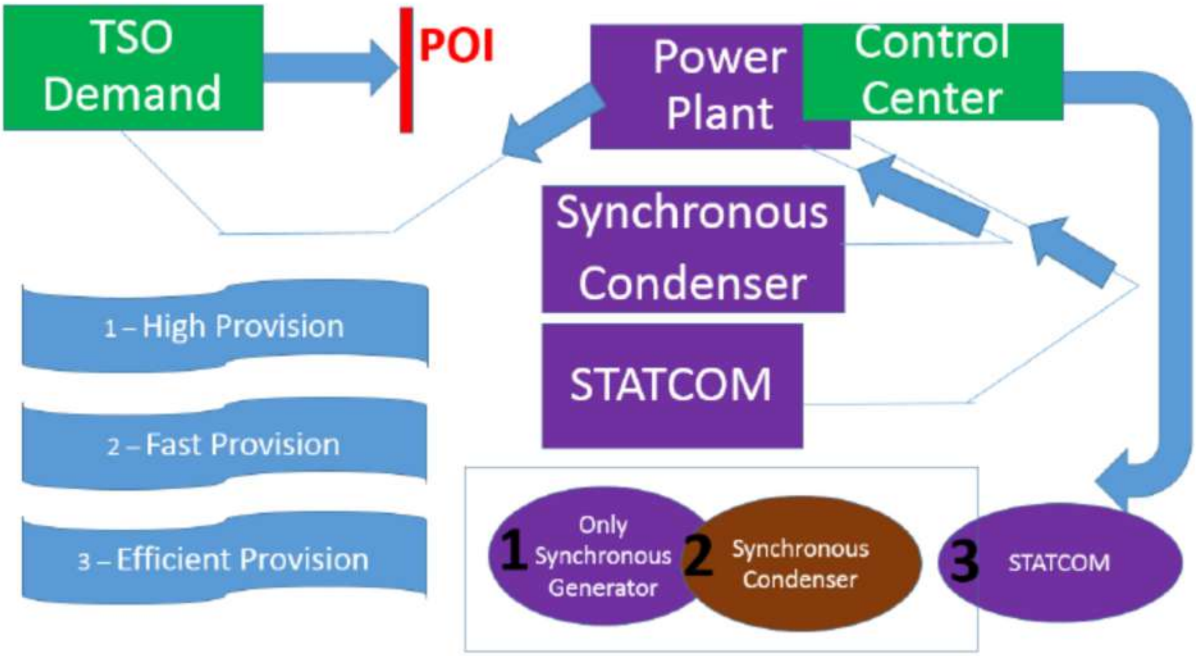

Figure 56: Aggregation Strategy – POI View

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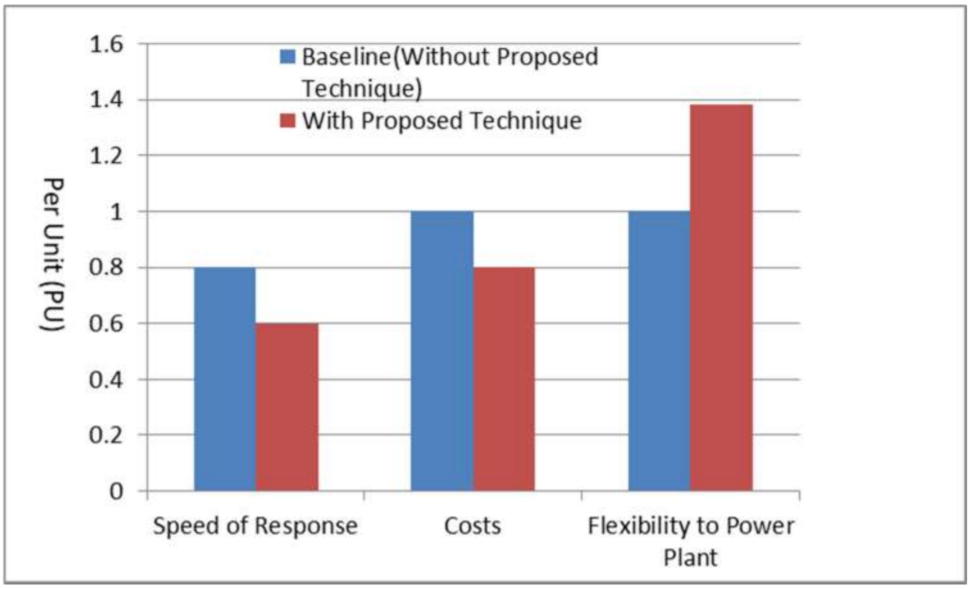

Figure 57: Benefits of Aggregation strategy

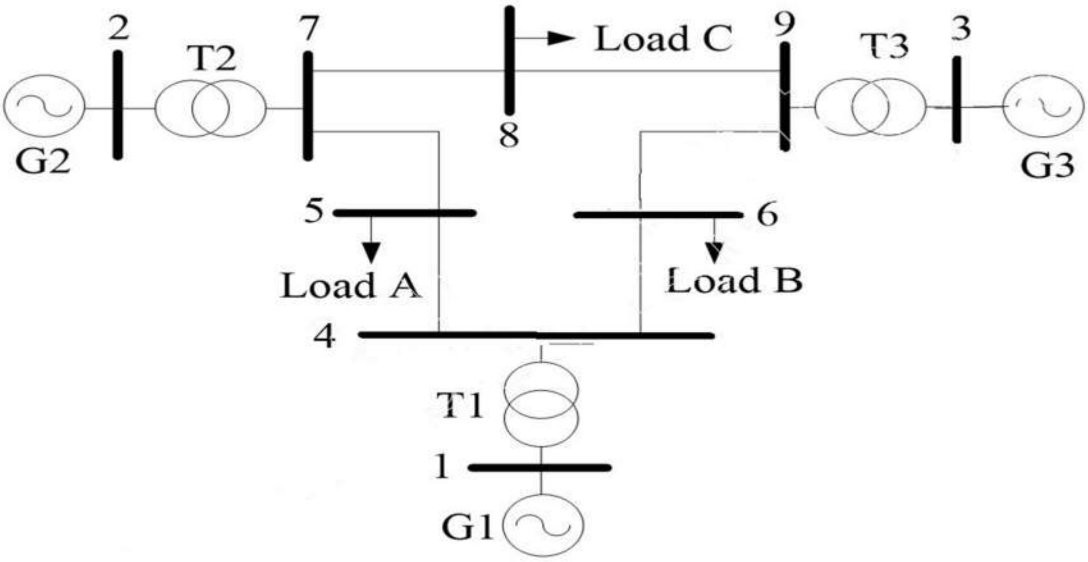

Figure 58: IEEE 9-bus Test System [2-3]

In the context of this chapter, the electrical output is the only point of interest, which is assumed to have an operating real power up to 200MW, reactive power, and voltage value. However, the model is used from DIgSILENT database, as in [4]. For the ease of analysis, the AVR and the primary frequency control libraries are directly used from [4]. Secondary frequency control is not used, and PSS is used for that purpose.

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The DIgSILENT model in [4] used the reference data from [3]; however, the data set is changed in the context of this thesis. The changes, with implementation, are indicated in the proceeding work. Next point is the definition of test cases for TSO services on this platform. The test cases are elaborated in Table 19, which complies with the following TSO actions at POI, as summarized in Figure 59:

1- Increase/decrease in reactive power for fast provision.
2- Increase/decrease in reactive power for high provision.
3- Increase/decrease in reactive power for distant provision. The reactive power is a local (zonal) ancillary service. For geographically distant (far) locations, the control strategy has to be changed.

Table 18. Validation Table for Analysis

Point(s) of Variation	Increase or decrease of reactive power?	TSO visibility for the variation
Bus/Node 5 (Load A)	Increase	Decrease in demand, i.e. the distribution system requires inductive reactive power
Bus/Node 5 (Load A)	Decrease	Increase in demand, i.e. the distribution system requires capacitive reactive power
Line from node 8 to node 9	Increase	Capacitive effect dominates on transmission network
Line from node 8 to node 9	Decrease	Inductive effect dominates on transmission network
Bus/Node 5 (Load A) and Line from node 8 to node 9	Increase	Overall reactive power mismatches, requires inductive reactive power
Bus/Node 5 (Load A) and Line from node 8 to node 9	Decrease	Overall reactive power mismatches, requires capacitive reactive power

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Figure 59: Test Cases VS. Operating Regions

Table 19 is used as an input for the mismatches at TSO, and the reactive power mismatch use cases. Parameter of variation is the reactive power mismatch, which can both be in incremental and detrimental ways. From the perspective of TSO, this effect is explained under "TSO visibility for the variation". In this thesis, increase in reactive power means the capacitive effect of reactive power; decrease in reactive power means the inductive effect of reactive power (in principle the generator convention).

Following the data-set description, for system in Figure 58, the changes are indicated here. The loads at bus 5 can consume up to 100 MVAR, and can generate up to 100 MVAR too. In other words, the loads are representatives of their inductive reactive power nature, but also includes transmission level co-generators with capacitive effects. This is seen as the equivalent demand change, represented with this load set. The real power has a rated value of 250 MW. For Line 8-9, the base values of X and B are assumed 30 Ohms, and 300 micro-Siemens. The line can endure the test sets up to 50 Ohms, and 450 micro-Siemens to represent variations in reactive power with respect to inductive (X) and capacitive (B) variations. Generator 3 has a rated real power of 140 MW and a rated reactive power of 50 MVAR.

Four cases are simulated in DIgSILENT. The results are elaborated one after another. The inputs for all the four cases are mentioned in Table 19. Line and transformer loading are provided in Table 20, which verifies that there is no issue of over-loading of lines and transformers. The node voltages for all the cases are given in Table 21 in PU.

Table 19. Definition of Input

Element	Values of dataset
Load A at Bus 5	Real power = 250 MW, Reactive power = 50 MVAR
Line 8-9	X = 30 Ohm, B = 300 Micro-Siemens
Generator at Node 3	Real power = 140 MW, Reactive power = 50 MVAR
Additional Synchronous Generator at node 3	Real power = 140 MW, Reactive power = 70 MVAR
Synchronous Condenser at node 3	Real power = 140 MW, Reactive power = 70 MVAR
STATCOM at node 3	Reactive power = 70 MVAR (inductive/capacitive)

Table 20. Quasi-Dynamic Simulation Report (Loading Range)

Element	Maximum Loading in %
Transformer 3	83.725
Transformer 2	73.273
Transformer 1	56.647
Line 4 to 5	32.089
Line 5 to 7	30.225
Line 6 to 9	21.639
Line 8 to 9	21.334
Line 7 to 8	11.114
Line 4 to 6	9.911

Table 21. Quasi-Dynamic Simulation Report (Voltage Range)

Bus	Voltage Min. [PU] without compensation	Voltage Max. [PU] without compensation	Voltage Min. [PU] with SG only	Voltage Max. [PU] with SG only	Voltage Min. [PU] with SG & SC	Voltage Max. [PU] with SG & SC
3	0.910	1.206	0.712	1.184	1.092	1.116
9	0.927	1.180	0.977	1.161	0.967	1.068
8	0.968	1.140	0.991	1.123	0.975	0.995
2	0.905	1.127	0.996	1.113	0.901	0.966
7	0.995	1.127	0.913	1.113	0.901	0.967
6	0.921	1.088	0.976	1.078	0.911	0.976
4	0.911	1.058	0.988	1.054	0.975	0.977
1	0.981	1.040	1.011	1.04	0.968	1.040
5	0.916	1.039	0.956	1.031	0.915	0.977

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In the first case, no additional compensation device is used. The results in Table 21 clearly reflects over-voltage violations at most of the buses (i.e. bus 2,3,7,8 and 9) with reference to the fact that transmission system operators are bound to ensure upper voltage variations up to 10%.

Next case aims to involve synchronous generator as additional compensation device. The results in Table 21 clearly reflect over-voltage violations again at most of the buses (i.e. bus 2,3,7,8 and 9) with reference to the fact that transmission system operators are bound to ensure voltage variations up to +10% and -15%. However, the maximum voltage variation at bus 3 is reduced by around 1.8% by the addition of synchronous generator.

Percentage of over-voltage is reduced at most of the buses, and hence it complies with the "Reactive power provider" mode of synchronous generator. For the minimum voltage, most of the buses get a boost in voltage to increase margin for under voltage violation, with a maximum margin of 10% at bus 2. However, there is a contradictory effect at two buses 3 and 7, where the minimum voltage is further reduced and this can be alarming for system operators to ensure under-voltage limits. The worst effect is at bus 3, where the under-voltage violation takes place. However, this issue can be resolved by the use of further compensation (either by SG or by aggregation). In addition, reactive power is better as a local control, and the changes at bus 3 (point of compensation) can easily be managed by TSO. This is shown later in the case with STATCOM.

Further addition of reactive power capacity through conventional power plants can avoid these over-voltage violations; however, this puts a lot of burden and responsibility on these power plants (normally coal and combined-cycle). References [5-7] form the basis of the description covered in this context of the chapter.

In order to give flexibility to these power plants, the next case is used to analyze the same plant with an additional synchronous condenser. Thus, synchronous generator and synchronous condenser are employed as compensation devices. It is clear from the results in Table 21 that the addition of sychronous condenser overcomes the over-voltage issue at almost all the buses, except for bus 3. The problem of under-voltage violation is also overcome at bus 3. Over-voltage violations are reduced up to 14% with respect to base case, and up to 13% with respect to SG compensation. At low voltage levels, most buses decrease their voltages and pose risk to under-voltage limits. However, the variation is up to 9% maximum and there still remains around 6% margin for under-voltage limits. The existing issue is the 1.116 PU maximum voltage at bus 3, and the idea is to use flexibility of STATCOM to the bus 3 violations, by operating the STATCOM at POI.

The problem can also be resolved by installing a shunt capacitor bank at bus 3. This gives three avantages:

1- There is no need to opearte the STATCOM at POI, in order to avoid the operational and maintenance costs.
2- The capital cost for STACOM installation at POI is very high.
3- Capacitor bank gives fast response, and almost linear response as compared to STATCOM.

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However, the solution is not feasible in case of violations at most of the buses, at POI, or the violations are huge in magnitude. Therefore, a trade-off is there in terms of costs and reliability. The next case is to install STATCOM at POI to ensure further flexibility, and a better transient response. This involves STATCOM on top of the previously employed compensation techniques. The improvements with STATCOM are reflected in the graphs: Figure 60 shows the response before the addition of STATCOM, whereas Figure 61 displays the STATCOM added behavior.

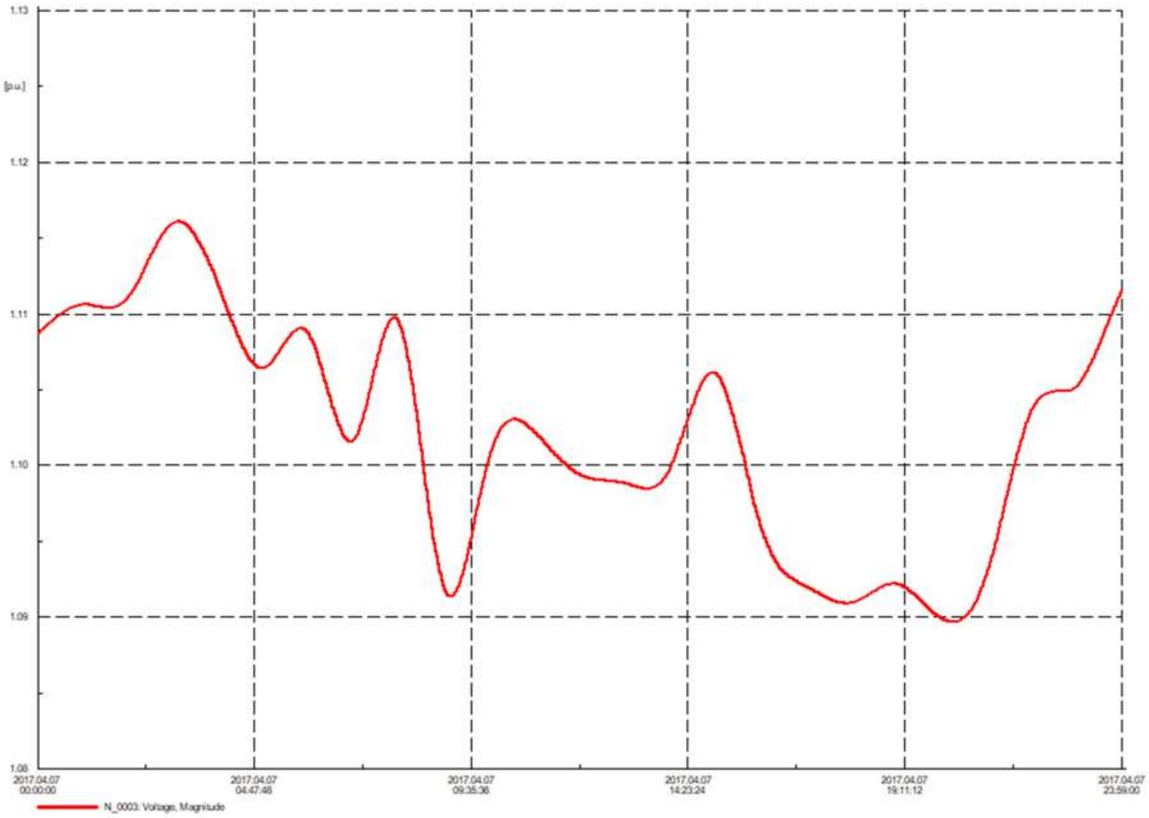

Figure 60: Voltage at Bus 3 before Addition of STATCOM

It is clear that the voltage loading at node 3 is improved with the addition of STATCOM. Without the use of STATCOM, the voltage goes above 1.1 PU for 57% of time that is the violation of over-voltage limits. Addition of STATCOM eliminates this over-voltage violation for 100% of the time. In order to better visualize the effects of STATCOM on node 3 voltages, the static simulations for initial one hour is shown in Figure 62, where the voltage variation is clearly visible.

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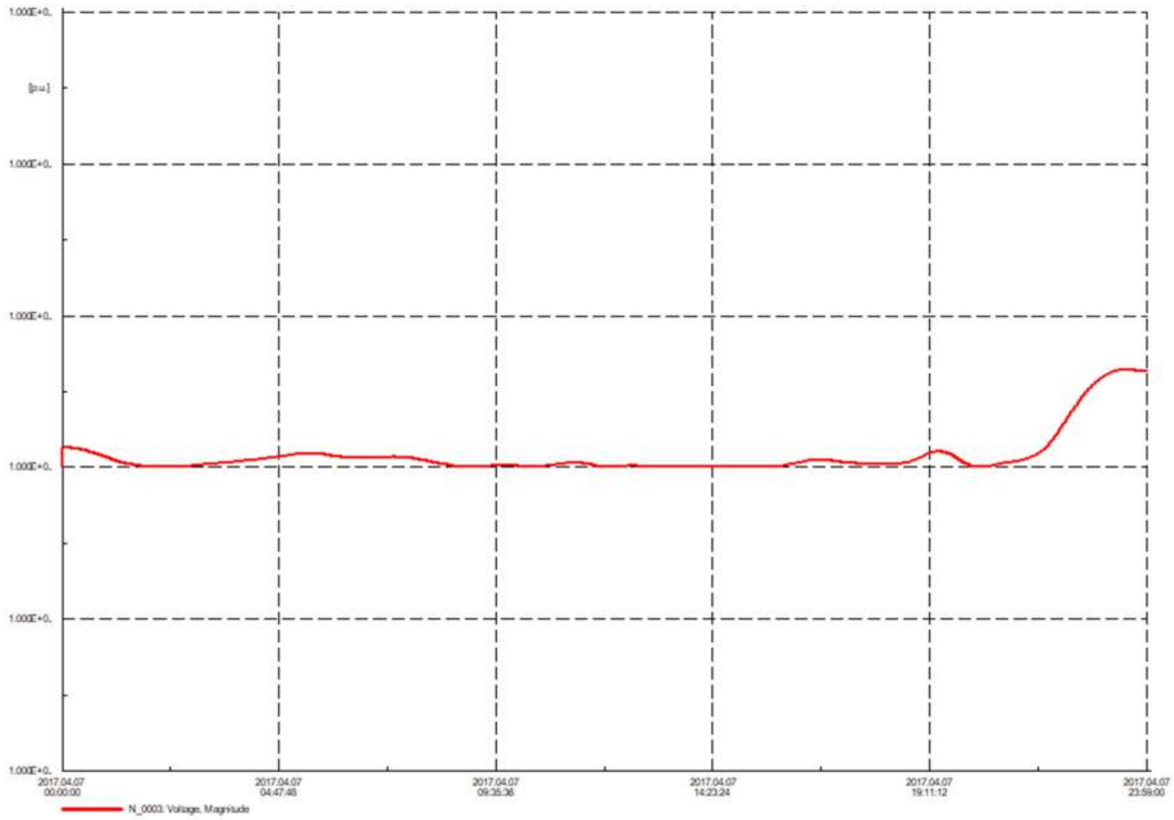

Figure 61: Voltage at Bus 3 after Addition of STATCOM

Next step is to test the transient behavior of voltage at buses for the achieved setup, by introducing another load at bus 5 with the similar characteristics of previous load. The changes to reactive power are compared with two cases: 1) With the use of additional SG and SC 2) With the use of additional SG, SC, and STATCOM. The time to reach voltage limits, after the over-voltage violation, is noted for each bus; the results are plotted in Figure 63. It is clear from the figure that STATCOM improves the transient performance, which is effective for faster response to TSO requests.

7.3 Validation of the VPP – Flexible Business VPP

The VPP-DSO flexible business model in Chapter 2 is used, as shown in Figure 6. The RTU has access to the respective substation voltage, current, and power flow information. In the same manner, RTU has access to the respective VPP in order to acquire its services to resolve local issues within the substation reach, before it goes to the DMS. Feeders, laterals, and loads are not visible to either RTU or VPP. Details of only selected ones are included to VPP.

There exist different parameters for latency, encryption, and standards limitations. For the confidentiality and security of substation devices, VPP can only view the logical nodes, and cannot monitor and/or control the actual physical device. Only the respective RTU has the lookup map for the physical-logical transformation.

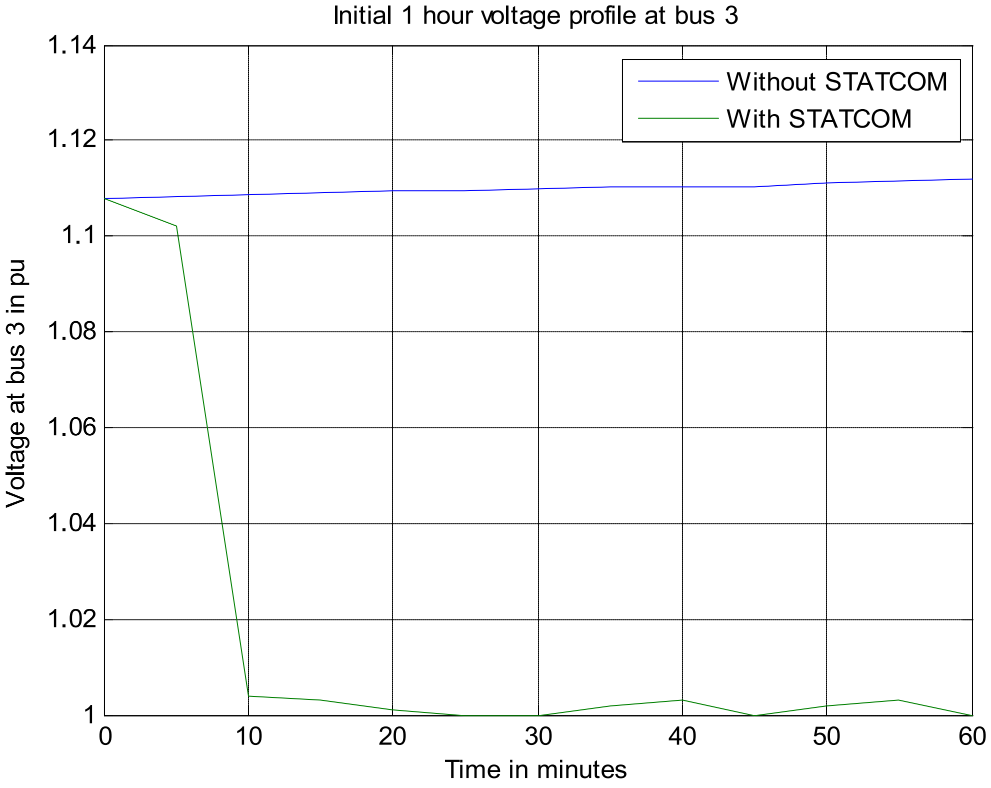

Figure 62: Node 3 Voltage With/Without STATCOM (1-Hour Profile)

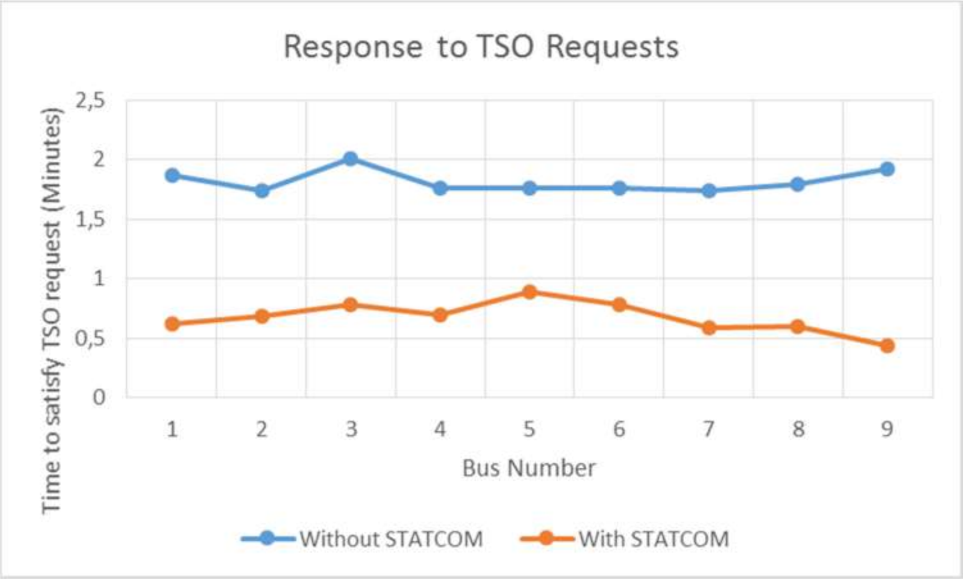

Figure 63: Response Time to TSO With/Without STATCOM

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Validation is performed on node basis. The test bed for the validation is as follows:

1- The distribution grid from Chapter 4 is used, from Figure 14, with all the relevant modeling details there.
2- At one of the selected nodes, i.e. 23, a residential load profile is added as shown in Figure 64 (from [8-9]).
3- RTU1, and VPP-RTU1 and VPP-RTU2 are represented by Matrikon based OPC servers.
4- WAN delay with SONET protocol.
5- Three cases are validated: congestion on node 23 with high loads in peak hours, peak shaving with and without RTU-VPP, and peak shaving with and without VPP-DMS.
6- Flexibility margins with storage, microgrid, and demand-response are indicated.

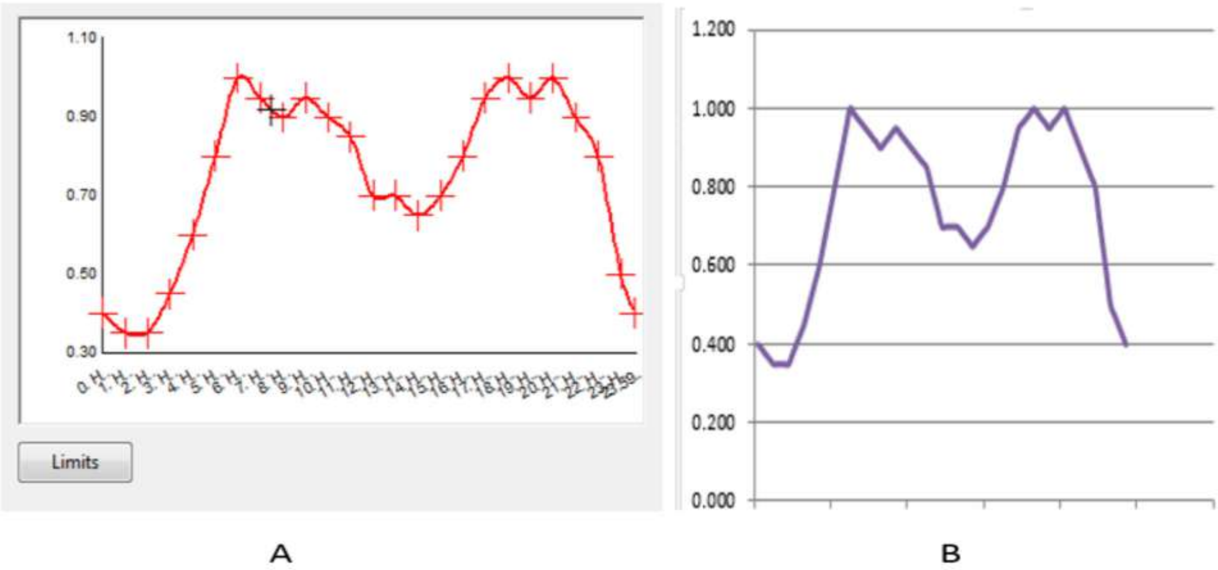
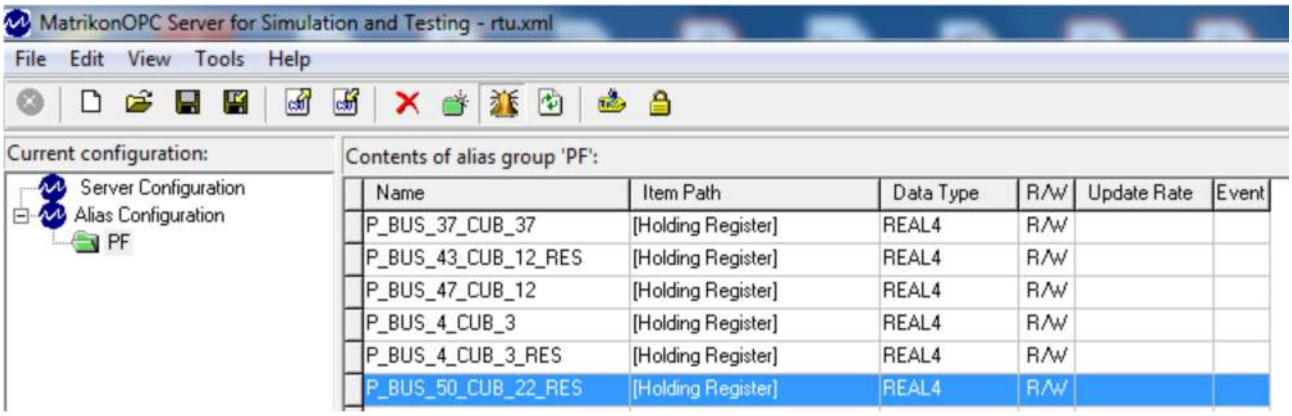


Figure 64: Residential Load Profile Representation in A) DIgSILENT B) MS EXCEL – Data from [7-8]

The level of maximum loading is marked and targeted, and is considered as the level of congestion with respect to overload conditions. After this addition, the quasi-dynamic analysis is performed. Results indicate congestion at node 23, and four nodes with the minimum loading, i.e. nodes 37, 43, 47, and 50. This information is reflected in the Matrikon OPC Explorer, and the idea of using OPC based communication is taken from [9].

The detailed description of microgrid, storage, and demand response participants is also available in [10]. Respective values of power, voltage, and current at these four nodes are available in the form of tags in the OPC explorer, which is shown in Figure 65.



Contents of alias group 'PF':

Name	Item Path	Data Type	R/W	Update Rate	Event
P_BUS_37_CUB_37	[Holding Register]	REAL4	R/W		
P_BUS_43_CUB_12_RES	[Holding Register]	REAL4	R/W		
P_BUS_47_CUB_12	[Holding Register]	REAL4	R/W		
P_BUS_4_CUB_3	[Holding Register]	REAL4	R/W		
P_BUS_4_CUB_3_RES	[Holding Register]	REAL4	R/W		
P_BUS_50_CUB_22_RES	[Holding Register]	REAL4	R/W		

Figure 65: Matrikon OPC Explorer with tags

These four tags are monitored by VPP-RTU2, which has the potential to ask for service from demand-response participant. VPP-RTU is also demonstrated by Matrikon OPC explorer in the similar fashion, with the only modification of being client, rather than server in previous RTU. Next step is the implementation of VPP-RTU1. VPP-RTU1 acts as client for OPC under demand-response, and server for microgrid. For energy storage system, it has both capabilities for positive and negative margins. Their flexibility is associated with RTU1.

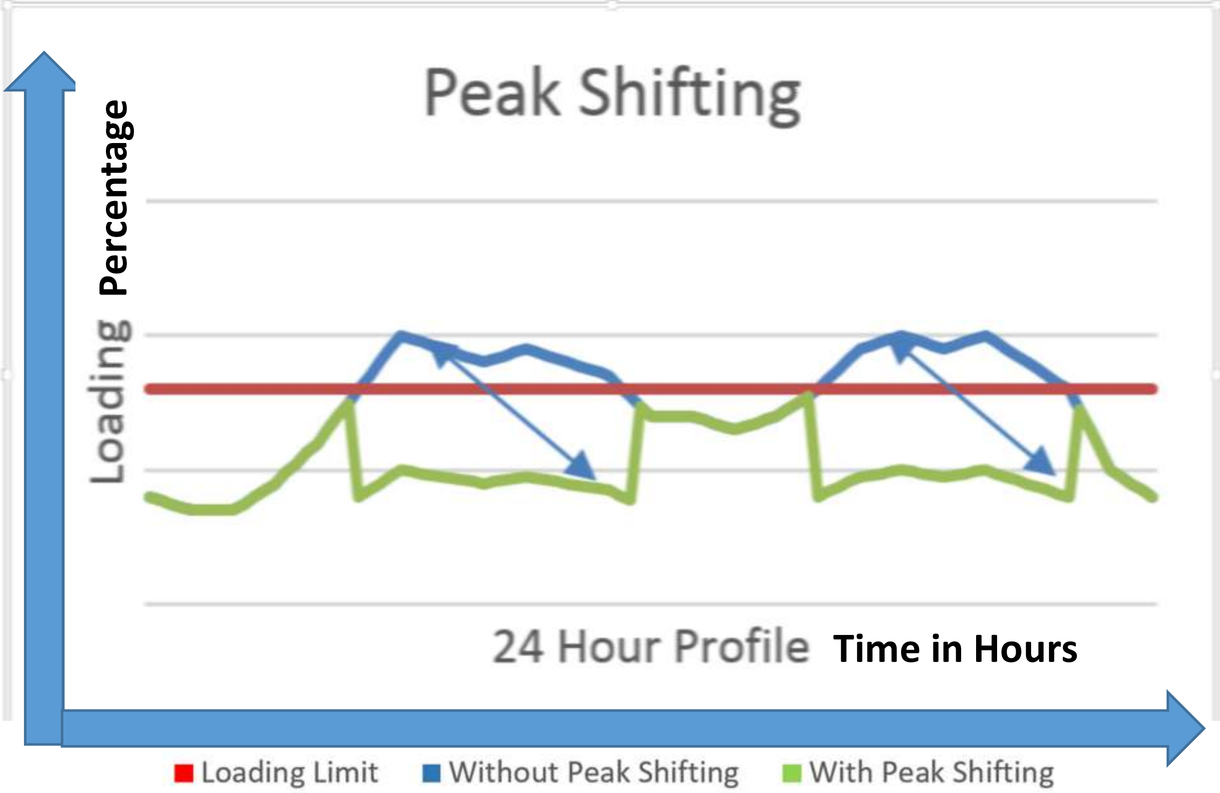


Figure 66: Congestion Management: Demand Response Flexibility

Consider that the VPP-RTU2 is used for peak shaving. Without the use of this RTU, the following delays are added: VPP internal delays, DMS delays, and SONET delays under WAN. The flexibility offered by demand response is shown in Figure 66 with the arrows.

To validate the results, the loading is observed at node 23 in DIgSILENT. It shows 78% loading, and hence there is no congestion. Consider that the VPP-RTU1 is used for time shifting. Without the use of this RTU, the following delays are added: VPP internal delays, DMS delays, and SONET delays under WAN. The flexibility margins offered by micro grid, DR, and storage are shown in Figure 67.

To validate the results, the loading is observed at node 23 in DIgSILENT. It shows 67% loading, and hence there is no congestion. Without the use of RTU, the associated delays pose a serious risk of overloading in the initial phase when the services are procured. The idea is shown in Figure 68, which shows overloading up to 97% in the initial phase. This is the phase during which the coordination amongst IED and DMS, and then DMS and VPP, occurs for the provision of service. Therefore, to avoid such coordination delays and early overload risks, it is beneficial to use RTU level coordination platform between VPP and DMS.

The chapter promotes digitalization of DSO business with the proposal of a platform, by using IEC 61850 standard for the communication amongst VPP and DMS RTUs. With the inclusion of these RTU levels, the flexibility for DSO is increased. Results are verified with the modelling of Italian distribution grid, and VPP on congestion based test cases.

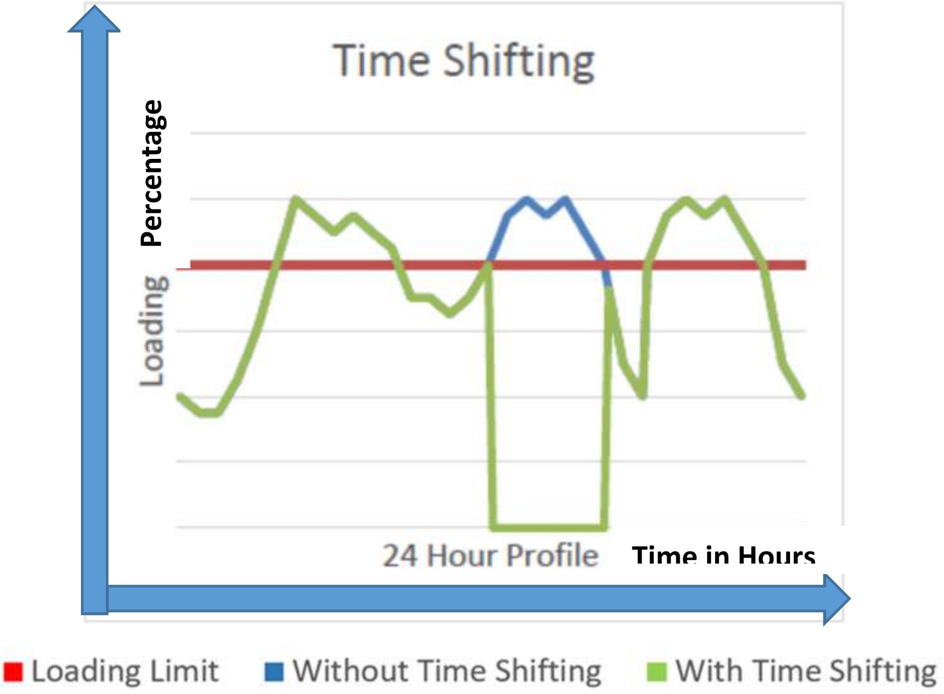


Figure 67: Congestion Management: Shifting in peak timing

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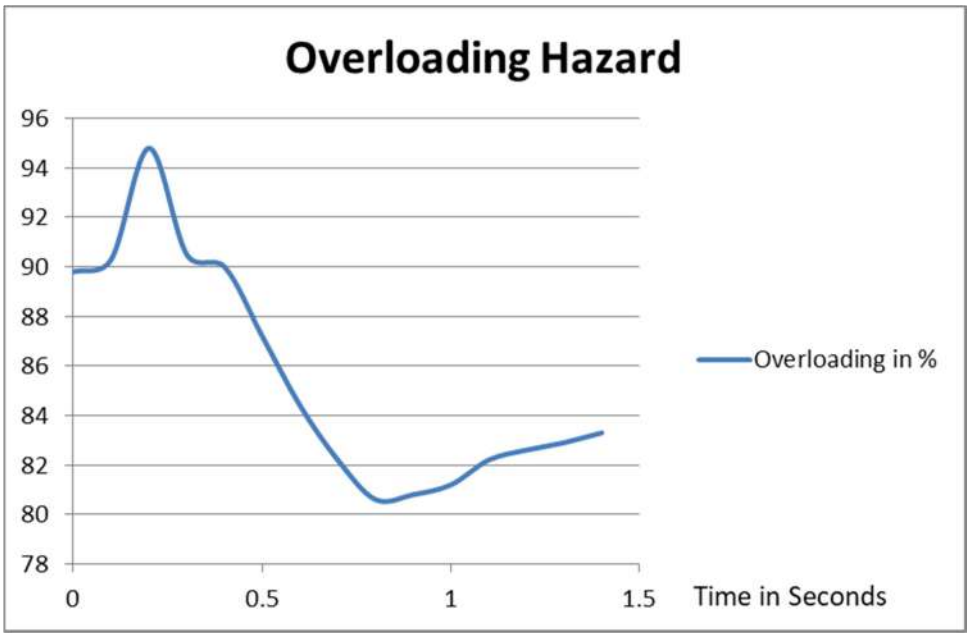

Figure 68: Overloading Hazard

Main motivation for the model is the involvement of different market players, and hence the trend which the later DSO should follow. The business case for this model can be developed with the utilization of four schemes presented in [11]. The four cases emphasize on different schemes of possible utilization of DERs effectively, in order to participate in ancillary market. Model presented in Figure 6 is compatible with these cases in all aspects. Therefore, all the technical benefits of operational planning, operational functions, and market functions, presented in [11], are also applicable for this model. The model gives novelty in terms of VPP participation for ancillary services with the concepts of using I) IEC 61850 standard II) VPP participation at RTU level III) Market opportunities at RTU level. The key points in adaptation of the proposal are:

1- Market opportunities and participation should be allowed to VPP at the level of substations
2- The subsidies for VPP should be reduced. The better is that DSO should provide incentives for adaptation of trend.
3- Regulatory barriers for VPP participation in service market should be removed.
4- The concerns regarding data, privacy, and information management should be regulated. A proper discretion of RTU, DMS, and VPP data for sharing should be done.
5- Demand response, storage, and in principle, reserve markets should be prevalent at both MV and LV levels.
6- New policies for IEC 61850 based interoperability of VPP, substation devices, and terminal units should be swift.

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Chapter 8: Application of VPP to Power System Protection

8.1 Conventional Power System Protection Techniques

One of the applications of the developed VPP is in the area of power system protection, which operates via relay. Power system relay is the most common equipment, which gives signals to circuit breakers for power system protection. It is the responsibility of relay to detect fault, and give indication to the circuit breaker so that the tripping takes place in the shortest possible time. This gives rise to two conditions for the correct operation of circuit breaker: tripping of circuit breaker when there is no fault, and this is due to misjudgment by relay as dependability issue, and no tripping of circuit breaker when there is a fault, and this is due to misjudgment by relay as security issue [1]. Different types of relay are used for the design of protection schemes for different power system components.

One of the protection schemes is over-current protection, which is used for radial distribution networks. Another common scheme is differential protection, which is used for transmission lines, bus bars, and transformers. Apart from these two conventional techniques, there are other techniques suggested by market and literature, i.e. distance protection, pilot protection etc. [2].

Irrespective of the type of fault, and the nature of protection scheme, the major principle quantities for fault detection are voltage and current. These two quantities differ in either magnitude, direction, or angle in order for the relay controller to sense the faults. The next section describes how this behavior is affected due to the presence of additional resources within the power grid.

8.2 Modern Power System Protection Issues

With the conventional power system, these techniques sense the current and voltage, and give signals to relays in order for the circuit breakers to trip correctly. The addition of distributed energy resources, and other unplanned components under the umbrella of virtual power plant, can cause these voltages and current to change with respect to the conditions for which they are designed. As an example, consider that an over-current relay is designed to trip the breaker when the fault current at a lateral reaches a given threshold, on the primary side of current transformer. However, the addition of photovoltaic panels, and demand response can cause the current through lateral to vary. Consider the equivalent circuit diagram in Figure 69.

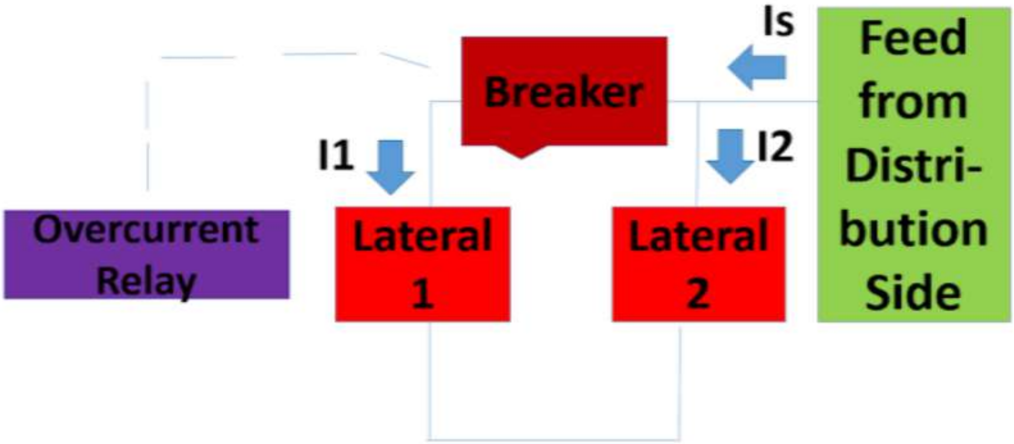

Figure 69: Equivalent Circuit for Overcurrent Relay in Normal Conditions

There is a distribution feeder that serves two laterals at different customer levels. The Thevenin current feed from the distribution end is taken to be I_s. The two laterals draw I_1 and I_2 currents respectively. There is a circuit breaker in between the two laterals for the design of protection for the distribution bus bar, and the two laterals. The breaker receives the signals from the relay in order to trip in case of necessary operation.

Consider the case in Figure 69, where overcurrent relay is used to protect the laterals and line. Consider the relay pickup current to be I_0. I_0 is designed relative to the current through the breaker, i.e. I_s - I_2 (I_1). Relay operates, and trips the circuit breaker in case I_1 exceeds I_0. In Figure 70, PV panels are added to the distribution end, and they can generate the current I_p as seen in Figure 70. In other words, PV panels act as a generation source, and thus can generate the current on that part of the system.

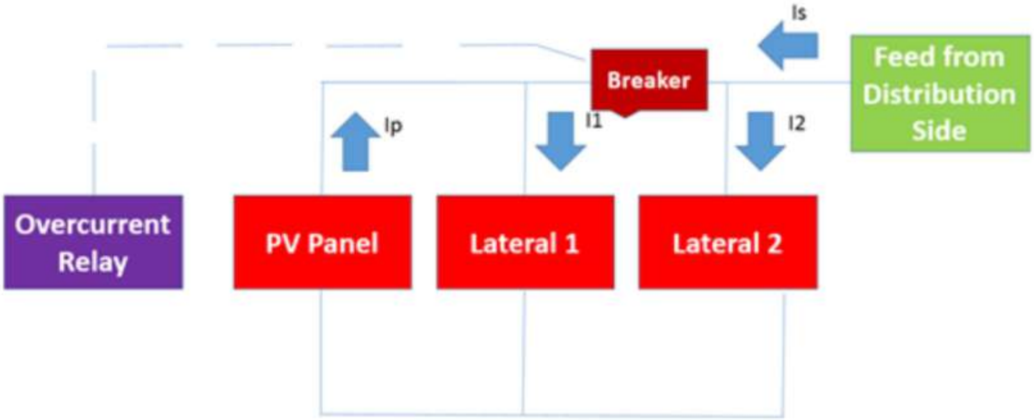

Figure 70: Equivalent Circuit for Overcurrent Relay under DER Conditions

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These PV cells generate I_p that causes the current through breaker to reduce to I_1 - I_p from I_1. Since, the breaker current should match with I_s - I_2, the scenario leads to three possibilities. First possibility is that lateral 1 draws more current, which is not seen by the breaker. Second possibility is that lateral 2 draws more current, which is again not seen by the breaker. Third possibility is the back feed from PV source to the distribution feed, and this causes breaker to sense unusual currents for the line than the ones for which it is designed. As a result, overcurrent protection would fail in this scenario, which requires significant modification in the design of a new scheme.

For the case 3, differential protection scheme is designed as shown in Figure 71. For the ease of analysis, ideal case is considered for differential protection with no current transformers mismatches, magnetizing inrush etc. as in [3]. The current difference is the only signal used for the tap setting of the differential relay. The tap settings are thus defined on $I_{difference}$ equal to I_1-I_s+I_2. After the addition of PV panel as in Figure 72, the $I_{difference}$ needs to be re-parameterized, and thus changes are required in the existing protection conditions.

8.3 Proposal of VPP for the Solution of Protection Issues

The idea now is to employ the major conventional relays, and to make them able to communicate with the major virtual power plants. Two layers of VPP are proposed; one deals with the faults at distribution levels, and the latter with the transmission and generation levels. The idea is illustrated with a layout in Figure 73. There is a centralized VPP master, which has direct communication with TSO. The centralized master is under the direct supervision of transmission level master VPP, and distribution level master VPP. There are chains of VPP operators at both transmission and distribution levels. The idea is that these operators share the operational data with their master controls.

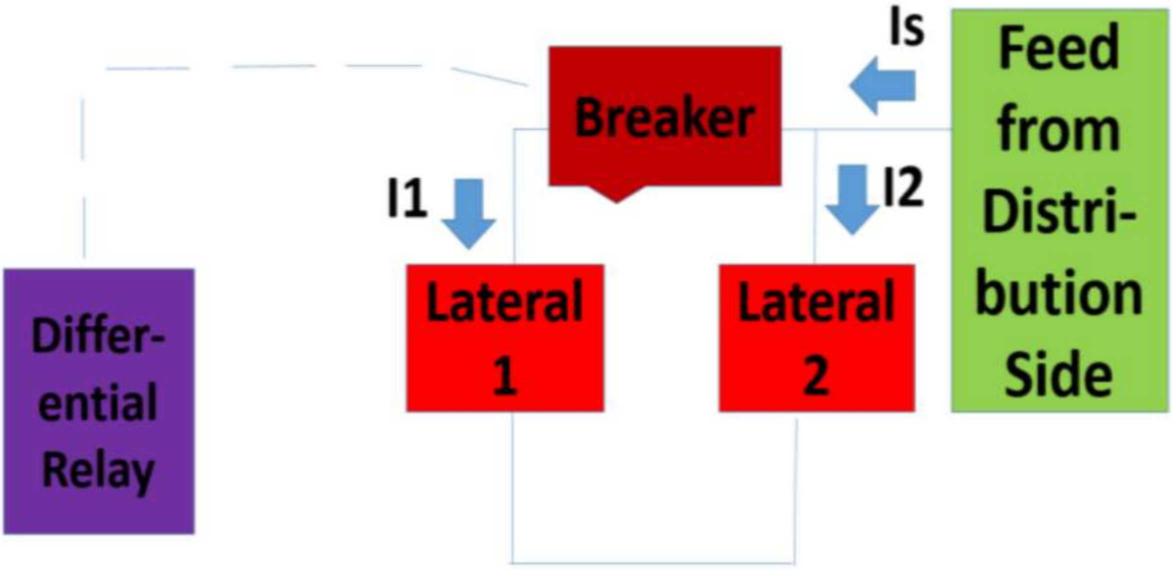

Figure 71: Equivalent Circuit for Differential Relay in Normal Conditions

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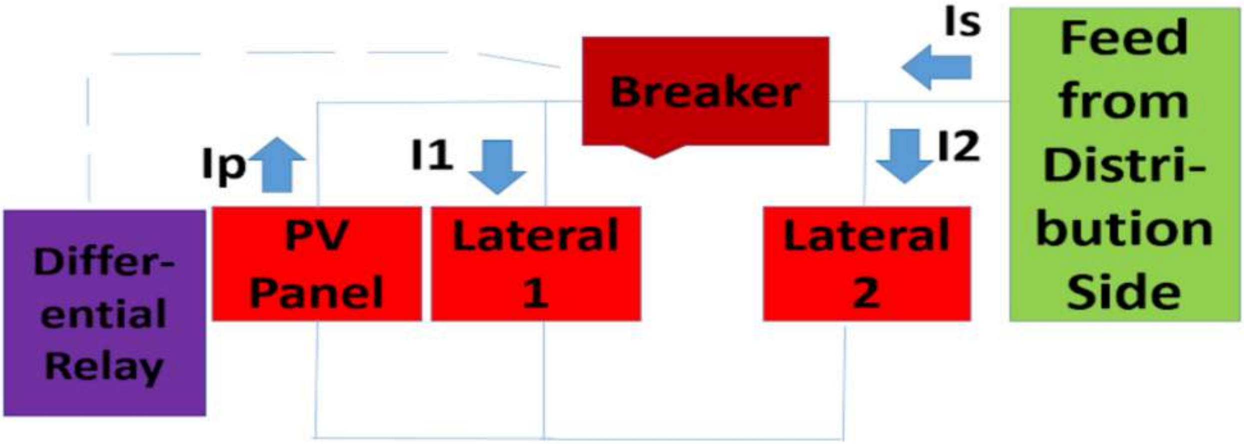

Figure 72: Equivalent Circuit for Differential Relay under DER Conditions

At the distribution level, the main distribution feeders and the distribution transformers are the points of scope for the chapter. These feeders and transformers employ digital relays, and ultimately create a VPP for protection purposes. These relays work on the principle of pilot protection.

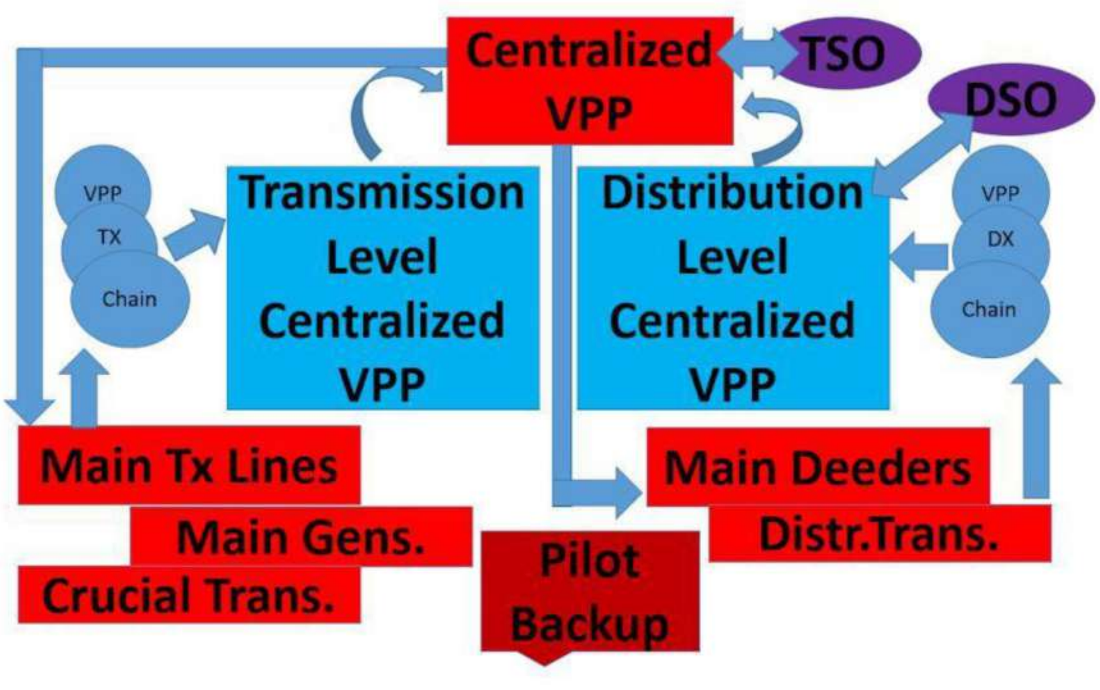

Figure 73: Application of VPP for the Solution of Protection Issues

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At the level of transmission, the main generators and the most crucial transmission and sub-transmission transformers are emphasized. These subsets are also supported through their protection based VPP, and employ digital relays that are compatible with pilot protection scheme. It is compulsory for all the VPP platforms to support the pilot protection schemes: Centralized VPP, Transmission Level Master VPP, Distribution Level Master VPP, VPP sub-chains on Transmission Level, VPP sub-chains on Distribution Level, the components' based VPP at Transmission Level, and the component' based VPP at Distribution Level.

Table 22 shows the visibility pattern for different participants in the network. Level 0 indicates direct visibility with no further interconnection. Level 1 indicates one, level 2 indicates two, and level 3 indicates three layers of interconnections.

Table 22. VISIBILITY PATTERN FOR PROTECTION SCHEME

Name of Component	Visibility to:	DSO Visibility Chain	TSO Visibility Chain
Component VPP Distribution Level	Distribution feeders, laterals, and transformers	Level 2	Level 3
Component VPP at Transmission Level	Generators/ transformers	NO VISIBILITY	Level 3
VPP sub-chains on Distribution Level	Component VPP at Distribution Level	Level 1	Level 2
VPP sub-chains on Transmission Level	Component VPP at Transmission Level	NO VISIBILITY	Level 2
Distribution Level Master VPP	VPP sub-chains on Distribution Level	Level 0	Level 1
Transmission Level Master VPP	VPP sub-chains on Transmission Level	NO VISIBILITY	Level 1
Centralized VPP	Transmission Level Master-VPP, Distribution Level Master-VPP, Component VPP at Transmission-Level, and Component VPP at Distribution Level	NO VISIBILITY	Level 0

Centralized VPP can access the information related to faults at all the levels of architecture. With the aid of backup protection scheme, the centralized tool can directly isolate a line, transformer, or a generator in case of urgent situations. Since TSO is sharing layer 0 with the centralized tool, it has access to all the VPP providers with the variations in delay. However, the visibility of DSO is limited to the network under its supervision. DSO can communicate with TSO only through the centralized platform. The communication is done when the network at lower level is unable to handle larger amount of faults. In the extreme case

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when all the VPP platforms fail, and there is a tremendous traffic on centralized controller, TSO can call for a restorative blackout. The chapter further defines test cases for better evaluation.

8.4 Demonstration of VPP for the Solution of Protection Issues

The architecture can be utilized for a number of case studies. The first case is to analyze the fault at one of the MV transformer under transmission network. For the primary protection, differential relay is used. In case of failure of which the Component VPP at transmission level can provide a primary backup protection through any recommended technique (let say over-current technique here). The primary backup is not always present for the proposal. The centralized controller, through pilot scheme, provides the main backup. The centralized VPP can observe this fault, and can manage the issue efficiently and in a timely manner. In fact, the controller can communicate with TSO, and they can provide flexibility for each other in terms of managing the faults.

Next case is to analyze the fault at one of the LV feeder laterals under distribution network. For the primary protection, over-current relay is used. In case of failure of which the Component VPP at distribution level can provide a primary backup protection through any recommended technique (let say differential protection technique here). The primary backup is not always present for the proposal. The centralized controller through pilot scheme provides the main backup. The centralized VPP can observe this fault, and can manage the issue efficiently and in a timely manner. In fact, the controller can communicate with DSO as well as TSO, and they can provide flexibility for each other in terms of managing the faults.

Last case is to analyze the efficiency of backup protection by the centralized controller. The pilot protection scheme is compared with the conventional backup scheme, for example, over-current relay. Then, the performance for both the backup schemes are compared for the fault parameters described in previous section. Overview of the basics of backup protection is available in [4]. For the analysis purposes, the software called Coordinaide S&C [5] is used. The over-current relay curve is shown in Figure 74, and the fuse curve in Figure 75.

The three test cases are analyzed, and the results are verified. The software aided in selecting the relay parameters. The chapter gives an idea that protection system can be improved (and less changes are needed in the conventional protection schemes), if the virtual power plants are coordinated in an efficient manner with TSO and DSO. The analyzed results for each case are discussed one by one.

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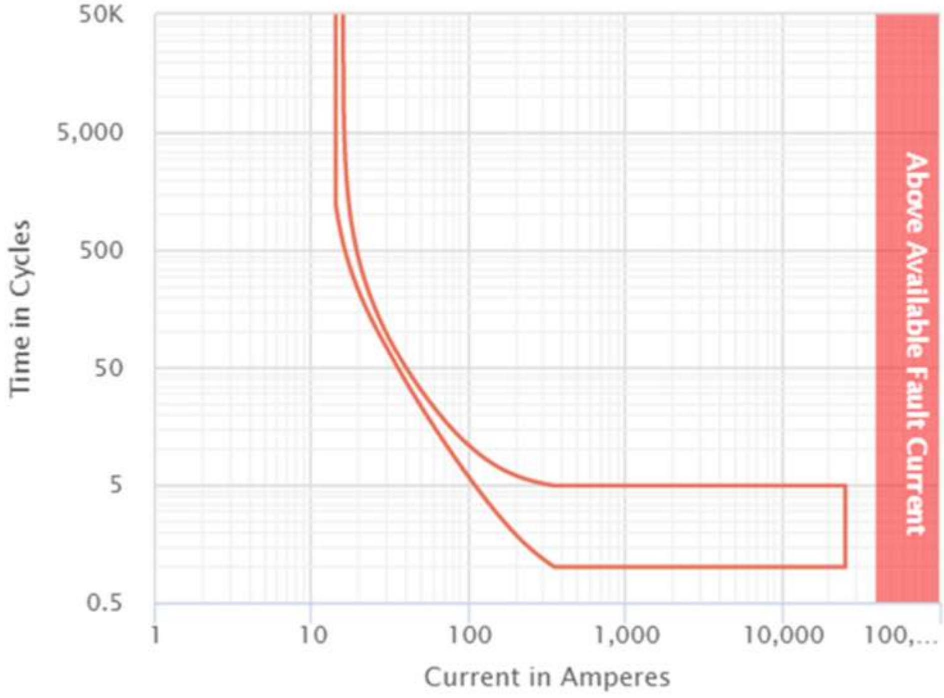

Figure 74: Selected Over-Current Relay Curve

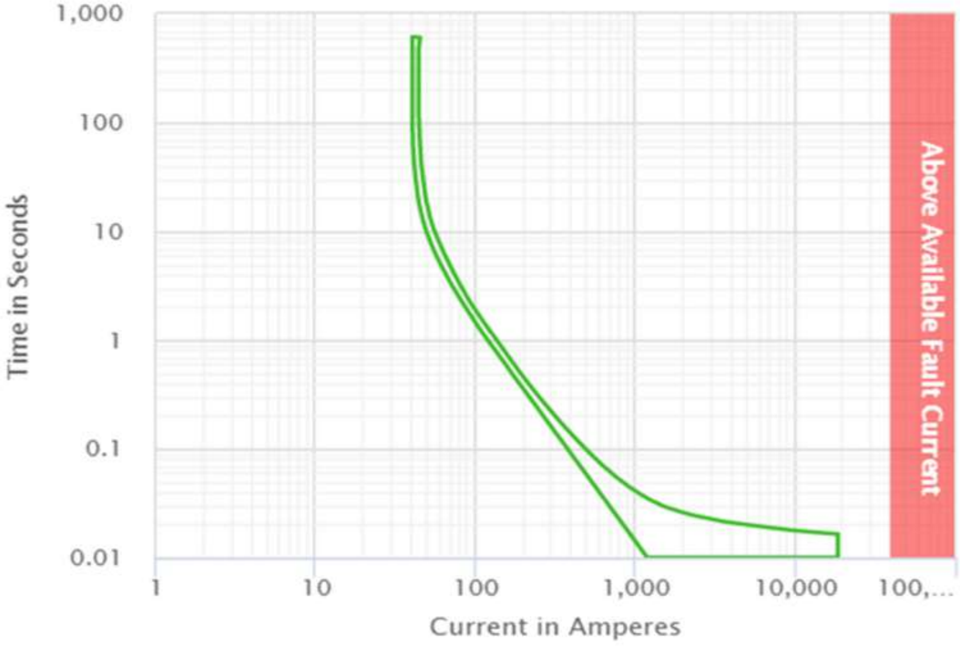

Figure 75: Selected Fuse Curve

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Analysis for case 1 is shown in Figure 76, where the fault is assumed to be at a MV transformer. The fault occurs at time = 2 seconds, and it is indicated by the blue line. The primary protection is reflected by the orange line which activates with the indication of the fault at the specified time. The primary protection clears the fault in 4 seconds, where it is assumed that it suffices with the protection criteria.

In the event of failure of backup protection, centralized VPP manages to provide the backup in 4 seconds, with total fault clearing time of 8 seconds. The region for TSO visibility is marked in the figure; however, DSO has no role to figure out these faults. The analysis for case study 2 is presented in Figure 77. For the same scenario as in case 1, the fault is cleared by primary protection in 2 seconds.

The secondary backup can have two possibilities here. DSO can access the fault through master VPP, and can clear the fault in a margin of 2 seconds. In case, DSO misses the fault, or manages TSO for the purpose, TSO can provide the backup in three additional seconds. DSO and TSO operational areas are marked in the Figure 77.

For the analysis of case 3, the assumptions are taken for the communication times, and the relay operational times. The communication requirements for the pilot protection are mentioned in [6]; SONET communication protocol is considered here for analysis over Ethernet as in [7]. For the comparison, overcurrent back up protection scheme is considered.

The IDMT type over-current relay is chosen as in [8]. For the overcurrent backup, the advantages are in terms of fast operation as IDMT operational delays are less than overall SONET communication and the protection relay operating time. However, backup fails in case of any further addition of distributed energy resources in the loop. The concepts of protection system design. and reliability are taken from [9-12].

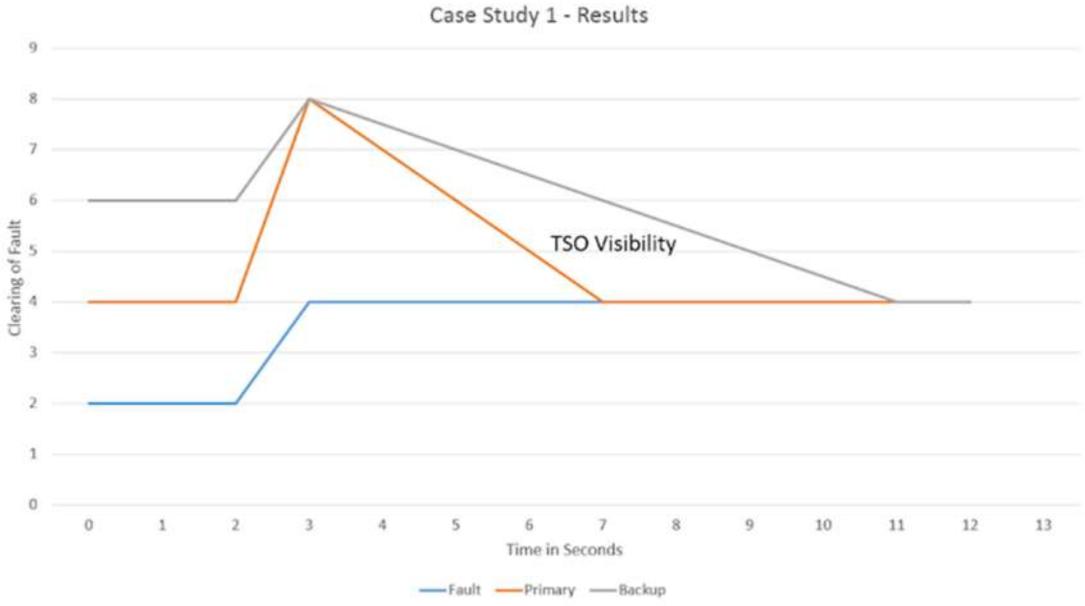

Figure 76: Analysis for Case Study No. 1

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In brief, VPPs are considered in the chapter to analyze their effects on the power system protection. It starts with the problems faced by power system due to the high integration of distributed energy resources. Emphasized issues are the power system protection methods (i.e. issues with radial configuration, and use of over-current protection), and effects on the working of protection devices (i.e. fuse, relays etc.). Presentation of test cases where faults in the system are visible to TSO, DSO, or both of them. Then the presentation of an architecture for communication between TSO-DSO-VPP, and then the examination of the visibility of faults to the common controller for the defined test cases.

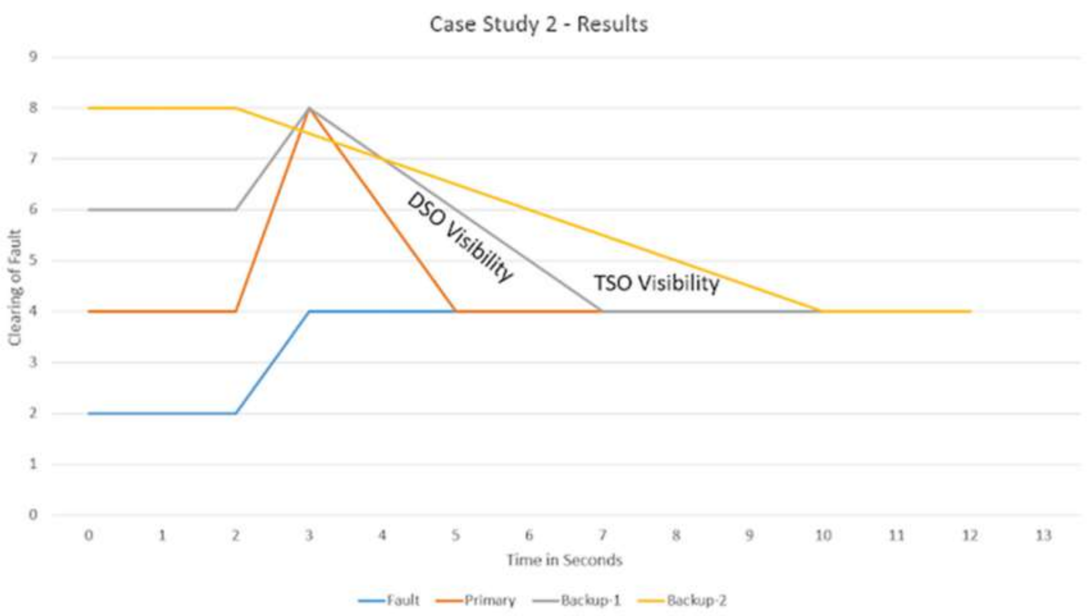

Figure 77: Analysis for Case Study No. 2

The idea is to utilize the existing VPP controller, and to communicate (deliberately) with TSO and DSO controllers for the purpose. Finally the analysis for the impacts on protection system, before and after the involvement of common controller is done. The results justify the statement of using VPP for solving the issues of power system protection.

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Chapter 9: CONCLUSIONS

9.1 Considerations about the work done

The thesis presents the way DERs cause issues to the power system as a whole, the way these issues are resolved in a conventional manner along with the potential proposals for better techniques utilizing different components forming VPP concept. A VPP by managing DERMS can give flexibility to DSO, while an aggregator at transmission level can give flexibility to TSO. The VPP can offer further flexibility, if the remedial actions are carried out at RTU levels within substations. The possible SGAM compliant VPPs are simulated and validated, and the results are scaled to different ancillary services and applications.

The thesis addresses the burden on power plants to provide the ancillary services, and thus covers the different aspects where the services can be provided, and thus to provide flexibility to conventional power plants. It starts with the study of SGAM architecture, and develops three models of VPP: for the TSO level that facilitates aggregators and large-scale units, for the DSO level that can act as DERMS, and the distribution substation level that acts like a community microgrid. All these VPPs are modelled, simulated, and validated with real test cases.

The VPP aggregator at TSO level is tested for the reactive power ancillary service. It is seen that the aggregator facilitates TSO for the provision of reactive power at high amount of provision, fast provision, and geographically distant provision. The aggregation strategy is also presented where the aggregator can provide the best possible solution using different reactive power compensation techniques. The strategy is tested using the standard IEEE 9 bus test system.

The VPP, responsible for DERMS, at DSO level is developed with the knowledge of DERS at various locations and with the utilization of the fact that these DERs are co-systems, and are accumulative as service providers. These co-simulator platforms are developed in different software: storage system in MATLAB/Simulink (tested for frequency restoration service), customers based DR facility in LabVIEW (tested for reactive power provision), and DERs together with stand-alone compensators in DIgSILENT (tested for reactive power provision). These co-simulators are interfaced using a centralized platform developed in LabVIEW-RT, with OPC supported communication. The platform is tested and validated with node level comparison of voltages with the use of platform, and without the use of platform (with the test case implementation in DIgSILENT). For the validation, an Italian distribution grid set-up under ATLANTIDE EU project is used where the DERs, compensators, and DR providers are added to develop a test case scenario for reactive power service.

For the possibility to support DSO with a new business case, it is proposed a community microgrid concept for VPP at distribution substation level. The idea is to utilize VPP as an IED for the substation RTU under IEC 61850 communication, and the concept is to visualize how the service can be provided at distribution substation level (localized and quick, in comparison with the accumulated burden at DSO with the DERMS case). The platform is developed in DIgSILENT, and it is tested for reactive power support. The use of VPP at DSO level, and at substation levels indicates a trade-off for quick and distant services, with potential technical, regulatory, and data confidentiality issues/solutions, that are highlighted with comparison to major European countries.

In the end, the thesis tests the developed VPPs for the application of power system protection. A test case is presented where overcurrent and differential protection (as backup) are used to protect feeder laterals, and bus bars. Then, as a secondary backup protection, the comparison is done amongst pilot protection and VPP based schemes. The parameters for protection are designed using the selected software Coordinaide, and the results are presented in MATLAB/Simulink. The result is an increased visibility to system operators for power system protection using VPP, with a potential quick backup.

9.2 Future developments

For future work, a cost analysis with an emphasis on ICT deployment, and communication protocols should be evaluated too. Implementations in other European countries will be focused, and their architectures should be studied and analyzed with respect to implementations in line with the proposed architecture.

A decision system algorithm can be developed, and it can be validated through a real time simulator. Another major source of imbalance, which is the transmission line, should be the point of emphasis in the future work.

Another point of addition is the inclusion of market scenarios, where a detailed market model for TSO is employed to give a real-time picture of the deployment of reactive power in power system. STATCOM is just one option for reactive power compensation, and there are other options, which are more economical.

Validation should be performed with real time monitoring and control, rather than a steady state validation for node congestion. For the creation of PHIL, the RTDS can be used. A valuable cost benefit analysis by considering an extensive business case to emphasize the fact that a better flexibility margin can be achieved by creating market at RTU level.

9.3 Acknowledgments

The thesis is disseminated under MEAN4SG project, ESR 6, http://www.mean4sg-itn.eu/. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 676042. The funding covers the publication charges (all forms) & trainings [Appendix B & C]

The author would like to thank Enel Produzione Italy for their industrial supervision for 3 years, as “Technical Specialist Expert” within Enel (January 2017 – January 2020], as the beneficiary of MEAN4SG project.

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The author would like to thank CIRCE – Spanish Research Institute for organizing courses 1 & 4 in Appendix B, as the beneficiary and coordinator of MEAN4SG project.

The author would like to thank University of Strathclyde – Glasgow for organizing training 2 & summer school 2 in Appendix B, as the beneficiary of MEAN4SG project.

The author would like to thank ORMAZABAL – Spain for summer school 3 in Appendix B, as the beneficiary of MEAN4SG project.

The project MEAN4SG (ESR 6) is disseminated orally at: https://sgc2018.ieee-smartgridcomm.org/ (**Germany** 2017), http://www.cired2018-workshop.org/ (**Slovenia** 2018), https://www.eeeic.net/eeeic/ (**Italy** 2018), http://upec2018.com/ (**Glasgow** 2018), http://medpower2018.com/ (**Croatia** 2018), https://aupec2018.org.nz/ (**New Zealand** 2018), http://www.cired2019.org/ (**Spain** 2019), and http://rtsi2019.ieeesezioneitalia.it/ (**Italy** 2019)

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APPENDIX A - FLEXIBILITY OFFERED BY POWER PLANT AUXILIARY LOADS:

For the design of a power plant, there are some loads (parasitic) to be operated for the functionality of plant. These loads are not intended in terms of net power generation. Thus, these are auxiliary loads, and require auxiliary power to support the power plant. These auxiliary services are not only needed for transient states, start-up, shutdown, and fault conditions, but also for the operation of power plant during the normal conditions [1].

However, these auxiliaries constitute a non-negligible part of power generated by the plant. According to EPRI (Electric Power Research Institute), 4.6% energy generated is wasted in auxiliary services [2]. It also depends on the type of fuel; Coal-based power plants utilize 5-8% of generating capacity, while CCGT (Combined Cycle Gas Turbine) power plants utilize 2-5% of generating capacity [3]. These auxiliaries are designed under the consideration of size of load to be served, and the degree of service continuity [1]. The conventional plants usually have loads like boiler feed pump, compressor, cooling tower, water treatment system, air conditioning system, generation step-up transformer etc. [3].

These loads also depend on the type of technology used by the power plant. For example, a combined cycle power plant includes additional loads like dampers, and shutdown diesel generator. It may also include fire protection system, continuous emission monitoring system, unit transformers etc. [4].

Combined cycle power plants (CCPP) have higher efficiency than coal and nuclear plants, and therefore they have low auxiliary power consumption. However, the rate of load change (in load follow mode) is low for high loading, and nuclear appears as a better option there. For low loading, CCPP works better than nuclear, and coal [5]. Particularly in Italy, with unavailability of nuclear power plants, the competition is amongst coal and CCGT (Combined Cycle Gas Turbine). At high capacity factor, coal is cheaper than CCGT, and the reverse is true in vice versa [6]. It therefore indicates coal to be used as base load. However, with the abundance of renewable resources in Italy, the base load is provided by these renewables (with zero fuel cost). Coal serves the purpose of intermediate loading, and CCGT plants are used as double-peaked power plants.

These peaked power plants run only when there is an increase in demand, and usually Italy has two peaks for energy requirement per day. Due to not only cost, but also flexibility, that makes CCGT a better option. For a hot start-up (time to start-up following shutdown within 8 hours), the time taken by CCGT plant is 30-60 minutes, as opposed to 80-150 minutes by coal based power plants. CCGT plants also have high start-up reliability (around 95-99%), as opposed to 87-93% by coal based power plants [5].

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This project MEAN4SG has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 676042.

APPENDIX B - ACTIVITIES DURING PHD:

Courses:

1- Participation in specific course on topics: “Basics of Metrology”, “Basics of DIgSILENT”, “Writing of Scientific Publications”, “Reference Managers and Scientific Papers search Tools”, and “Using LaTeX”, 31 Jan-Feb 2 2017, Zaragoza, Spain. (21 hours)
2- Tutorial on DIgSILENT. (20 hours)
3- Individual course on learning Italian language, June-October 2017, Genova, Italy. (30 hours)
4- Participation in specific course on topics: “Research Applications”, “Patents”, “Academic Cooperation for Research”, “Useful Ways to Disseminate Research”, “Ethics with the growth of Energy Resources”, “Career Path in Industry”, “License, Agreement, and Start-Ups for Technology Transfer”, “Industrial Research”, and poster session 28-30 November 2017, Zaragoza, Spain. (11 hours)
5- Tutorial on LabVIEW-Real Time. (10 hours)
6- Post graduate certification from University of Strathclyde, UK (Nov 2016 – Oct 2019).

Workshops:

1- Workshop focusing on working in team, and communication skills, 6 April 2017, Pisa, Italy. (8 hours)

Training:

1- Training on writing effective research paper, with a task to write a sample IEEE paper as part of MEAN4SG program, May 2017.(8 hours)
2- Training on making posters presentations, with a task to create a poster for the research theme as part of MEAN4SG program in Glasgow, June 2017. (5 hours)
3- Training on peer review of scientific publications, with a task to review two scientific publications as part of MEAN4SG program, June 2017. (5 hours)
4- Site study of a hydroelectric power plant, 18 May 2017, Italy. (6 hours)
5- Training on OPAL-RT, 26-28 July 2017, Genova, Italy. (12 hours)
6- Training on PLEXOS, 1 September 2017. (2 hours)
7- Participation in IEEE International Conference on Smart Grid Communications, 23-26 October 2017. (13 hours)
8- Participation in CIRED Workshop on Microgrids and Local Energy Communities, 7-8 June 2018, Slovenia. (12 hours)
9- Participation in IEEE 18th EEEIC on Environment and Electrical Engineering with emphasis on Power Systems, along with presentation of a research paper, 12-15 June 2018, Palermo, Italy. (24 hours)
10- Participation in UPEC 2018 with emphasis on Power Systems, along with presentation of a research paper, 4-7 September 2018, Glasgow, UK. (24 hours)
11- Participation in MEDPOWER Conference 2018 with emphasis on Power Systems, along with presentation of a research paper, 12-15 November 2018, Croatia. (24 hours)
12- Participation in AUPEC Conference 2018 with emphasis on Power Engineering, along with presentation of a research paper, 27-30 November 2018, New Zealand. (24 hours)

13- Participation in CIRED Conference 2019 with emphasis on Power Distribution Systems, along with their operations, planning, and applications, 3-6 June 2019, Spain. (24 hours)

Summer Schools:

1- Participation in summer school based on the final workshop of EURAMET projects SmartGrid-II, FutureGrid, and GridSens, 19-20 April 2017, Haarlem, Netherlands. (14 hours)
2- Participation in summer school on topics: “Elevator Pitch”, “Measurement Applications in Modern and Hybrid Power System”, “Uncertainty in Power System Measurements”, “Testing and Validation Procedures”, “Laboratory Based Power Systems Training”, and “Uncertainty in Measurement and Modelling along with an Example Project”, 23-25 January 2018, Glasgow, UK. (24 hours)
3- Participation in summer school on topics: “Conventional Partial Discharge Measurements”, “Practical Learning for High Voltage Lab”, “ICT Standards for Smart Grid”, “Non-Conventional Partial Discharge Measurements”, “Practical Learning for Grid Laboratory”, “Power Hardware in the Loop Simulations for DER and Smart Grid”, and Labs along with other Validation Procedures, 19-21 June 2018, Bilbao, Spain. (18 hours)
4- Participation in summer school on topics: “Changing Role of DSOs”, “Current Status of Renewable Integration”, “Ancillary Services”, “Flexibility and Reliability in Smart Grid”, and “Large Scale Integration of Renewables in the Grid”. Topics also include “Evolution of Ancillary Service Provision in TERNA”, “Uncertainty Impacts of DER Integration”, and “Provision of Distribution Network Services by DER ”,“ DER Aggregation and Energy Storage, Enel Future Distribution Grid”, and visit to TERNA dispatch center, 2-5 July 2018, Salerno, Italy. (5 ECTS)

International Dissemination:

1- Oral presentation of paper, “Reactive Power Provision to TSO/DSO by Aggregators and Conventional Generators” at IEEE International Conference on Smart Grid Communications, October 2017, Dresden, Germany.
2- Poster presentation of paper, “Participation of Customers to Virtual Power Plants for Reactive Power Provision” at Proc. CIRED 2018 Workshop, Slovenia, June 2018.
3- Oral presentation of paper, “Coordinated Control Mechanism for Voltage Stability Utilizing Aggregation of Reactive Power Compensation Techniques” at IEEE 18th EEEIC on Environment and Electrical Engineering, Palermo, Italy, June 2018.
4- Oral presentation of paper, “Participation of Customers to Virtual Power Plants for Reactive Power Provision” at IEEE UPEC, Glasgow, Sep 2018.
5- Oral presentation of paper, “STATCOM Applications for Voltage Profiling of a Distribution Grid with High Penetration of Distributed Energy Resources” at IET Proc. MEDPOWER, Croatia, Nov 2018.
6- Poster presentation of paper, “Virtual Power Plant for Improving Power System Protection Issues – Solution to the Problem of Power System Reliability under Distributed Energy Resources” at IEEE AUPEC, New Zealand, Nov 2018.
7- Poster presentation of paper, “Flexibility to DSO by VPP – Benefits, Regulatory Barriers, and Potential Solutions” at Proc. CIRED 2019 Conference, Madrid, June 2019.

Reviewer:

1- Reviewer of IEEE PES ISGT-Asia Conference 2018.

2- IEEE EEEIC Conference 2019.

Abroad Period:

1- Validation of subset of VPP (customer-aggregator) is performed, using LabVIEW-RT and DIgSILENT, at French Metrology Institute, LNE, June 1-July 31 2018, Paris, France.
2- Validation of full-scale VPP is performed, using OPAL RT, MATLAB/Simulink, and DIgSILENT, at OFFIS, Oct 1 – Nov 30, Oldenburg, Germany. This work is part of ERIGrid EU H2020.

Industrial Experience:

1- Technical Specialist Expert, Enel Produzione, Jan 2017- Jan 2020, Pisa, Italy.

APPENDIX C - PUBLICATIONS DURING PHD:

Disclaimer: The thesis comprises of the material published as part of publications mentioned here (publications during PhD).

Conference Papers:

1- Jibran. Ali, Stefano. Massucco, and Giacomo. Petretto, "Reactive Power Provision to TSO/DSO by Aggregators and Conventional Generators," in Proc. IEEE International Conference on Smart Grid Communications, Germany, Oct 2017.
2- Jibran. Ali, "Coordinated Control Mechanism for Voltage Stability Utilizing Aggregation of Reactive Power Compensation Techniques," in Proc. EEEIC, Palermo, June 2018.
3- Jibran. Ali, Stefano. Massucco, Federico. Silvestro, and Andrea. Vinci, "Participation of Customers to Virtual Power Plants for Reactive Power Provision," in Proc. UPEC, Glasgow, Sep 2018.
4- Jibran. Ali, Stefano. Massucco, and Federico. Silvestro, "STATCOM Applications for Voltage Profiling of a Distribution Grid with High Penetration of Distributed Energy Resources," in Proc. MEDPOWER, Croatia, Nov2018.
5- Jibran. Ali, Federico. Silvestro, and Mahmood. Jamil, "Virtual Power Plant for Improving Power System Protection Issues – Solution to the Problem of Power System Reliability under Distributed Energy Resources," in Proc. AUPEC, New Zealand, Nov 2018.
6- Jibran. Ali, Stefano. Massucco, and Federico. Silvestro, "Flexibility to DSO by VPP – Benefits, Regulatory Barriers, and Potential Solutions", CIRED 2019, Madrid, June 2019.
7- Jibran. Ali and Federico. Silvestro, "Conventional Power Plants to TSO Frequency Containment Reserves - A Competitive Analysis for Virtual Power Plant Role", RTSI 2019, Firenze, September 2019.

Workshop Paper:

1- Jibran. Ali, Stefano. Massucco, and Federico. Silvestro, "Architecture of Virtual Power Plant for Ancillary Services," in Proc. CIRED 2018 Workshop, Slovenia, June 2018.

Journal Papers:

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