Peer-to-Peer Energy Trading in Electrical Distribution Networks

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Abstract

In response to the challenges posed by the increasing penetration of distributed generation from renewable energy sources and the increasing electricity retail prices with decreasing Feed-In Tariff rates, a new energy trading arrangement, "peer-to-peer (P2P) energy trading" has been proposed. It refers to the direct energy trading among consumers and prosumers in distribution networks, which is developed based on the "P2P economy" concept (also known as sharing economy).

A hierarchical system architecture model has been proposed in order to identify and categorise the key elements and technologies involved in P2P energy trading. A P2P energy trading platform called "Elecbay" is designed. The P2P bidding is simulated using game theory. Test results in a grid-connected LV Microgrid with distributed generators and flexible demands show that P2P energy trading is able to improve the local balance of energy generation and consumption, and the enhanced variety of peers is able to further facilitate the balance.

Two necessary control systems are proposed for the Microgrid with "Elecbay". A voltage control system which combines droop control and on-load-tap-changer (OLTC) control is designed and simulated. Simulation results show that the proposed voltage control system is sufficient for supporting the P2P energy trading in the Microgrid. The total number of operation times of the OLTC is reduced with P2P energy trading compared to the reference scenario.

The information and communication technology (ICT) infrastructures for the P2P bidding platform and the voltage control system are investigated. The information exchange among peers and other parties (Elecbay, distribution system operators, etc.) is designed based on TCP/IP protocol. Existing and private communication networks with different communication medium, bandwidths, etc., are modelled. Simulation results show that the existing ICT infrastructures are sufficient for supporting both the P2P energy trading platform and the voltage control system. Therefore, no large amount of additional investments are required.

Declaration

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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Acknowledgement

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Nomenclature

List of abbreviation

ABSVD	Applicable Balancing Services Volume Data
ACK	Acknowledge
AD	Anaerobic Digestion
AMI	Advanced Metering Infrastructures
AMR	Automatic Meter Reading
BETTA	British Electricity Trading and Transmission Arrangements
BMU	Balancing Mechanism Unit
BOA	Bid Offer Acceptance
BSAA	Balancing Services Adjustment Actions
BSAD	Balancing Services Adjustment Data
BSC	Balancing and Settlement Code
CHP	Combined Heat and Power
CREST	Centre for Renewable Energy System Technology
DER	Distributed Energy Resource
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DNO	Distribution Network Operator
DSO	Distribution System Operator
ECVN	Energy Contract Volume Notification
ESR	Electricity Supply Regulations
EU	European Union
EV	Electrical Vehicle
FDDI	Fiber Distributed Data Interface
FIN	Finish

FIT	Feed-In Tariff
FPN	Final Physical Notification
FTP	File Transfer Protocol
GB	Great Britain
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
HAN	Home Area Network
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IANA	Internet Assigned Numbers Authority
ICT	Information and Communication Technology
IP	Internet Protocol
LDC	Line Drop Compensation
LTE	Long-Term Evolution
MDM	Meter Data Management
MPT	Maximum Power Tracker
NAN	Neighbourhood Area Network
NETA	New Electricity Trading Arrangements
Ofgem	Office of Gas and Electricity Markets
OLTC	On-Load-Tap-Changer
OMS	Outage Management Systems
OSI	Open Systems Interconnection
P2P	Peer-to-Peer
PLC	Power-Line Communication
PN	Physical Notifications
PPP	Point-to-Point Protocol
PV	Photovoltaic
QoS	Quality of Supply

RES	Renewable Energy Sources
RF	Radio Frequency
RTP	Real-time Transport Protocol
SBP	System Buy Price
SCSI	Small Computer System Interface
SGAM	Smart Grid Architecture Model
SGSN	Serving GPRS Support Node
SLC	Supply Licence Condition
SMTP	Simple Mail Transfer Protocol
SO	System Operator
SSL	Secure Shell
SSP	System Sell Price
SVC	Static VAR Compensator
SYN	Synchronise
TCP	Transmission Control Protocol
TELNET	Teletype Network
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UK	United Kingdom
VoLL	Value of Lost Load
WAN	Wide Area Networks
WWW	World Wide Web

Chapter 1

Introduction

In this chapter, the potential challenges in the current distribution networks are discussed. Peer-to-peer (P2P) energy trading arrangements are able to provide promising solutions to address those challenges. The requirements of the control systems and information and communication technologies (ICT) infrastructures for facilitating P2P energy trading arrangements in distribution networks are further outlined. The research objectives of designing the P2P trading arrangements and the relevant control and communication systems are specified. Finally, the thesis structure is provided.

1.1 Potential challenges in distribution networks

Conventional electric power systems in most countries have been developed following the arrangement indicated in Fig. 1.1. Electricity is produced at central power stations. Transformers increase the voltage to high levels which are suitable for transmission, and gradually step it down to lower levels as the electricity flows through the transmission and distribution networks until it is delivered to the consumers. Most consumers are billed based on the quantity (kWh) of electricity they use over a fixed period of time (e.g., a quarter). Meter readings are collected either by meter readers who physically visit individual meters, or by smart meters [1]. The flow of electricity and the flow of information are both unidirectional, but in opposite directions.

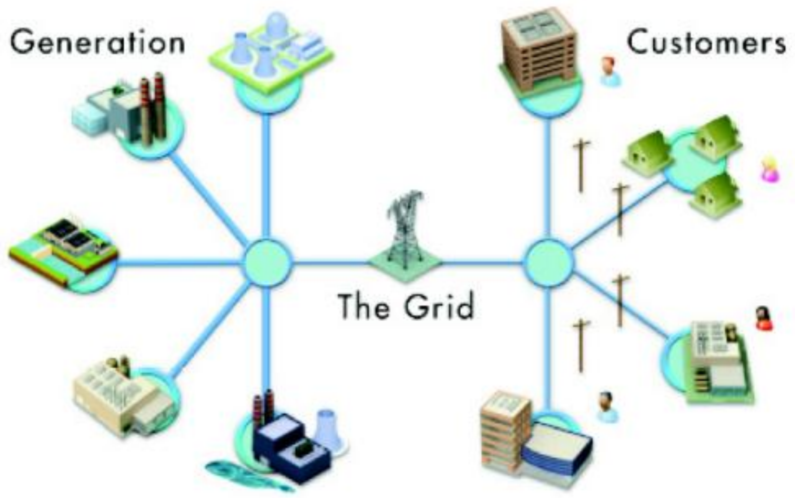


Fig. 1.1. Conventional Electric Power System

The conventional arrangement of electric power systems has a number of advantages. Large generating units can be made efficient and operated with only a relatively small staff. The interconnected high voltage transmission network allows the most efficient generating plants to be dispatched at any time, bulk power to be transported over long distances with limited electrical loses and generation reserve to be minimised. The distribution networks can be designed simply for unidirectional flows of power and sized to accommodate customer loads [2].

However, the use of fossil fuel for energy generation and consumption is recognised as one of the main reasons for green-house gas emissions [3], which lead to climate change. In response to that, the governments of many countries in the world have set ambitious targets to increase the use of renewable energy and to reduce green-house gas emissions from fossil fuel.

The European Union (EU) has set the following "20/20/20" energy and climate targets for the year of 2020 [4]:

- 20% cut in green-house gas emissions (from 1990 levels);
- 20% of EU energy from renewables;
- 20% improvement in energy efficiency.

In October 2014, the European Council agreed on a climate and energy policy framework for the EU, and enclosed new climate and energy targets for 2030 [5]:

- a binding target of at least a 40 % reduction in domestic GHG emissions, compared with 1990 levels;
- a target for RES (Renewable Energy Sources) consumption to be at least 27 % of final energy consumption by 2030;
- an indicative target at EU level of at least a 27 % improvement in energy efficiency in 2030 compared with projections of future energy consumption (based on the European Commission's 2007 Energy Baseline Scenario)

In the United Kingdom (UK), the 2008 Climate Change Act established the world's first legally binding climate change target - to reduce the UK's green-house gas emissions by at least 80% (from the 1990 baseline) by 2050 [6].

In order to meet the energy and climate change targets, there are a series of actions that have been put into practice. In many countries various financial mechanisms have been proposed to encourage the development of renewable energy generation, e.g. Feed-In Tariffs (FIT) [7], carbon taxes, etc. These policies result in a higher penetration of RESs and an increasing electricity demand due to the electrification of heat and transport sectors [8], which will create new challenges in distribution networks.

1.1.1 Increasing electricity demand and retail prices with decreasing Feed-In Tariff

The increase of population, economy and electrification of heating and transport all contribute to the increase of electricity demand in the Great Britain (GB) power system, leading to the increase of electricity retail prices. More power plants are under construction, more fuel needs to be imported, and the costs of electricity transmission and distribution also rise.

Feed-In Tariff was designed to encourage the installation of small-scale generators using RESs. It was very successful with a rapid growth of generation from renewable energy sources, especially solar power, over years. However, the number of new installations increased unexpectedly fast, and as a result the government started to decrease the Feed-In Tariff rates more significantly and frequently (every three month most recently).

The increasing electricity retail prices and decreasing Feed-In Tariff rates are threatening the interests of all the household and business consumers and the future development of distributed generation from renewable energy sources.

1.1.2 Higher penetration of distributed generation from renewable energy sources

The higher penetration of distributed generation from renewable energy sources creates new challenges for the operation of distribution networks.

With a high penetration of distributed generation, the power flows become reversed and the distribution network is no longer a passive circuit supplying loads but an active system with power flows and voltages determined by the generation as well as the loads [2]. The change in real and reactive power flows caused by distributed generation has important technical and economic implications for the distribution network.

Besides, the generation of renewable energy sources is intermittent and very difficult to predict, which makes it more challenging for distribution network operators (DNOs) to manage the networks in real-time.

1.1.3 Rapid growth of the volume of data transmission

An increasing number of communication mechanisms and techniques are being implemented in the conventional power system for economic and technical purposes nowadays.

For example, Smart Metering is to replace the traditional electro-mechanical meters in households with electronic ones, together with the implementation of an advanced communication network for collecting meter readings. It was originally designed to upgrade the billing process for energy usage, and further expanded into other areas such as Outage Management Systems (OMS) [9], voltage control [10], etc.

The implementation of those communication infrastructures and its relevant Smart Grid applications contributes to a rapid growth of the volume of data transmission in distribution networks. ICT-related issues, e.g. connection failures, information transmission latencies, data errors, etc., are expected to become more and more critical.

1.2 Peer-to-peer energy trading

P2P energy trading is an emerging local market arrangement in distribution networks, in response to the challenges posed by the increasing penetration of distributed generation from renewable energy sources and the increasing electricity retail prices with decreasing FIT rates. P2P energy trading has the potential to increase the benefits of all the consumers and prosumers, and to facilitate the local balance of consumption and intermittent generation from renewable energy sources, thus being beneficial to the power system as well.

1.2.1 Concept of peer-to-peer energy trading

With the increasing connection of renewable energy sources, traditional energy consumers are becoming prosumers, who can both consume and generate energy [11]. Renewable energy sources are usually intermittent and difficult to predict. When prosumers have surplus electricity, they can curtail it, store it with energy storage devices, export it back to the power grid, or sell it to other energy consumers. The direct energy trading among consumers and prosumers is called peer-to-peer energy trading, which was developed based on the "P2P economy" concept (also known as sharing economy) [12], and is usually implemented within a local electricity distribution system.

A peer in the P2P energy trading refers to one or a group of local energy customers, and may include generators, consumers and prosumers. The peers buy or sell energy directly with each other without intermediation by conventional energy suppliers [13]. P2P energy trading is usually enabled by ICT-based online services [12].

The conventional energy trading is mainly unidirectional. Electricity is usually transmitted from large-scale generators to consumers over long distances, while the cash flow goes the opposite way. However, the P2P energy trading encourages multidirectional trading within a local geographical area. Trials of energy trading based on the "P2P economy" concept have already been carried out across the globe, for example, Piclo in the UK [14], Vandebron in Netherlands [15], and sonnenCommunity in Germany [16]. These trials mainly focused on providing incentive tariffs to electricity customers from the energy suppliers' perspective.

In the research reported in this thesis, for the first time, a system architecture, a trading arrangement, an associated bidding system and the supporting control systems and communication systems are introduced for the P2P energy trading in distribution networks.

1.2.2 Four-layer system architecture of peer-to-peer energy trading

The Smart Grid Architecture Model (SGAM) [17] was proposed by the European Standardization Organizations to perform continuous standard enhancement and development for Smart Grids. Based on the SGAM, a four-layer system architecture is proposed for P2P energy trading in this thesis, as shown in Fig. 1.2, in order to identify and categorise the key elements and technologies involved in P2P energy trading based on the roles they play.

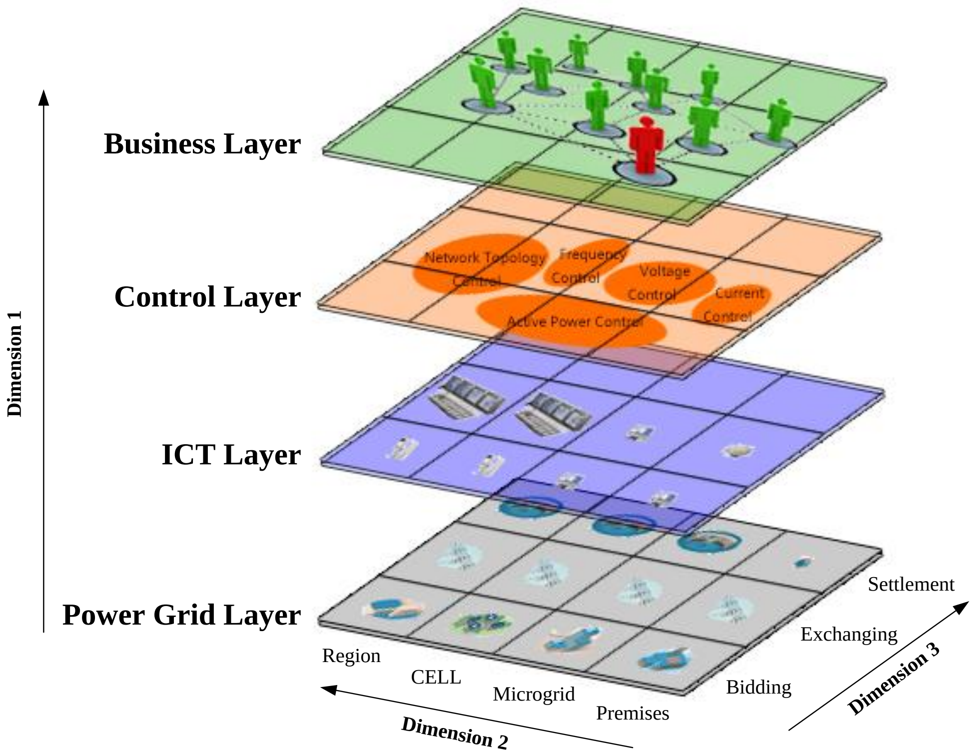


Fig. 1.2. A Four-Layer System Architecture of Peer-to-Peer Energy Trading

There are three dimensions in the system architecture.

In the first dimension, the key functions involved in P2P energy trading are categorized into four interoperable layers of different functionalities. The layers are introduced as follows.

The power grid layer consists of all physical components of the power system, including feeders, transformers, smart meters, loads, DERs, etc. These components form the physical electricity distribution network where P2P energy trading is implemented.

The ICT layer consists of communication devices, protocols, applications and information flow. Communication devices refers to sensors, wired/wireless communication connections, routers, switches, servers and various types of computers. Protocols include TCP/IP (Transmission Control Protocol/Internet Protocol), PPP (Point-to-Point Protocol), X2.5, etc. Communication applications can be various, such as information transfer and file exchange. The information flow refers to the senders, the receivers, and the content of each message transferred among communication devices.

The control layer mainly consists of the control functions of the electricity distribution system. Different control strategies are defined in this layer for preserving the quality and reliability of power supply and control the power flow. Voltage control, frequency control and active power control are examples of possible control functions in the control layer.

Business layer determines how electricity is traded among peers and with the third parties. It mainly consists of peers, suppliers, Distribution System Operators (DSOs), energy market regulators. Various kinds of trading arrangements could be developed in this layer to implement different forms of P2P energy trading.

The second dimension of the system architecture is categorised based on the size of the peers participating in the P2P energy trading, i.e. premises, Microgrids, CELLs, and regions (consists of multi-CELLs). Individual premise refers to one single house connected to the electricity distribution system. It is the smallest entity that could participate in the P2P energy trading. Microgrids are electricity distribution systems containing loads and distributed energy resources (DERs, including distributed generators, storage devices, or controllable loads) that can be operated in a controlled and coordinated way either while connected to the main power network or while is islanded. It normally consists of a collection of individual premises and DERs in a local geographical area that share the same MV/LV transformer. Similarly, CELLs are electricity distribution systems containing loads and DERs that is connected to the transmission system via HV/MV transformers. It may contain several Microgrids, and it can also be operated in either grid-connected or islanded mode. A region can be as large as a city or a metropolitan area which consists of multiple CELLs. A Microgrid, a CELL or a region can all be considered as a peer and trade with each other.

The third dimension shows the time sequence of the P2P energy trading process. Bidding is the first process of P2P energy trading when prosumers sign trading agreements with each other prior to the energy exchange. During the bidding process, prosumers interact with each other and agree on the price and amount of energy to be traded. Energy exchanging is the second process, during which energy is generated, transmitted and consumed. Settlement is the final process when bills and transactions are finally settled via settlement arrangements and payment. Considering the physical network constraints and uncertainty of DERs, a seller who has promised to sell a certain amount of electricity sometimes is unable to generate that exact amount as listed in the orders. The similar situation also applies to a buyer. The difference between the promised and actual electricity generation or consumption quantity needs to be calculated and charged during the settlement.

The research reported in this thesis discusses the design of a P2P energy trading arrangement in the business layer, the control layer and the ICT layer separately.

1.3 Research objectives

This thesis focuses on the design of a P2P energy trading arrangement in distribution networks, including the bidding platform, control systems and ICT infrastructures. The research objectives are:

- <u>To investigate the P2P bidding among peers in the business layer during the bidding time period:</u>

  A software platform, called “Elecbay”, was proposed and simulated using game theory. The impact of P2P energy trading on the balance of generation and consumption in the local distribution network was studied.

The impact of variety of peers in P2P energy trading on the balance of local generation and consumption was further explored.

- <u>To investigate the control of the local distribution network with P2P energy trading in the control layer before and during the exchanging time period:</u>

  The necessary control mechanisms for the P2P energy trading arrangement based on "Elecbay" was discussed. A voltage control strategy based on droop control and On-Load-Tap-Changer (OLTC) control was proposed and simulated using power flow analysis. The impact of P2P energy trading on the control systems of the local distribution networks was studied.

- <u>To investigate the requirements of ICT infrastructures for the P2P bidding and control in the ICT layer during the bidding time period and exchanging time period respectively:</u>

  Both the P2P bidding platform and its relevant control systems require communication systems. The communication between peers and other parties (Elecbay, DSOs, etc.) was designed based on TCP/IP protocol. Communication networks with different medium and bandwidths were modelled in OPNET. The performances of the networks were compared and analysed in order to prove if the existing ICT infrastructures are sufficient for supporting P2P energy trading, and if not, what additional investments are necessary, and what improvements are expected to be made.

1.4 Thesis structure

The structure of the thesis is as follows:

In Chapter 2, electricity trading arrangements in the GB electricity markets, control in distribution networks, and ICT infrastructures for P2P energy trading were reviewed. The current trading arrangements and Feed-In Tariff in the retail market, and the settlement and imbalance mechanism in the wholesale market were explained. Existing trails on P2P energy trading arrangements were summarised and compared. The impact of distributed generation and the corresponding voltage control methods in distribution networks were discussed. The concepts and technologies on Smart Grid, Smart Metering, OSI communication network model, and TCP/IP protocol were described.

Chapter 3 presented the P2P bidding among peers in the business layer during the bidding time period. A software platform, called “Elecbay”, was proposed to support the P2P bidding. The P2P bidding was then simulated using game theory. Case studies based on the EU benchmark Microgrid were undertaken in order to verify the impact of P2P energy trading on the balance of local generation and consumption in the Microgrid. The impact of the peer variety was further discussed.

Chapter 4 focuses on the control of the local distribution network with P2P energy trading in the control layer before and during the exchanging time period. Necessary control systems were proposed for the P2P energy trading arrangement based on “Elecbay”. A bid acceptance/rejection system was considered for the period after Gate Closure and before the start of energy exchange. A voltage control strategy which combined droop control and OLTC control was designed and simulated. Case studies were carried out in order to demonstrate the impact of P2P energy trading on the voltage control system of a grid-connected LV Microgrid.

Chapter 5 investigated the requirements of ICT infrastructures for the P2P bidding and control in the ICT layer during the bidding time period and exchanging time period respectively: The information exchange among peers and other parties (Elecbay, DSOs, etc.) was designed. Communication networks with different communication medium and bandwidths were modelled in OPNET. The performances of the networks were compared and analysed in the case studies in order to verify the technical feasibility of existing ICT infrastructures for supporting P2P energy trading platform and its relevant control systems.

Chapter 6 concludes and summarises the thesis. Contributions of the thesis, suggestions for future work and publications are listed.

Chapter 2

State of the Art of Peer-to-Peer Energy Trading, Voltage Control and ICT Infrastructures

This chapter reviews electricity trading arrangements, distribution network control and ICT infrastructures for P2P energy trading. The current trading arrangements, Feed-In Tariff and the settlement and imbalance mechanisms in the GB electricity market are reviewed. Existing trails on P2P energy trading arrangements are summarised and compared. The impact of distributed generation and the corresponding voltage control methods in distribution networks are reviewed. The concepts and technologies on Smart Grid, Smart Metering, Open Systems Interconnection (OSI) communication network model, and TCP/IP protocol are described.

2.1 Trading arrangements for the GB electricity market

2.1.1 Trading arrangements of the GB electricity retail market

In the electricity retail market, suppliers sell the electricity that they have purchased from generators in the electricity wholesale market to end consumers [18].

Electricity supply in Britain was a monopoly activity until the start of the privatization of the electricity industry in November 1990 [19]. Full competition was introduced in 1999. Since then domestic and non-domestic consumers have been able to choose and change their electricity suppliers freely [20].

Ofgem (Office of Gas and Electricity Markets) is the regulator of the GB electricity retail market. The role of Ofgem is to make sure that the electricity retail market works in the interests of consumers by monitoring the market and taking necessary actions to strengthen competition or enforce the rules with which suppliers must comply [18]. Suppliers need to acquire supply licences from Ofgem in order to start up their business. With the licence there are a set of obligations called SLCs (Supply Licence Conditions) [21]. They place rules on how licence holders are able to operate within their licence, including compliance with industry codes, metering, supply contracts, tariffs, FIT, Green Deal obligations, Smart Metering, etc [22].

The GB retail energy supply markets have six substantial companies (Centrica, EDF Energy, E.ON, RWE, Scottish and Southern Energy and Scottish Power) competing for the business of domestic consumers. However, the competition is not fully effective in all sectors of the retail market [23]. The rapid increase in domestic energy prices in recent years and the perception that profits and overall prices are too high have been a major source of public concern [24].

The historical domestic electricity prices in Britain is demonstrated in Fig. 2.1.

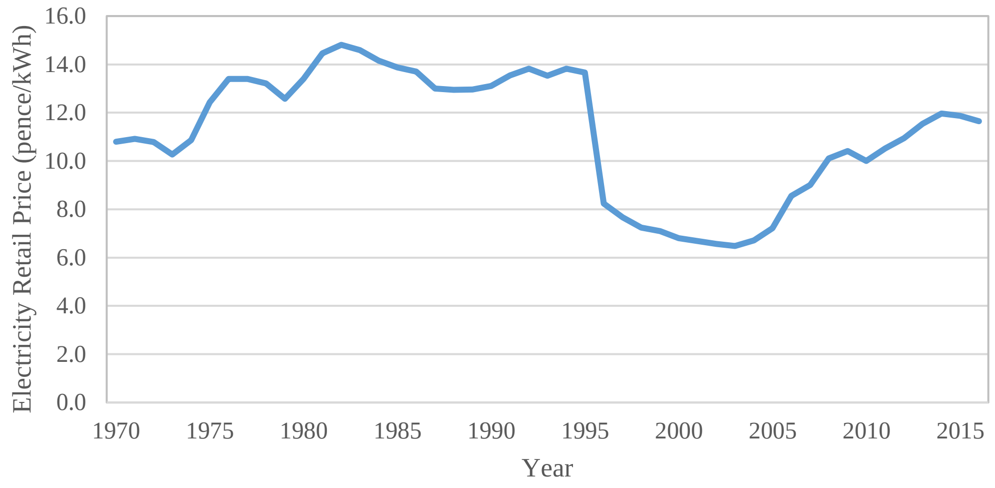


Fig.2.1. Historical Domestic Electricity Prices (1970 - 2016) [25]

The conventional energy trading is mainly unidirectional. Electricity is usually transmitted from large-scale generators to consumers over long distances, while the cash flow goes the opposite way. With the increasing penetration of distributed generation (DG) in the distribution networks, more and more small-scale residential or commercial electricity consumers become prosumers. They are able to inject their surplus electricity generated by DGs back to the distribution networks. The surplus electricity is paid by the suppliers based on the FIT scheme.

The FIT scheme is a government programme designed to promote the uptake of small-scale renewable and low-carbon electricity generation technologies. Introduced on 1 April 2010, the scheme requires participating licensed electricity suppliers (FIT Licensees) to make payments on both generation and export from eligible installations [26].

The FIT scheme is available for anyone who has installed, or is looking to install, one of the following technology types up to a capacity of 5MW, or 2kW for CHP:

- Solar photovoltaic (solar PV)
- Wind

- Micro combined heat and power (CHP)
- Hydro
- Anaerobic digestion (AD)

Electricity prosumers who are eligible to receive FITs payments are able to benefit in three ways:

- Energy bill saving: less electricity purchased from the suppliers;
- Generation tariff: receiving payment from the suppliers based on a set rate for each unit (or kWh) of electricity generated by DGs;
- Export tariff: receiving payment from the suppliers based on a set rate for each unit (or kWh) of electricity exported back to the electricity grid.

However, with the rapidly increasing number of prosumers who participate in the FIT scheme, the rates for both the generation tariff and export tariff decline. Fig. 2.2 shows the historical rates for the FIT scheme in Britain compared to the increasing domestic electricity prices.

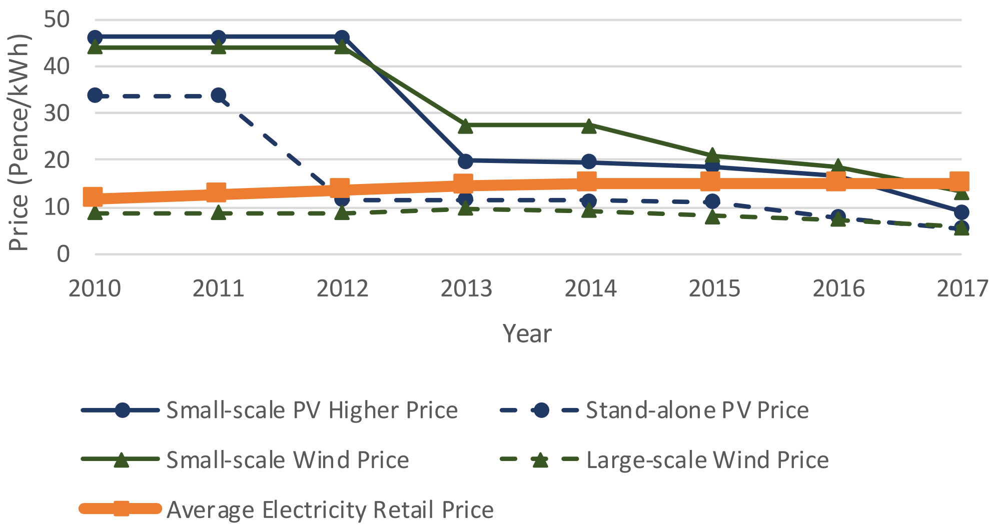


Fig. 2.2. Historical Rates for FIT Scheme and Domestic Electricity Prices [25] [26]

2.1.2 Trading arrangements of the GB electricity wholesale market

The electricity wholesale market is the market for the sale and purchase of electricity between suppliers (to meet the demands of their customers) and generators [27]. The current trading arrangements in the GB electricity wholesale market allow suppliers to buy the electricity they need to meet their customers' demands from the generators of their choices. Competition is achieved through unrestricted bilateral contract trading [27]. The interaction between the electricity wholesale and retail markets is illustrated in Fig. 2.3.

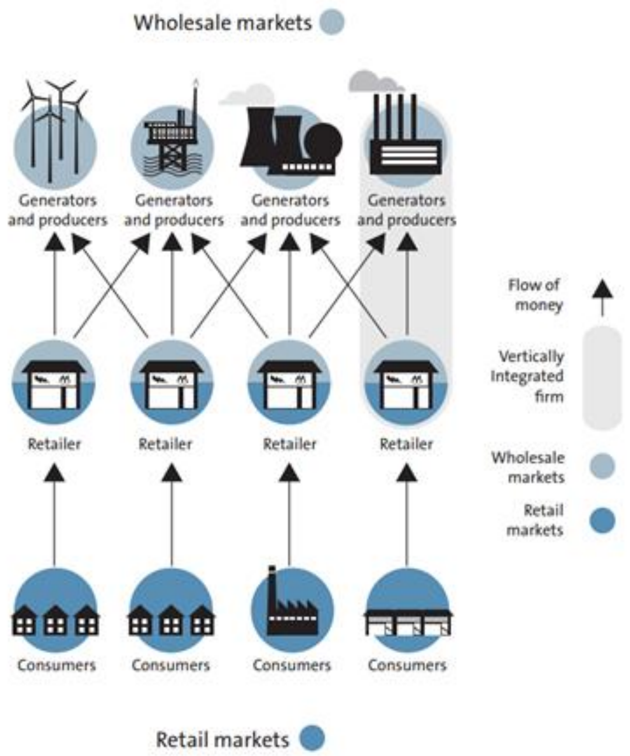


Fig. 2.3. Interaction between the electricity wholesale and retail markets [24]

Prior to 1990, there was no electricity wholesale market in Britain. The Central Electricity Generating Board decided who should generate and how much they should generate [28].

The wholesale market began its life in 1990 as the Pool, a compulsory day-ahead market for bulk physical trading between generators and purchasers (suppliers and large-scale consumers) [28]. However, the two dominant generators at that time (PowerGen and National Power) had too much market power, which resulted in a series of problems including non-sufficient competition (manipulation of the pool selling price), unnecessary increase of system marginal price, etc.

The New Electricity Trading Arrangements (NETA) came into effect in England and Wales on 27 March 2001, replacing the Pool [28]. Bilateral trading against a rolling gate closure was introduced. Suppliers were able to participate in the bilateral trading by offering to move their customers' demand up or down. On the other hand, generators became responsible for dispatching their own plant.

The British Electricity Trading and Transmission Arrangements (BETTA) extended NETA into Scotland in April 2005.Since then, National Grid has acted as the GB System Operator [28], and ELEXON has acted as the Settlement Agent in the GB electricity wholesale market by administering the Balancing and Settlement Code (BSC) [27].

The current electricity trading arrangements in the wholesale market is described as follows [27].

Electricity is generated, transmitted, distributed and consumed continuously in real-time, and supply must always match demand. Although the generation, transmission, distribution and consumption of electricity is continuous, for the purposes of trading and settlement electricity is considered to be generated, transmitted, distributed and consumed in chunks called Settlement Periods. The length of each Settlement Period in the GB wholesale market is currently half an hour.

For each Settlement Period, those with demand for electricity (e.g. large-scale consumers) and / or those with customers to supply (e.g. suppliers) have to assess in advance how much the demand will be. Then they contract with generators for that volume of electricity. Contracts are able to be struck up to an hour before the Settlement Period which the contract is for (this cut-off is known as Gate Closure and contracts are not allowed to be struck after this time, as illustrated in Fig. 2.4). During the half-hourly Settlement Period, generators are expected to generate and deliver their contracted volume of electricity and suppliers are expected to consume their contracted volume of electricity so that they do not have a surplus or deficit of electricity.

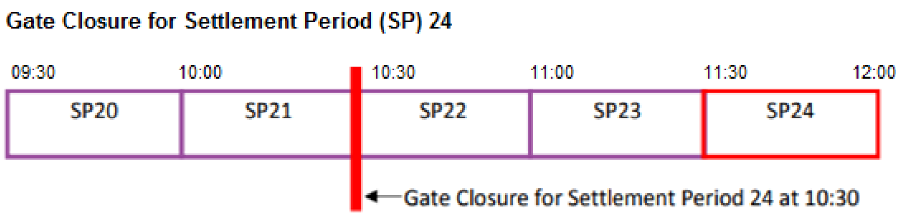


Fig. 2.4. An Example of Settlement Periods and Their Gate Closures [27]

However, in practice, the following situations may happen:

- Suppliers may have forecasted their electricity consumption incorrectly;
- Generators may be unable to generate the contracted amount; or
- There may be problems with the transmission networks.

Therefore there is a requirement for real-time management to ensure that supply matches demand and to address any issues with transportation and delivery. This is the role of the GB System Operator (National Grid). These surpluses and deficits of electricity are referred as imbalances, and the main purpose of the imbalance trading arrangements is to measure these imbalances and to determine the price at which the imbalance energy is to be settled. These are defined in the BSC.

Generators with additional capacity are able to make additional volume available for the System Operator to fulfill electricity deficits and set the price they wish to receive for the additional volume provided. Similarly, generators are also able to reduce the volume being generated to deal with electricity surpluses, and set a price for the reduction. Suppliers with flexible demands are also able to offer to reduce or increase their demands and set the corresponding prices. These actions are called Bids and Offers:

- An Offer is a proposal to increase generation or reduce demand; and
- A Bid is a proposal to reduce generation or increase demand.

The System Operator is required to match supply and demand in real-time during each half-hourly Settlement Period by accepting Bids or Offers depending on whether it is necessary to increase or reduce electricity generation to meet demand.

Afterwards, metered volumes are collected for each Settlement Period from generators and suppliers, and compared against their contracted volumes (which are adjusted considering any Bids or Offers accepted). All parties have their contracted volumes compared to determine whether the volumes they bought and sold match. Where the contracted volumes do not match the metered volumes, the following applies:

- Where a supplier has used more electricity than they contracted for, they must buy additional electricity from the grid with System Buy Price to meet the amount used;
- Where a generator has generated less than they contracted for, they must buy additional electricity from the grid with System Buy Price to meet their contracted levels.

And vice-versa:

- Where a supplier has contracted for more electricity than they used, they must sell that additional electricity to the grid with System Sell Price;

- Where a generator has generated more electricity than they were contracted for, they must sell that additional electricity to the grid with System Sell Price.

The above rules are summarized in Table 2.1. The differences between generation and demand are referred as imbalances, and settlement is the process of calculating the volumes of imbalance and the price (System Buy Price and System Sell Price) to be paid for these imbalances. It is concluded that

$$\text{Energy Imbalance Volume} = \text{Energy} - (\text{Balancing Services} + \text{Contracts}) \tag{2.1}$$

$$\text{Energy Imbalance Cashflow} = \text{Imbalance Volume} \times \text{Imbalance Price} \tag{2.2}$$

Table 2.1. Rules of Determining the Imbalance Prices Based on Imbalance Position

	Supplier	Generator
System Sell Price (SSP)	Paid if under consume	Paid if over generate
System Buy Price (SBP)	Pay if over consume	Pay if under generate

The calculation of the SSP and the SBP is further demonstrated in Section 2.1.3.

2.1.3 Imbalance pricing in the GB electricity wholesale market

This section demonstrates the definition of imbalance, balancing actions that could be taken by the System Operator to balance the generation and demand, and the calculation of the imbalance prices (SSP and SBP) for a single Settlement Period based on the balancing actions that have been taken by the System Operator (SO).

Electricity cannot be stored economically in large quantity. Generation must always be equal to demand plus energy lost (transmission losses). If it does not, then the frequency of the transmission system moves away from the target frequency (50Hz) and the transmission system becomes unstable.

However, the contracts between generators and suppliers do not always completely balance the transmission system. Where the transmission system is not balanced, National Grid, as the SO, ensures the transmission system is always balanced.

In order to balance the transmission system, the SO needs to know what generators intend to generate and what suppliers intend to consume for each Settlement Period. The SO needs this information before the start of the Settlement Period so that it is able to understand the transmission system imbalance, plan how to balance it and take balancing actions.

Therefore, generators and suppliers submit Physical Notifications (PNs) for each Balancing Mechanism Unit (BMU) to the SO for each Settlement Period, and one hour before each Settlement Period the PNs of Parties are frozen. This is called gate closure. At this point the PNs become Final Physical Notifications (FPNs). After gate closure, Parties must try to adhere to the FPNs submitted to the SO. They should only deviate from their FPN at the instruction of the SO [27].

Parties also submit Energy Contract Volume Notifications (ECVNs) to the BSC Systems for each Settlement Period before gate closure. The ECVNs notify the BSC Systems of parties' contracted volumes, and are used for calculating parties' imbalances.

Following gate closure, the SO is able to evaluate the net imbalance of the transmission system. The SO does this by assessing the FPNs of the generators and suppliers and comparing that assessment to its own forecasts for the Settlement Period. The Transmission System's net imbalance is also called the transmission system length [27].

- A "long" Transmission System is one where there is more generation than demand.

- A “short” Transmission System is one where there is more demand than generation.

The SO has a number of ways for balancing the transmission system. Whatever mechanism the SO uses, it is trying to balance the transmission system as efficiently as possible. Ideally the SO would choose the cheapest balancing action, then the next cheapest, then the next cheapest, and so on. However, this is not always possible as the SO also considers:

- Technical limitations of the power station or demand manager - is it able to increase or decrease generation/demand quickly enough to meet the requirement; and
- Technical limitations of the transmission system - can the generation/demand be transmitted to the part of the transmission system where it is needed.

The SO submits balancing actions to the BSC Systems using:

- The Balancing Mechanism – for Bid Offer Acceptances (BOAs); and
- Balancing Services Adjustment Data (BSAD) – for balancing actions taken outside of the Balancing Mechanism.

The Balancing Mechanism operates after Gate Closure, whereas balancing actions submitted through BSAD can be taken at any point, which is illustrated in Fig. 2.5.

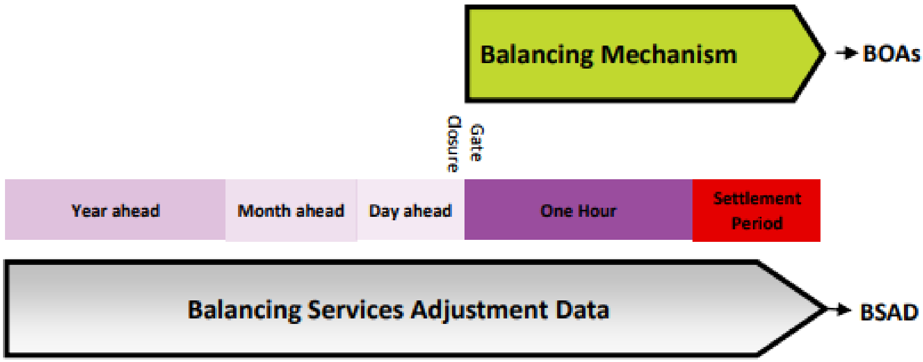


Fig. 2.5. Timing of the Balancing Mechanism and BSAD

In addition to the Balancing Mechanism and BSAD, the SO also uses ancillary and commercial services to balance the transmission system. Ancillary and commercial services include:

- Reactive Power;
- Frequency Response;
- Black Start; and
- Reserve Services.

These services are system balancing services, and therefore are not normally considered while calculating the energy imbalance prices. However, SO does send data of the volumes involved to the BSC Systems, so that the parties that provide these services can have their imbalance volumes suitably adjusted. This is called Applicable Balancing Services Volume Data (ABSVD).

The balancing mechanism operates from gate closure to real time and is managed by the SO. It works in a similar way to an auction. Parties submit notices telling the SO how much it would cost for them to deviate from their Final Physical Notification, as described earlier.

The SO assesses all the Bids and Offers for each Settlement Period and chooses the ones that, alongside the balancing actions submitted through BSAD, best satisfy the balancing requirements of the transmission system.

Accepted Bids and Offers are called BOAs. For each BOA, the SO contacts the BM Unit directly and instructs it to deviate from its FPN.

There are some actions that the SO uses only as a last resort to balance the system in the rare event that there is insufficient capacity in the market to meet demand. These include contingency balancing reserve and Demand Control. If they are used they will be included in the imbalance price calculation at a price of Value of Lost Load (VoLL) [27].

The BSC Systems calculate the energy imbalance price using balancing actions accepted by the SO for that Settlement Period.

For most periods the price calculation reflects the costs of balancing the transmission system for that Settlement Period. These depend on the system's overall imbalance. Where the transmission system is long, the price calculation is based on actions taken by the System Operator to reduce generation or increase demand. Where the transmission system is short, the price calculation is based on actions taken by the System Operator to increase generation or decrease demand.

There are three types of balancing action which are considered:

- BOAs;
- Balancing Services Adjustment Actions (BSAAs); and
- Demand Control Actions.

Some balancing actions are taken purely to balance the half-hourly energy imbalance of the transmission system. These are energy balancing actions. However, some balancing actions are taken for non-energy, system-management reasons. These are called system balancing actions.

Examples of system balancing actions are:

- Actions that are so small in volume that they could be the result of rounding errors;
- Actions which have no effect on the energy balancing of the System but lead to an overall financial benefit for the SO;
- Actions taken for locational balancing reasons; and
- Actions taken to correct short-term increases or decreases in generation/demand.

A number of processes are used to minimise the price impact of system balancing actions on the energy imbalance price calculation, including flagging, classification and tagging. A detailed description of the calculation processes (with 17 steps) is provided in [27].

2.1.4 Trails on peer-to-peer energy trading arrangements

Existing power systems were designed to accommodate large-scale generating plants, with demand traditionally considered as uncontrollable and inflexible. However, with the increasing integration of DERs, traditional energy consumers will become prosumers, who can both generate and consume energy [29]. Generation of DERs is unpredictable and intermittent, and prosumers who have surplus energy can either store it with energy storage devices, or supply others who are in energy deficit. This energy trading among prosumers is called P2P energy trading [30].

In recent years, P2P energy trading has also been investigated in distribution level. In [31], a paradigm of P2P energy sharing among neighboring Microgrids was proposed for improving the utilization of local DERs and saving the energy bills for all Microgrids. [32] integrated a demand side management system coordinated with P2P energy trading among the households in the smart grid in order to minimize energy cost. In [33], an energy sharing model with price-based demand response was proposed. In [34], a non-cooperative game-theoretical model of the competition between demand response aggregators for selling energy stored in energy storage was illustrated.

A number of trails and projects on P2P energy trading have also been carried out in recent years. Some of them focus on business models and platforms for energy markets acting similarly as a supplier's role in the electricity sector, while some are targeted at the local control and ICT systems for Microgrids. This section summarises the details of those trails.

1. Piclo

Piclo was established in the UK. It was a collaboration between an innovative technology company called "Open Utility" and a renewable energy supplier "Good Energy", where business consumers could buy electricity directly from the local renewables. The meter data, generator pricing and consumer preference information were used to match electricity demand and supply every half hour. Generators have control and visibility over who buys electricity from them. Consumers can select and prioritize from which generators to buy electricity. Piclo matches generation and consumption according to preferences and locality, providing customers with data visualizations and analytics. Good Energy provides contracts, meter data, billing, award-winning customer service, and balances the market place. [35]

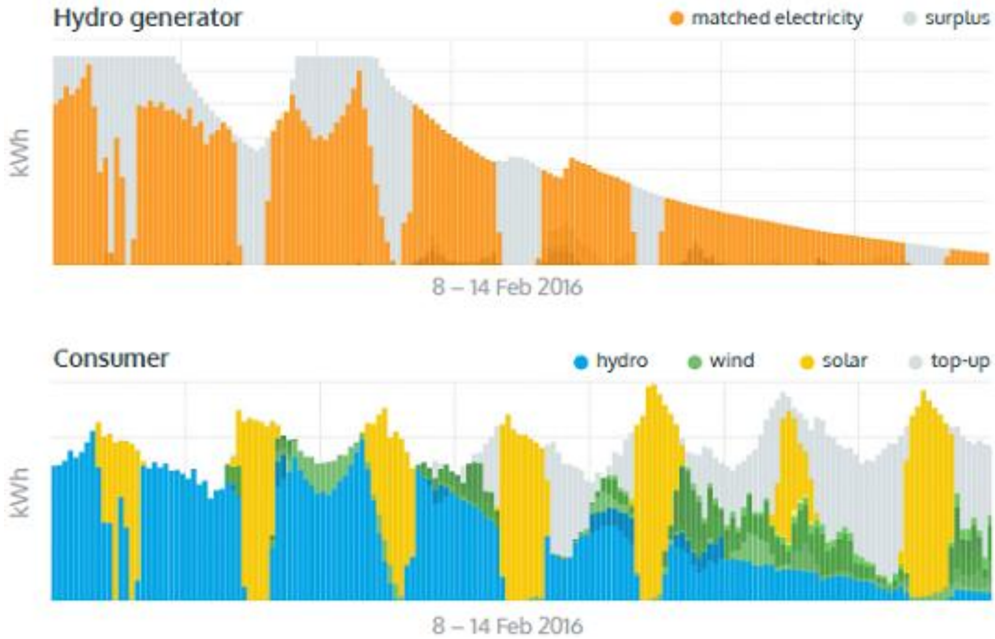


Fig. 2.6. Example of Matching Generation and Consumption in Piclo [35]

2. Vandebron

Vandebron is an online platform in Netherland where energy consumers can buy electricity directly from independent producers, such as farmers with wind turbines in their fields. [36] Very similarly to Piclo, it acts as an energy supplier who links consumers and generators, and balances the whole market.

3. PeerEnergyCloud

PeerEnergyCloud is a project in Germany. It developed cloud-based technologies for a local electronic trading platform for dealing with local excessive production. It was established in order to investigate innovative recording and forecasting procedures for device specific electricity consumption, to establish a virtual marketplace for power trading and to develop value added services within a Microgrid. [37]

4. Smart Watts

Smart Watts was also a German project. It proposed new approaches for optimizing energy supply through the use of modern ICTs, and these ICTs were developed and tested. It has exploited the optimization potential of ICTs in order to achieve greater cost-effectiveness and security of supply. [38]

5. Yeloha and Mosaic

Both Yeloha and Masaic were trails in the US. They allow interested consumers, such as apartment owners and others who do not own solar systems, to pay for a portion of the solar energy generated by the host's solar system. The subscribers get a reduction on their utility bills, so that in total, they save money, even if they move [39] [40]. They are similar to Piclo and Vandebron, but more interested in solar power than other renewables.

6. SonnenCommunity

The sonnenCommunity is developed by sonnenBatterie, which is a storage manufacturer in Germany. It is a community of sonnenBatterie (a type of battery produced by the sonnenBatterie company) owners who can share self-produced energy with others. As a result, there is no need for a conventional energy supplier anymore.

With a sonnenBatterie and a photovoltaic system, members can completely cover their own energy needs on sunny days – often even generating a surplus. This surplus is not fed into the conventional power grid, but into a virtual energy pool that serves other members in times when they cannot produce enough energy due to bad weather. A central software links up and monitors all sonnenCommunity members - while balancing energy supply and demand [41].This idea is very similar to Piclo's and Vandebron's, but sonnenCommunity obviously highlights the importance of storage system.

7. Lichtblick Swarm Energy

Swarm Energy is a set of services provided by energy supplier Lichtblick in

Germany. Swarm Conductor, which is one part of Swarm Energy services, is a unique IT platform in the energy market. On the platform, the processes of an increasingly complex world of energy to customer-friendly products and services for residential and business customers are combined. Customers' local power plants and storage are optimized. Swarm Energy allows a meaningful interaction of distributed and renewable energy sources. [42]

8. Community First! Village

Community First! Village is a 27-acre master-planned community that provides affordable, permanent housing and a supportive community for the disabled, chronically homeless in Central Texas. The project organizers are trying to supply the village with power from donations. [43]

9. TransActive Grid

TransActive Grid is a community energy market, and a combination of software and hardware [2-23] that enables members to buy and sell energy from/to each other securely and automatically, using smart contracts and the blockchain. The current prototype uses the Ethereum blockchain. Located in Brooklyn, New York City, consumers can choose where to buy renewables from. Home energy producers can sell their surplus to their neighbours, and communities can keep energy resources local, reducing dissipation and increasing micro and macro grid efficiency [44].

10. Electron

Electron is a revolutionary new platform for gas and electricity metering and billing systems in the UK, which is still under development. It will open the way for exciting innovative consumer energy services. It is a completely secure, transparent, decentralized platform that runs on a blockchain and provides a provably honest metering, billing and switching service using Smart Contracts and the power of Distributed Consensus. The platform will be open source and operate for the benefit of all users. It will not be owned or controlled by suppliers or brokers. [45]

Table 2.2. Comparison of different projects

Project Name	Country	Start Year	Objectives	Network Size	P2P? Layers	Outcomes	Shortcoming
Piclo	UK	2014	P2P energy trading platform from suppliers perspective	National	Business	A P2P energy trading platform	No discussion on local markets
Vandebron	Netherland	2014	P2P energy trading platform from suppliers perspective	National	Business	A P2P energy trading platform	No discussion on local markets
PeerEnergyCloud	Germany	2012	Cloud-based P2P Energy Trading Platform, Smart Home	Microgrids	Energy Network, ICT	Cloud-based platform for smart homes	No discussion on control system
Smart Watts	Germany	2011	Optimizing energy supply via ICT	Regional	Energy Network, ICT	A smart meter gateway as interface to Internet of energy	No discussion on control system
Yeloha, Mosaic	US	2015	Solar sharing network for lower energy bills.	Regional	Business	Terminated due to funding issues	No discussion on local markets
SonnenCommunity	Germany	2015	P2P energy trading with storage system	National	Energy Network, Business	A P2P energy trading platform (online)	No discussion on local markets
Lichtblick Swarm Energy	Germany	2010	IT platform for energy markets and customers	National	Energy Network, ICT	Plenty of services provided by the energy supplier	No discussion on local markets
Community First! Village	US	2015	Energy sharing from donations	Community	Business	Saving energy bills for poor people	No discussion on ICT and control system
TransActive Grid	US	2015	P2P energy trading within Microgrids using Blockchain	Grid-connected Microgrids	Energy Network, Control, ICT, Business	Automatic energy trading platform within Microgrids	Communication before exchange was ignored
Electron	UK	2016	Energy metering and billing platform using Blockchain	Unknown	Energy Network, ICT, Business	Not started yet	Not started yet

A comparison of the above projects has been summarized in Table 2.2.

As presented in Table 2.2, many of the above trails have some similarities. For example, Piclo, Vandebron, SonnenCommunity, Yeloha and Mosaic are all national or regional online platforms that support P2P energy trading among their members and these platform owners acted similarly to a supplier’s role in the electricity sector. They only focus on the development of business models, and ignore the possibility of introducing the models to smaller-scale local energy markets. Also, the design of ICT and control systems were not considered. Apart from those similarities, the projects, on the other hand, have different research focuses. Piclo and Vandebron aim to provide connections between energy consumers and generators, so that the unit price of electricity differs from time to time, while SonnenCommunity highlights the importance of storage system, and tends to adopt a more stable tariff.

Both PeerEnergyCloud and Smart Watts are based in Germany, and focus on the ICT technologies suitable for local P2P energy markets. They proposed different scenarios that described the business arrangements for P2P energy trading. However, the development of ICT technologies was treated as their main research direction rather than the P2P energy trading.

Finally, both TransActive Grid and Electron introduced the blockchain technology into the energy sector to simplify the metering and billing system in the energy markets. However, TransActive Grid is more interested in developing a local P2P energy market in Microgrids, while Electron is targeted only at an advanced billing platform for energy suppliers.

2.2 Distribution networks control to facilitate peer-to-peer energy trading

2.2.1 Distributed generation and its technical impacts on distribution networks

Traditionally, electrical power has been generated in centralized large power stations, such as fossil fuel, nuclear or hydropower plants which are located either close to sources of fuel or far from concentration of load centres [46]. Due to the low carbon energy policy from the government, the use of small scale generations that are connected in local distribution networks rather than transmission networks, i.e. DG has become more and more popular.

Established technologies include wind power, micro-hydro, solar photovoltaic systems, landfill gas, energy from municipal waste, biomass and geothermal generation. Emerging technologies include tidal stream, wave-power and solar thermal generation [47].

Renewable energy sources have a much lower energy density than fossil fuels. Therefore many renewable generation plants are smaller and geographically widely spread [47]. For example, biomass plants are usually of limited size due to the cost of transporting fuel with relatively low energy density. Those smaller plants, typically of less than 50-100 MW in capacity, are connected into the distribution system directly [47].

Some cogeneration or CHP schemes make use of the waste heat of thermal generating plant for either industrial process or space heating and are a well-established way of increasing overall energy efficiency. Transporting the low temperature waste heat from thermal generation plants over long distance is not economic. Therefore it is necessary to locate these CHP plants close to the heat load [47]. This leads to relatively small generation units, geographically distributed and with their electrical connection made to the distribution network. Although CHP units can, in principle, be centrally dispatched, they tend to be operated in response to the heat requirement or the electrical load of the host installation rather than the needs of the public electricity supply system [47].

The electrical machines like synchronous or asynchronous generators are used as the main equipment in DG technologies with direct connection or power electronic technique interface to distribution networks [46]. The DG technologies of cogeneration, biomass, solar thermal and geothermal generally employ synchronous generators to produce electricity and control reactive power. Asynchronous generators are usually used for wind farms and small hydropower plants. The power electronic device interfaces are used in solar photovoltaic systems, fuel cells and wind turbines with controllable reactive power output [46].

A basic grid-connected solar system is demonstrated in Fig. 2.7, while a wind turbine with a squirrel cage induction generator and a DFIG (doubly-fed induction generator) type wind turbine are demonstrated in Fig. 2.8 and Fig. 2.9 respectively.

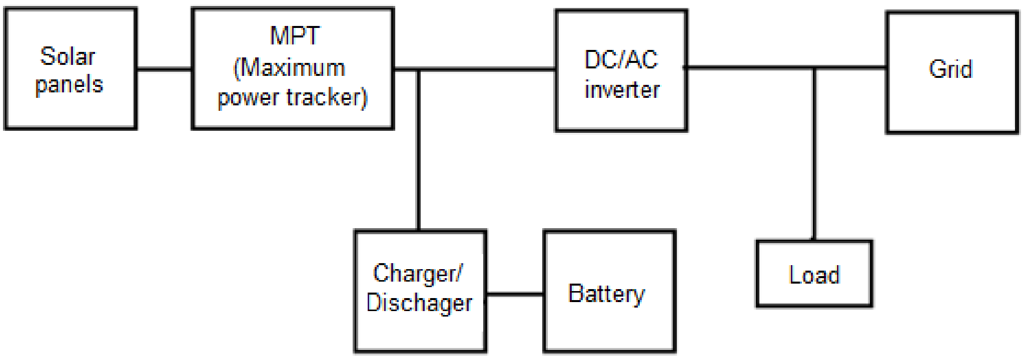


Fig. 2.7. Basic Grid-Connected Solar PV System [46]

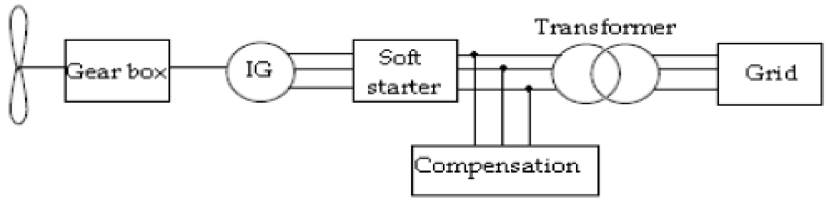


Fig. 2.8. Wind Turbine with a Squirrel Cage Induction Generator [46]

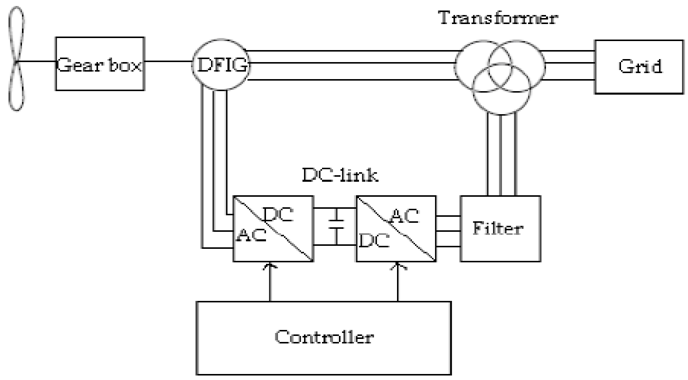


Fig. 2.9. DFIG Type Wind Turbine [46]

Traditionally, distribution networks are designed to accept power from the transmission network and to distribute it to customers. Thus both real power and reactive power flow from the higher to the lower voltage levels. However, with significant penetration of distributed generation, the power flows may become reversed and the distribution network is no longer a passive circuit supplying loads but an active system with power flows and voltages determined by the generation as well as the loads [47].

The change in real and reactive power flows caused by distributed generation has important technical implications for the power system. Standards were developed in some countries in order to deal with the technical issues of connecting and operating generation in distribution systems [48] [49]. The approach adopted was to ensure that any distributed generation did not reduce the quality of supply voltage offered to other customers and considered the generators as negative load [47]. The philosophy was of fit-and-forget where the distribution system was designed and constructed so that it functioned correctly for all combinations of generation and load with no active control actions of the generators, loads or networks being taken [47].

The technical impacts of distributed generation on the distribution networks include:

- Network voltage changes;
- Increase in network fault levels;
- Power quality (mainly transient voltage variations and harmonic distortion of the network voltage);
- Protection of distributed generators;
- Stability.

2.2.2 Voltage control in distribution networks

Voltage and frequency are the primary factors in the Quality of Supply (QoS) for power distribution networks. In distribution networks, only voltage control is considered since supply frequency is generally controlled at the transmission level [46].

Since 2003, the steady-state voltage magnitudes of power systems are required to be maintained within ±6% of nominal voltage for systems above 1kV and below 132kV. For voltage levels between 50V and 1kV, the permitted statutory limits are +10%/-6% of nominal voltage according to Electricity Supply Regulations (ESR) [46]. DNOs are responsible for maintaining the voltage within the permitted voltage limit.

In a simple radial distribution network, as illustrated in Fig. 2.10, voltages are determined by active and reactive power flows, P and Q; and by the line parameters, R and X. The per-unit voltage rise in this system, $V_2 - V_1$, is approximately given by equation 2.3 [50].

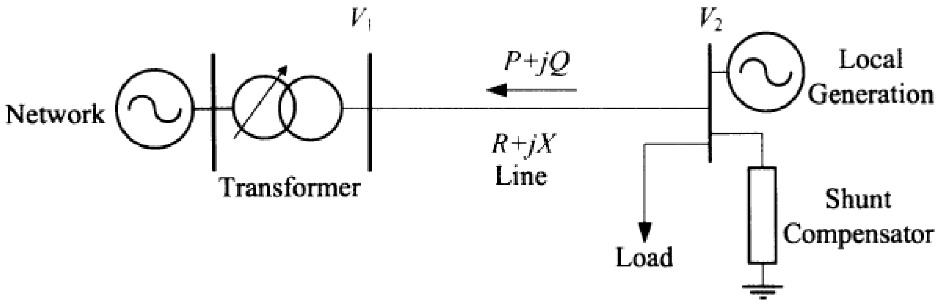


Fig. 2.10. A Simple Radial Distribution Network

$$V_2 - V_1 \approxeq PR + QX \tag{2.3}$$

The value of V_2 may be regulated through changing P, Q, or V_1.

There are three main categories of methods that are able to be used for regulating voltage:

1. Active Power Curtailment

Active power flow, P, has a large effect on the voltage levels in distribution networks due to the low X /R ratio [50] [51]. If the generation is much higher than the load, voltage may exceed its limit. In this case, generation must be curtailed [2-31].

2. Reactive Power Control

Reactive power flow, Q, may be changed using reactive power compensators (e.g. shunt reactors, shunt capacitors, static VAR compensators (SVCs), synchronous phase modifier, etc.) or generator reactive power control (e.g. control of synchronous machines, control of power electronics interfaces, etc.) [52]. The effect of reactive power on voltage levels is less than that of active power due to the low

X / R ratio [51]. Nevertheless, it has still been widely used to regulate the voltage and reduce generation curtailment.

3. Tap Changing Transformers

Voltage, V_1, can be controlled by regulating transformers, which can be either On-Load Tap Changing Transformers or Off-Load Tap Changing Transformers. These transformers have multiple taps on one of their windings, usually the HV windings. Selecting a different tap position changes the transformer turns ratio, and consequently its voltage ratio [50].

The On-Load Tap Changer (OLTC) is used to change tap position (which is the connection point along transformer winding) while the transformer is on-load without a supply interruption to provide a direct control [51]. They are usually installed where frequent tap changes are required. Off-Load Tap Changing transformers have to be disconnected from the network before changing their taps. In this case, taps are changed only to allow load growth or seasonal changes [50].

Fig. 2.11 shows a mechanical selector-diverter switch mechanism of OLTC. This mechanism is robust and reliable. On the other hand, it is slow, expensive, and bulky. Its life is limited by a total number of tap changing operations [50].

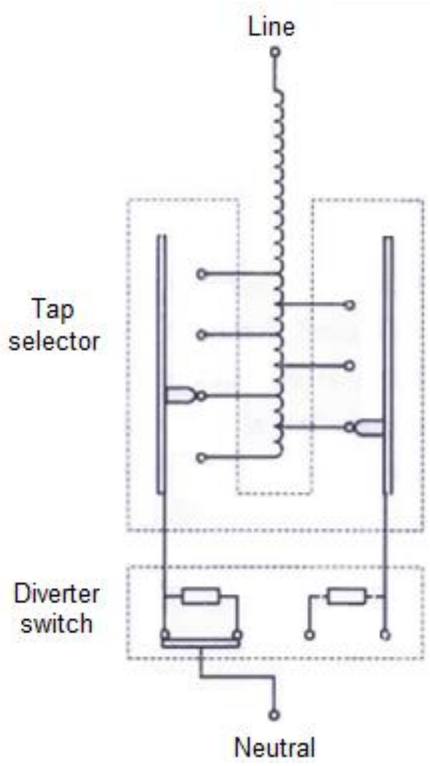


Fig. 2.11. Mechanical selector-diverter switch OLTC

The basic operation of OLTC is described using the typical two resistor configuration of OLTC shown in Fig.2.12 [46]. Operation process is as follows.

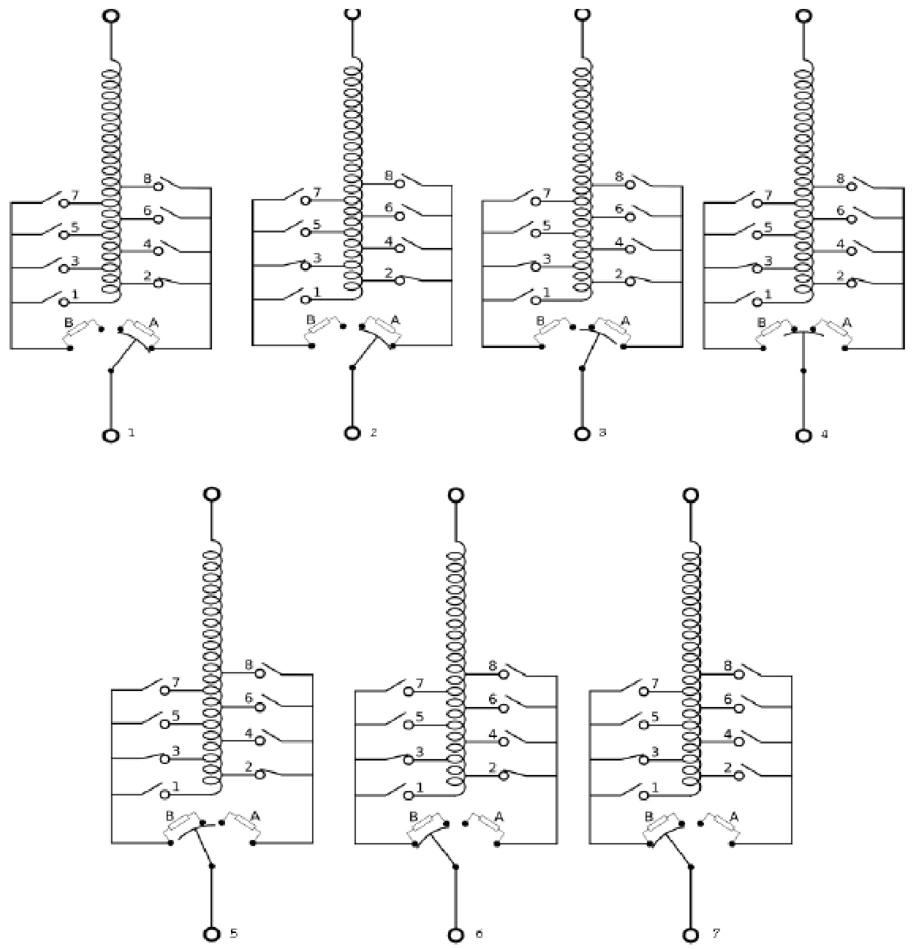


Fig. 2.12. Basic Operation of OLTC [53]

1. Switch 2 closed and other switches are opened. Diverter resistor A is short-circuited by rotary switch and diverter B is unused.

2. Switch 3 closes by an off-load operation.

3. Rotary switch moves left and disconnects the right connection. The load current is conducting through diverter resistor A.

4. Rotary switch moves left and connects both contacts A and B. Load now supplied via diverter resistors A and B, winding turns bridged via A and B.

5. Rotary switch moves left and disconnects contact with diverter A. Load now

supplied via diverter B only, winding turns no longer bridged.

6. Rotary switch moves left and shorts diverter B. Diverter A is unused now.

7. Switch 2 opens by an off-load operation.

Then the operation is completed that the tap position is changed from 2 to 3 and fewer windings are switched [53].

An OLTC is normally provided with LDC (Line Drop Compensation) function in order to keep the voltage at a remote point constant without using any communication link. LDC monitors the voltage at secondary side of transformer and then uses a measure of secondary current to simulate the voltage drop across feeder that exists between the transformer and load [46] [54].

2.3 ICT Infrastructures for peer-to-peer energy trading

2.3.1 Smart Grids and Its Communication Requirements

"A Smart Grid is an electricity network that intelligently integrates the actions of all users connected to it – generators, consumers, and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies." A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies to:

- Better facilitate the connection and operation of generators of all sizes and technologies;
- Allow electricity consumers to play a part in optimising the operation of the system;
- Provide consumers with greater information and choice of supply;

- Significantly reduce the environmental impact of the total electricity supply system and
- Deliver enhanced levels of reliability and security of supply. [55]

Fig. 2.13 shows the general structure of a Smart Grid

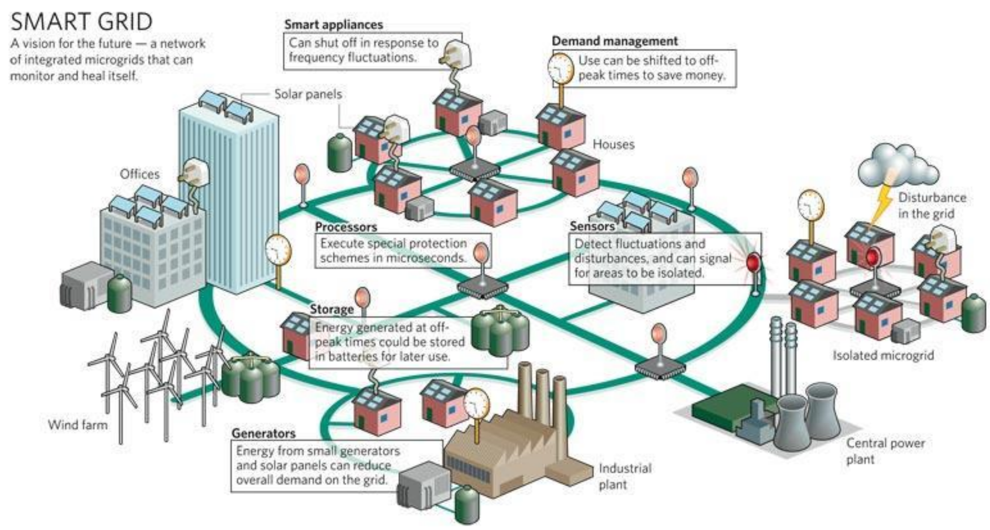


Fig. 2.13. Structure of Smart Grid [56]

The basic concept of Smart Grid is to have system-wide monitoring with data integration, advanced analysis to support system control and enhanced power security, meeting the power demand as well as reducing energy consumption and costs [57]. Communication technology plays a critical role in the Smart Grid development.

Conventionally, the communication infrastructure for monitoring and control of the power grid consists of many protocols and systems, including leased lines, fixed Radio Frequency (RF) networks, microwave links and optical fibre [57]. However, the poor communications infrastructure underlying the monitoring of distribution networks leads to inadequate situational awareness for distribution network operators who are often blind to network constraints violations [57].

The main change over the next 10-20 years in distribution networks will be the numerous connections of energy generation devices at all voltage levels and the predicted increase in electricity usage for transportation and heating [58]. In order to maximise the usage of the existing electricity network without reinforcing the lines, the current headroom of the lines will have to be used to make the distribution networks more efficient. This can only happen if the elements in the distribution networks can be managed and controlled and if automation is introduced [58]. Deployment of communications services to these existing and new network elements becomes vital and forms part of the Smart Grid.

Fig. 2.14 shows a high-level view of the Smart Grid. The solid black lines represent the distribution network. The dotted blue lines show the communications path between the elements in the distribution network.

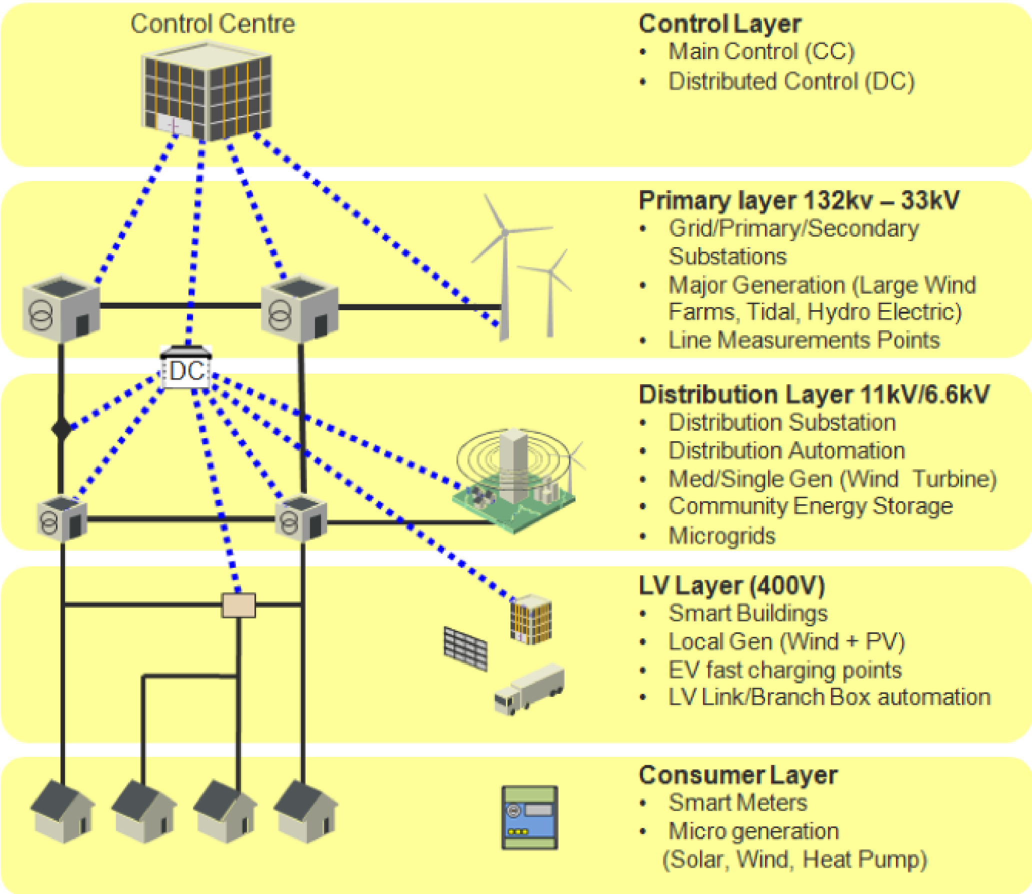


Fig. 2.14. Smart Grid Elements and Layers [58]

The summary of the characteristics of the smart grid data flow is concluded in Fig. 2.15.

Site Type	Smart Grid Use Cases	Criticality (H/M/L)	Timeliness (Max delay)	Volume & Frequency of data	
				2020	2030
Control					
Main Control Centre (CC)	Overall Smart Grid Management	High	1s	All traffic	-
Distributed Controller (DC)	Overall Smart Grid Management	High	1s	All traffic	-
132kV - 33kV					
Major Generation (Wind Farms, Tidal, Hydro)	Alarms	High	100ms,1s	10bytes every week	-
	Regular sensor data	Med	1s,1min	1000bytes every min	-
	Restoration of faults	High	100ms,1s,10s	10bytes every week	-
Primary Substations (inc Grid interconnect)	Alarms	High	1s	10bytes every 6sec, day	-
	Regular sensor data real-time	Med	10s	10-1000bytes every min,hour,day	10x volume
	Asset data mng power quality	Low	1min	1Mbyte every day	-
	Asset data mng load	Low	1min	10bytes every 3 days	-
	Restoration of faults	High	1s,10s	10bytes every day,week	-
	Exchange of demand mgmt data with adjacent subs	High	1s	100-1000bytes constant	-
	Status monitoring / real-time event data	High, Med, Low	1s,1min	10-100bytes every min,hour	10x volume
	Asset data mng of status monitoring equipment	Low	1min	10bytes every 3 days	-
	Protection	High	6ms	Continuous	-
	Security (CCTV etc)	Med, Low	1s	1Mbyte every day, week	-
	Voice (operational)	High	150-300ms	infrequent (non-blocking)	-
	Corp n/w access	Low	1s,10s	1Mbyte every day, weekly	-
Added Prim Sub based on 2011		-	-	-	-
Line Measurement Points	Regular sensor data real-time	Med	1s	100bytes every hour	-
11kV / 6.6kV					
Medium Generation (Wind Turbine)	Alarms	High, Med	100ms,10s	10bytes every day, week	-
	Regular sensor data real-time	Med, Low	10s,1min	10-100bytes every hour,day	10x volume
	Asset data mng power quality	Low	1min	1Mbyte every day	-
	Asset data mng load	Low	1min	10bytes every 3 days	-
	Restoration of faults	High, Med	100ms,10s	10bytes every week	-
Community Energy Storage	Alarms	High, Med	10s	10bytes every day	-
	Regular sensor data real-time	Med, Low	10s,1min	10-100bytes every hour,day	10x volume
	Asset data mng power quality	Low	1min	1Mbyte every day	-
	Asset data mng load	Low	1min	10bytes every 3 days	-
	Restoration of faults	High, Med	10s	10bytes every week	-
Microgrids	Smart Grid Management (regional)	High	1s	100bytes every hour	-
Substation Automation (inc Distribution Automation, circuit isolator switches and fuses)	Alarms	High, Med	10s	10bytes every day	-
	Regular sensor data real-time	Med, Low	10s,1min	10-100bytes every hour,day	10x volume
	Asset data mng power quality	Low	1min	1Mbyte every day	-
	Asset data mng load	Low	1min	10bytes every 3 days	-
	Restoration of faults	High, Med	10s,1min	10bytes every week	-
	Exchange of demand mgmt data with adjacent subs	Med	10s	100bytes every hour	-
	Security (CCTV etc)	Low	1s	1000kbytes every week	-
Added Sub auto based on 2011		-	-	-	-
Fault Passage Indicator	Alarms	Low	10min	10bytes every month	-
Intelligent fuses (LV) / Circuit isolator switch	Alarm after switchover, comms through 11kV sub	Low	1min	10bytes every hour	-
400V					
Smart Buildings	Monitor status - demand mgmt via aggregator	Low	1min,10min	10bytes every hour	-
Local Generation (WT & PV)	Monitor status	High, Low	10s,1min,10min	10bytes every day, hour	-
EV fast charging points	Monitor status	High, Low	10s,1min,10min	10bytes every day, hour	-
LV Connection Box automation	Monitor status	High, Low	10s,1min	10bytes every day, hour	-
	Restoration of faults	High, Med	10s	10bytes every week, month	-
Consumer					
Smart Meters	Monitor status	N/A	N/A	N/A	N/A
Micro Generation	Monitor status	N/A	N/A	N/A	N/A

Fig. 2.15. Data Flow Summary and Criticality [58]

Table 2.3 summarises the main characteristics of each communication technology in terms of range, data rate, constrains and suitable voltage level. These technologies have the potential to be applied in Smart Grids, and the specific technology choice and combination depend on practical scenarios.

Table 2.3 Communication Technology Summary [46]

Communication technology	**Range**	**Data rate**	**Constrains**	**Voltage level recommendation**
2G/ General Packet Radio Service (GPRS)/3G/ Long-Term Evolution (LTE, 4G) CELLULAR	Long range depend on mobile operator, GPRS national coverage	9.6kbps/ 171.2kbps/ 2Mbps/ 100Mbps	Coverage at rural areas is limited, must rent from cellular carrier, high service cost	GPRS in EHV and HV distribution networks for core communication; LTE for last mile communication in rural area
Ultra High Frequency (UHF)	40km point-to-point; 25km point-to-multipoint	9.6kbps to 50kbps	Low data rate	Some critical EHV and HV substations outside GPRS coverage
WiMAX (IEEE 802.16)	Up to 50km	Up to 70 Mbps	Low data rate for long distance; spectrum availability depends on licence	Last mile communication in rural area for connecting the customers point to control centre
Wi-Fi (IEEE 802.11)	100m	Up to 20 Gbps (802.11ay)	Limited coverage; cannot penetrate building obstacle	LV network for monitoring in small buildings
ZigBee (IEEE 802.15.4)	10-100m	20-250kbps	Low data rate; limited coverage; cannot penetrate structures	LV level for home automation
Bluetooth (IEEE 802.15.1)	1-100m	Up to 24Mbps	Short distance; lack of security	LV level for local monitoring
Optical Fibre	80km	Several Gbps	Extremely high installation cost; long installation time	EHV distribution network and rural areas for high speed communication
Power-line communication (PLC)	15km	Up to 45Mbps	High noise and interference	LV level in urban areas for last mile communication

2.3.2 Smart Metering

Smart Metering is commonly recognised as the first step towards Smart Grid. EU has announced that at least 80% of consumers should be equipped with intelligent metering system by 2020. As a response, the UK government committed that the majority of consumers, including home, business and public sector users, would receive their smart meters during the upcoming mass roll-out from 2014 to 2019.

Much different from traditional manual reading and Automatic Meter Reading (AMR), Smart Metering is based on 2-way communications and supports variety of applications such as AMR, Demand Response and Remote Connect/Disconnect introduced from Smart Grid vision.

Three key components of smart metering systems are introduced in this section, including smart meters, communication network and Meter Data Management (MDM) System.

1. Smart Meters

There are many advantages of replacing traditional electro-mechanical meters with electronic ones. Electronic meters measure a lot of parameters including instantaneous power, energy consumption over time, power factor, reactive power, voltage and frequency with high accuracy. Data can be measured and stored at specific intervals. Moreover, they are more reliable as the accuracy of them is hardly influenced by either external magnets or orientation of themselves. [59]

The basic architecture of low-cost meters with current and voltage sensors is as shown in Fig. 2.16.

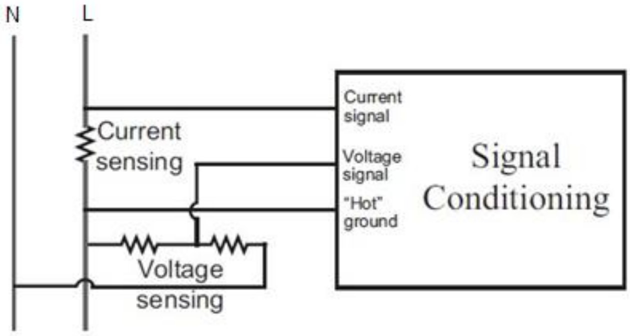


Fig. 2.16. Basic Architecture of Low-cost Meters with Current and Voltage Sensors [59]

Function block diagram of a smart meter is illustrated in Fig. 2.17.

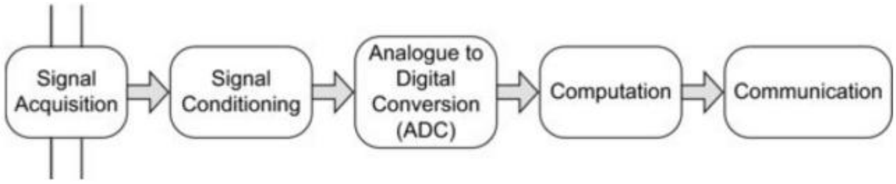


Fig. 2.17. Function Block Diagram of a Smart Meter [59]

2. Communication networks for smart metering

An example of typical communication architecture for smart metering is shown in Fig. 2.18. It has three communication interfaces: Wide Area Networks (WAN), Neighbourhood Area Network (NAN) and Home Area Network (HAN).

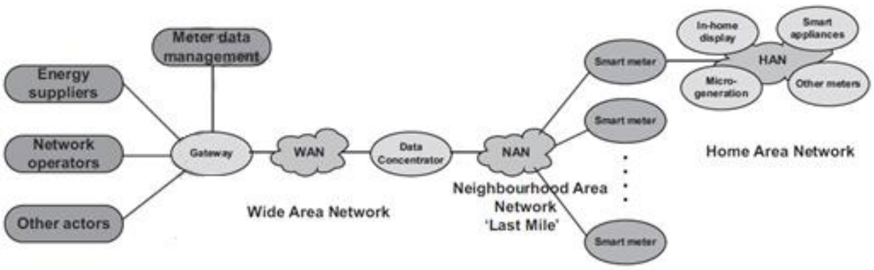


Fig. 2.18. Typical Communication Architecture for Smart Metering [59]

A HAN is an integrated system of smart meter, in-home display, micro-generation, smart appliances, smart sockets, HVAC facilities and plug-in hybrid/electric vehicles. Both wired and wireless protocols are used, so are the security mechanisms. A HAN enables centralized energy management and services as well as providing different facilities for the convenience and comfort of the household.

The primary function of the NAN is to transfer consumption reading from smart meters. It should also facilitate diagnostic messages, firmware upgrades and real-time messages for the power system support. The communication technology used for the NAN is based on the volume of data transfer inside the channels. In practical deployment of smart metering systems, most of the investment will be spent on the installation of NAN network. GPRS was considered for implementing the NAN network for Smart Metering in the UK, and therefore was also used for the simulation of the Smart Metering in the research reported in this thesis.

A WAN is used between the data concentrator and the gateway, behind which the Meter Data Management System, energy suppliers, network operators and other actors are located. The data concentrator acts as a relay between the smart meters and the gateway. It manages the meters by automatically detecting them, creating and optimizing repeating chains, coordinating bi-directional delivery of data, and monitoring the conditions of meters. Different protocols for the WAN can be implemented according to different requirements and situations for the communication network.

3. Meter Data Management Systems

Database is the core of a meter data management system. It provides services such as data acquisition, validation, adjustment, storage and calculation according to different smart metering applications designed for different groups of system users. Besides, it should also provide functions such as remote access, meter connection/disconnection, power status verification, etc. The main challenge of data management system is how to make it open and flexible enough for integrating applications and delivering better services to customers while ensuring data security.

Currently there are several different standards (including communications protocols and data structure) for communications of smart metering all around the world, which are used for AMR and AMI (Advanced Metering Infrastructures) solutions based on variety of communication medium.

A summary of main standards and their characteristics are listed in Fig. 2.19.

Specification	Field of application				Data model	Communication media supported							
	Local AMR	Remote AMR	AMI	Home automation		Local bus	PSTN	GSM	GPRS	Internet	PLC	Walk by radio	Mesh radio
IEC 61334 PLC	-	Y	Y	-	Y	-		-	-	-	Y	-	-
IEC 62056-21"FLAG"	Y	Y	-	-	-	Y		Y	Y	-	-	-	-
IEC 62056-31 Euridis	Y	Y	-	-	-	Y		-	-	-	-	-	-
IEC 62056 DLMS/COSEM	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
EN 13757 M-Bus	Y	Y	Y	Y	-	Y		-	-	-	-	Y	-
SML	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
DIN 43863-4		Y	Y		Y		Y	Y	Y	Y			
IEC 60870-5	Y	Y	-	-	-	-	-	-	-	-	-	-	-
IEC 61968-9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SITRED	Y	Y	Y	-							Y		
PRIME	Y	Y	Y	-							Y		
I IEC 61850						Y							
KNX				Y		Y		Y	Y	Y	Y		
Zigbee SmartEnergy			Y	Y									Y
6LoPAN													Y
Homeplug				Y							Y		
Z-Wave													Y
Wavenis									Y				Y
EverBlu	Y	Y	Y	-					Y				Y
OPERA/UPA	-	Y	Y	-	-	-	-	-	-	Y	Y	-	-
ITU–G.hn	-	-	-	Y	-	-	-	-	-	Y	Y	-	-

Fig. 2.19. Summary of Standards for Smart Metering, AMR and AMI [60]

2.3.3 Communication protocols and technologies

1. OSI model

The OSI model (ISO/IEC 7498-1) is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers, as demonstrated in Fig. 2.20. The model is a product of the Open Systems Interconnection project at the International Organization for Standardization (ISO). [61]

Fig. 2.20. OSI Network Model

The model categorises similar communication functions into one of seven logical layers. A layer serves the layer above it and is served by the layer below it. For example, a layer that provides error-free communications across a network provides the path needed by the applications above it, while it calls the next lower layer to send and receive packets that make up the contents of that path. Two instances at one layer are connected by a horizontal connection on that layer.

Detailed explanation of each layer of the model is provided in the following paragraphs.

Layer 1: physical layer

The physical layer has the following major functions: It defines the electrical and physical specifications of the data connection. It defines the relationship between a device and a physical transmission medium. It defines the protocol to establish and terminate a connection between two directly connected nodes over a communication medium. It may define the protocol for flow control. It defines a protocol for the provision of a connection between two directly connected nodes, and the modulation or conversion between the representation of digital data in user equipment and the corresponding signals transmitted over the physical communications channel. This channel involves either physical cabling or a wireless radio link.

The physical layer of Parallel Small Computer System Interface (SCSI) operates in this layer, as do the physical layers of Ethernet and other local-area networks, such as token ring, FDDI, and IEEE 802.11, as well as personal area networks such as Bluetooth and IEEE 802.15.4.

Layer 2: data link layer

The data link layer provides a reliable link between two directly connected nodes, by detecting and possibly correcting errors that may occur in the physical layer.

PPP is an example of a data link layer in the TCP/IP protocol stack.

Layer 3: network layer

The network layer provides the functional and procedural means of transferring variable length data sequences (called datagrams) from one node to another connected to the same network. A network is a medium to which many nodes can be connected, on which every node has an address and which permits nodes connected to it to transfer messages to other nodes connected to it by merely providing the content of a message and the address of the destination node and letting the network find the way to deliver ("route") the message to the destination node. In addition to message routing, the network may implement message delivery by splitting the message into several fragments, delivering each fragment by a separate route and reassembling the fragments, report delivery errors, etc. Datagram delivery at the network layer is not guaranteed to be reliable.

Other functions of the network layer include traffic control, addressing, etc. The IP address is an example of an address used in the network layer. [59]

Layer 4: transport layer

The transport layer provides the reliable sending of data packets between nodes (with addresses) located on a network, providing reliable data transfer services to the upper layers.

An example of a transport layer protocol in the standard Internet protocol stack is TCP, usually built on top of the IP protocol.

Layer 5: session layer

The session layer controls the dialogues (connections) between computers. It establishes, manages and terminates the connections between the local and remote application. It provides for full-duplex, half-duplex, or simplex operation, and establishes checkpointing, adjournment, termination, and restart procedures. The OSI model made this layer responsible for graceful close of sessions, which is a property of the Transmission Control Protocol, and also for session checkpointing and recovery, which is not usually used in the Internet Protocol Suite. The session layer is commonly implemented explicitly in application environments that use remote procedure calls.

Layer 6: presentation layer

The presentation layer establishes context between application-layer entities, in which the application-layer entities may use different syntax and semantics if the presentation service provides a mapping between them. If a mapping is available, presentation service data units are encapsulated into session protocol data units, and passed down the TCP/IP stack. [61]

This layer provides independence from data representation (e.g., encryption) by translating between application and network formats. The presentation layer transforms data into the form that the application accepts. This layer formats and encrypts data to be sent across a network. It is sometimes called the syntax layer.

Layer 7: application layer

The application layer is the OSI layer closest to the end user, which means both the OSI application layer and the user interact directly with the software application. This layer interacts with software applications that implement a communicating component. Such application programs fall outside the scope of the OSI model. Application-layer functions typically include identifying communication partners, determining resource availability, and synchronizing communication. When identifying communication partners, the application layer determines the identity and availability of communication partners for an application with data to transmit. When determining resource availability, the application layer must decide whether sufficient network or the requested communication exists. In synchronizing communication, all communication between applications requires cooperation that is managed by the application layer. Some examples of application-layer implementations also include: Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), Simple Mail Transfer Protocol (SMTP), etc. [61]

2. TCP/IP protocol

The TCP is one of the core protocols of the Internet protocol suite, and is so common that the entire suite is often called TCP/IP. TCP provides reliable, ordered, error-checked delivery of a stream of octets between programs running on computers connected to a local area network, intranet or the public Internet. It resides at the transport layer. [62]

The protocol corresponds to the transport layer of TCP/IP suite. TCP provides a communication service at an intermediate level between an application program and the Internet Protocol. That is, when an application program desires to send a large chunk of data across the Internet using IP, instead of breaking the data into IP-sized pieces and issuing a series of IP requests, the software can issue a single request to TCP and let TCP handle the IP details.

IP works by exchanging pieces of information called packets. A packet is a sequence of octets (bytes) and consists of a header followed by a body. The header describes the packet's source, destination and control information. The body contains the data IP is transmitting.

Due to network congestion, traffic load balancing, or other unpredictable network behaviour, IP packets can be lost, duplicated, or delivered out of order. TCP detects these problems, requests retransmission of lost data, rearranges out-of-order data, and even helps minimize network congestion to reduce the occurrence of the other problems. Once the TCP receiver has reassembled the sequence of octets originally transmitted, it passes them to the receiving application. Thus, TCP abstracts the application's communication from the underlying networking details.

TCP is utilized extensively by many of the Internet's most popular applications, including the World Wide Web (WWW), E-mail, File Transfer Protocol, Secure Shell (SSL), peer-to-peer file sharing, and some streaming media applications.

TCP is optimized for accurate delivery rather than timely delivery, and therefore, TCP sometimes incurs relatively long delays (on the order of seconds) while waiting for out-of-order messages or retransmissions of lost messages. It is not particularly suitable for real-time applications such as Voice over IP. For such applications, protocols like the Real-time Transport Protocol (RTP) running over the User Datagram Protocol (UDP) are usually recommended instead. [62]

TCP is a reliable stream delivery service that guarantees that all bytes received will be identical with bytes sent and in the correct order. Since packet transfer over many networks is not reliable, a technique known as positive acknowledgment with retransmission is used to guarantee reliability of packet transfers. This fundamental technique requires the receiver to respond with an acknowledgment message as it receives the data. The sender keeps a record of each packet it sends. The sender also maintains a timer from when the packet was sent, and retransmits a packet if the timer expires before the message has been acknowledged. The timer is needed in case a packet gets lost or corrupted. [62]

While IP handles actual delivery of the data, TCP keeps track of the individual units of data transmission (segments) that a message is divided into for efficient routing through the network. For example, when an Hypertext Markup Language (HTML) file is sent from a web server, the TCP software layer of that server divides the sequence of octets of the file into segments and forwards them individually to the IP software layer (Internet Layer). The Internet Layer encapsulates each TCP segment into an IP packet by adding a header that includes (among other data) the destination IP address. When the client program on the destination computer receives them, the TCP layer (Transport Layer) reassembles the individual segments and ensures they are correctly ordered and error free as it streams them to an application. [62]

A TCP connection is managed by an operating system through a programming interface that represents the local end-point for communications, the Internet socket. During the lifetime of a TCP connection the local end-point undergoes a series of state changes: [62]

- Connection establishment

To establish a connection, TCP uses a three-way handshake. Before a client attempts to connect with a server, the server must first bind to and listen at a port to open it up for connections: this is called a passive open. Once the passive open is established, a client may initiate an active open. To establish a connection, the three-way (or 3-step) handshake occurs:

1. SYN (Synchronise): The active open is performed by the client sending a SYN to the server. The client sets the segment's sequence number to a random value A.

2. SYN-ACK (Synchronise-acknowledge): In response, the server replies with a

SYN-ACK. The acknowledgment number is set to one more than the received sequence number i.e. A+1, and the sequence number that the server chooses for the packet is another random number, B.

3. ACK: Finally, the client sends an ACK back to the server. The sequence number is set to the received acknowledgement value i.e. A+1, and the acknowledgement number is set to one more than the received sequence number i.e. B+1.

At this point, both the client and server have received an acknowledgment of the connection. The steps 1 and 2 establish the connection parameter (sequence number) for one direction and it is acknowledged. The steps 2 and 3 establish the connection parameter (sequence number) for the other direction and it is acknowledged. With these steps, a full-duplex communication is established

- Connection termination

The connection termination phase uses a four-way handshake, with each side of the connection terminating independently. When an endpoint wishes to stop its half of the connection, it transmits a FIN (Finish) packet, which the other end acknowledges with an ACK. Therefore, a typical tear-down requires a pair of FIN and ACK segments from each TCP endpoint. After both FIN/ACK exchanges are concluded, the side which sent the first FIN before receiving one waits for a timeout before finally closing the connection, during which the local port is unavailable for new connections; this prevents confusion due to delayed packets being delivered during subsequent connections.

- Data transfer

There are a few key features that set TCP apart from User Datagram Protocol: [62]

- Ordered data transfer - the destination host rearranges according to sequence number;

- Retransmission of lost packets - any cumulative stream not acknowledged is retransmitted;

- Error-free data transfer;
- Flow control - limits the rate a sender transfers data to guarantee reliable delivery. The receiver continually hints the sender on how much data can be received (controlled by the sliding window). When the receiving host's buffer fills, the next acknowledgment contains a 0 in the window size, to stop transfer and allow the data in the buffer to be processed;
- Congestion control.

The process of TCP connection establishment and termination is illustrated in Fig. 2.21.

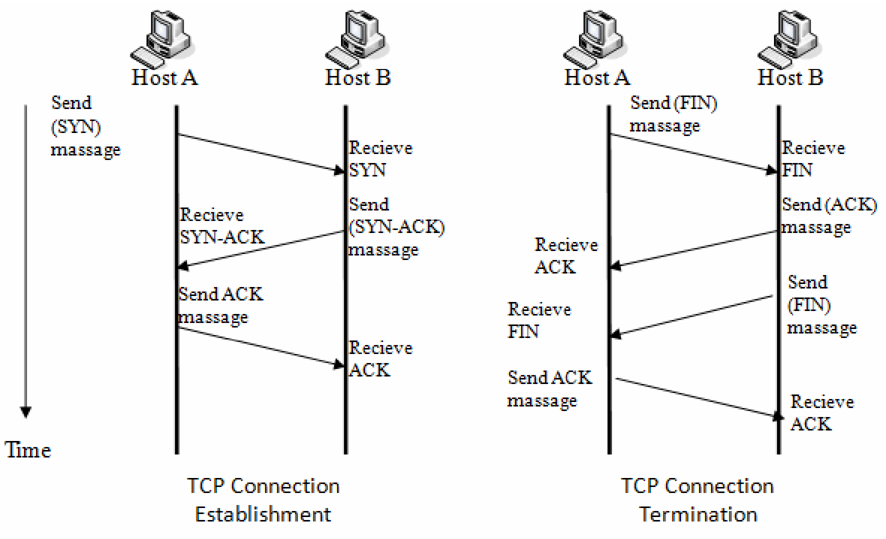


Fig. 2.21. TCP Connection Establishment and Termination

TCP uses port numbers to identify sending and receiving application end-points on a host, or Internet sockets. Each side of a TCP connection has an associated 16-bit unsigned port number (0-65535) reserved by the sending or receiving application. Arriving TCP data packets are identified as belonging to a specific TCP connection by its sockets, that is, the combination of source host address, source port, destination host address, and destination port. This means that a server computer can provide several clients with several services simultaneously, as long as a client takes care of initiating any simultaneous connections to one destination port from different source ports.

Port numbers are categorized into three basic categories: well-known, registered, and dynamic/private. The well-known ports are assigned by the Internet Assigned Numbers Authority (IANA) and are typically used by system-level or root processes. Well-known applications running as servers and passively listening for connections typically use these ports. Some examples include: FTP (20 and 21), SSH (22), Teletype Network (TELNET) (23), SMTP (25), SSL (443) and HTTP (80). Registered ports are typically used by end user applications as ephemeral source ports when contacting servers, but they can also identify named services that have been registered by a third party. Dynamic/private ports can also be used by end user applications, but are less common. Dynamic/private ports do not contain any meaning outside of any particular TCP connection. [62]

The TCP/IP protocol is used for the simulation of the communication systems for P2P energy trading in the research reported in this thesis.

2.4 Conclusions

The review of literature indicates that existing power systems were designed to accommodate large-scale generating plants, with demand traditionally considered as uncontrollable and inflexible. The trading of energy is unidirectional. With the increasing integration of DERs, traditional energy consumers will become prosumers, who can both generate and consume energy. Prosumers who have surplus energy can either store it with energy storage devices, or supply others who are in energy deficit. Different types of new trading arrangements have been proposed in order to deal with the changes. P2P energy trading is one of them.

A number of trails and projects on P2P energy trading have been carried out in recent years. However, most of them focused on the development of business models from the traditional energy suppliers' perspective, and ignored the possibility of introducing the models to smaller-scale local energy markets. Besides, the design of ICT and control systems also remained to be developed.

Main methods used for voltage control in distribution networks are active power curtailment, reactive power control, and OLTC control. They have been widely investigated and used. However, few works were carried out in order to examine the feasibility of traditional control methods for facilitating P2P energy trading.

ICT infrastructures play an important role in the development of Smart Grid and Smart Metering technologies. A variety of protocols and standards are available in the related areas. P2P energy trading also relies on these techniques, and the requirements are even higher. The minimum requirements of ICT infrastructures for facilitating P2P energy trading still need to be identified.

The research gaps on P2P energy trading is summarised as follows: The platform for P2P energy trading has not been benchmarked. The P2P bidding among small-scale residential and commercial prosumers in LV distribution networks has not been investigated. The impact of P2P energy trading on the current control systems of LV distribution networks has not been revealed. The necessary ICT infrastructures for implementing P2P energy trading and its relevant control systems has not been discussed. The research reported in this thesis was carried out in order to address those research gaps.

Chapter 3

Design of a Peer-to-Peer Energy Trading Platform

This chapter presents the P2P bidding among peers in the business layer during the bidding time period. A software platform, called “Elecbay”, is proposed to support the P2P bidding. The P2P bidding is then simulated using game theory. Case studies based on the EU benchmark Microgrid are undertaken in order to verify the impact of P2P energy trading on the balance of local generation and consumption in the Microgrid. The impact of the peer variety is further discussed. Simulation results show that P2P energy trading is able to reduce the energy exchange between the Microgrid and the utility grid and balance local generation and demand, and therefore, has the potential to facilitate a large penetration of renewable energy resources in the power grid. The increased variety of energy consumers and prosumers in the Microgrid is able to further improve the benefits of P2P energy trading.

3.1 Introduction

Different energy trading arrangements for local distribution networks have been investigated. For example, the local pool concept was used to aggregates the distributed generation from a local area (pooling) to supply the local consumers without using additional wholesale market intermediaries [63]. The objective of the local pool is to balance the local energy generation and demand with minimum generation costs [27].

“P2P economy”, also known as “sharing economy”, was recently introduced for the energy trading arrangements in local distribution networks. P2P energy trading allows each peer (a consumer, a prosumer, a generator, or even a supplier) to decide with which peer to trade (buy from or sell to) energy according to its own objective, e.g. minimum costs, maximum profits, minimum pollution, most reliable energy supply, etc.

P2P energy trading cannot be applied without a software platform, which enables the information exchange among peers, and also assists the system regulators (e.g. DSOs) to monitor and control the distribution network. In addition, different trading rules defined by the platform also have significant influences on the decisions made by peers when trading with other peers.

3.2 A platform for peer-to-peer energy trading arrangements

Various software platforms can be designed to facilitate P2P energy trading. The “Elecbay” proposed in this chapter is used for the P2P energy trading in a grid-connected Microgrid. The key players of P2P energy trading include buyers, sellers, suppliers (suppliers can act as buyers or sellers), DSOs and the “Elecbay”. The interactions of the key players during P2P energy trading are illustrated by Fig. 3.1.

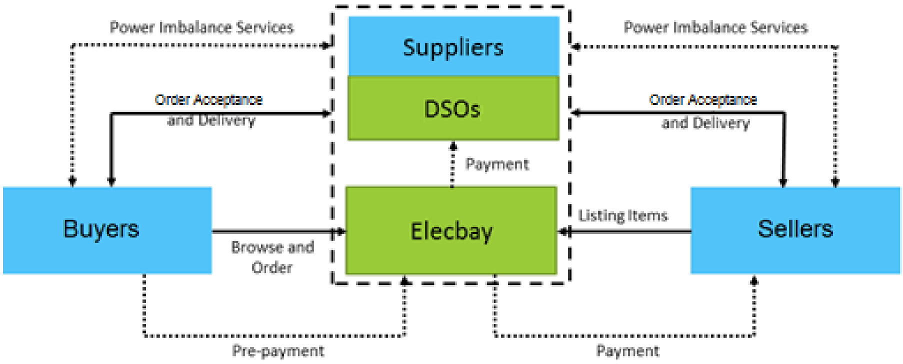


Fig. 3.1. Interactions of Key Players during P2P Energy Trading

"Elecbay" in Fig. 3.1 is a software platform on which peers (either energy sellers or buyers) trade energy with others. Energy sellers list the items, i.e. the surplus energy over half an hour, for sale. Energy buyers browse all the listed items and then place orders. Each order contains the information including the time period for the energy exchange, the amount of energy to be exchanged, the price of the energy to be exchanged and the details about the seller and buyer, e.g. the identities, the ratings of energy supply reliability, etc. Alternatively, energy sellers can also browse the items listed by energy buyers, i.e. the required energy over half an hour, and then place orders.

After the orders are placed by peers, they are either accepted or rejected by Elecbay, DSOs, and energy suppliers as shown in Fig. 3.1. The acceptance or rejection of each order is determined based on the network constraints, e.g. voltage excursion, thermal overloading, etc.

After the order acceptance or rejection, each peer generates / consumes the amount of energy as promised in the accepted orders. Energy is delivered through the distribution network. The energy balancing services are provided by Elecbay. The actual energy generation and consumption of each peer is recorded by smart meters.

However, as is energy (electricity) traded on Elecbay, there can possibly be a disparity between the promised amount of energy in the placed orders and the actual energy consumption or generation recorded by smart meters. For peers who fail to generate / consume the promised amount of energy, they are required to trade with suppliers with less beneficial (selling or buying) prices and even charged with penalty. In this chapter the selling and buying prices with suppliers and penalty are calculated based on the existing methods that are currently used in the GB electricity wholesale market [64]. Payments are all made to Elecbay. After deducting service charges, Elecbay allocates the money to suppliers, DSOs, energy sellers, and energy buyers if they contribute to the energy balancing.

The processing of each order placed in Elecbay is further demonstrated in a time sequence in Fig. 3.2.

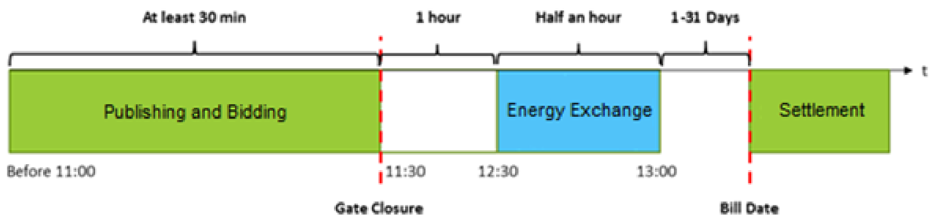


Fig. 3.2. An Example of Processing of an Order in Elecbay

The publishing and bidding time period is the first time period of order process in Elecbay, during which peers are able to list items (the surplus energy over half an hour for sale, or the required energy over half an hour for purchase) and place orders. This time period starts several days, weeks or months before the half-hourly energy exchange time period, and ends by the gate closure, which is one hour before the energy exchange time period in this chapter. Orders can be placed, cancelled or modified by peers only before the gate closure. Peers list items and place orders based on the forecast of their own energy generation and consumption. They make decisions to trade with other peers by comparing the amount and price of energy to be exchanged.

During the one hour time period between the gate closure and the energy exchange time period, the order acceptance / rejection is carried out by the DSOs. They evaluate if there is going to be a network constraint violation, e.g. voltage excursion, thermal overloading, etc., when all the placed orders are accepted. Once a network constraint violation is identified, DSOs are the only entities which have the permission to modify or cancel orders after the gate closure. The rules for order modification or cancellation are various. For example, with the last on first off principle, the orders placed at a later time (i.e. closer to the gate closure) have a higher possibility to be cancelled.

During the half-hourly energy exchange time period, Elecbay provides the energy balancing services. The cost of all the actions taken for the energy balancing is recorded for the settlement time period. Besides, the actual energy generation and consumption of each peer is also recorded by the smart meter in each premise.

In the settlement time period, Elecbay liaises with DSOs and suppliers and provides the energy bill of each peer. This settlement and billing process takes time, and therefore the bills cannot be available to peers immediately. For example, 1 day to 1 month is considered in this chapter as the length of this time period. As mentioned previously, for peers who fail to generate / consume the promised amount of energy, they are required to trade with suppliers with less beneficial (selling or buying) price and even be charged with penalty. Elecbay collects the payment received from energy buyers, keeps the service charges, and then sends the rest to the relevant energy sellers and suppliers.

The publishing and bidding time period is the most unique time period that makes P2P energy trading arrangements different from other existing energy trading arrangements in the distribution networks. Therefore it is the basis of the study on other time periods in P2P energy trading. The simulation method and case study demonstrated in the following sections, which validate the publishing and bidding time period in a grid-connected LV Microgrid with different types of energy prosumers, are both based on the design of Elecbay proposed in this section.

3.3 Validation of the peer-to-peer electricity trading platform with game theory

The simulation of the bidding through the P2P energy trading platform “Elecbay” is of great importance, which could be used to:

- demonstrate how energy consumers and prosumers within a grid-connected LV Microgrid carry out P2P energy trading with each other;
- obtain new load profiles of energy consumers and prosumers to quantify how their energy consumption is affected by the P2P energy trading; and
- enable analysis and control of grid-connected Microgrids and power grids under the P2P energy trading.

The simulation mimics the bidding of energy consumers and prosumers before the gate closure. Input data of the simulation, including the generation profiles of energy prosumers and the consumption profiles of energy consumers and prosumers, is based on forecast information. Besides, the following assumptions were made:

- The P2P energy trading through “Elecbay” is competitive, which means energy consumers and prosumers are not aggregated with each other for achieving higher benefits via co-operation.
- Energy consumers and prosumers are considered as “good citizens”, who contribute to maintaining local energy balance.
- Energy suppliers (i.e. the electricity retailers) are passive peers in this chapter. They buy energy from energy prosumers with low unit prices, and sell energy to energy consumers and prosumers with high unit prices. Energy consumers and prosumers consider energy suppliers as the last peer to trade with during the P2P bidding. This assumption is consistent with

the reality in many countries such as the UK.

- Service charges of Elecbay are neglected in this chapter.

3.3.1 Roles of Flexible Demand and Storage in Peer-to-Peer Energy Trading

In Elecbay, energy consumers and prosumers sell and buy energy by scheduling the energy devices in their own premises. There are mainly three types of energy devices owned by typical small-scale residential and commercial energy consumers and prosumers, as shown in Fig. 3.3. Generation includes PV panels, wind turbines, CHPs units, micro-turbines, etc. Demand includes non-flexible demand and flexible demand. Electrical storage, which is able to either provide or consume energy, includes batteries, electrical vehicles (EVs), etc.

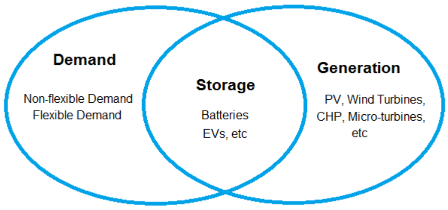


Fig. 3.3. Categories of Energy Devices in Residential / Commercial Premises

P2P energy trading among small-scale energy consumers and prosumers mainly relies on the scheduling of flexible demand and storage systems, if the generation is considered to be from the uncontrollable renewable energy. However, generally, energy storage is still very expensive, although it can provide significant amount of flexibility for P2P energy trading. Therefore, this chapter focuses on investigating the flexibility of energy consumption by scheduling flexible demand. Specifically, electric water heaters with tanks are considered as representatives. The use of energy storage was not considered in this chapter.

3.3.2 Simulation of a Single Time Period using Game Theory

This section illustrates the method used for simulating the P2P bidding within a single energy exchange time period through the P2P energy trading platform Elecbay. Game theory was used for the simulation.

There are two basic types of games in game theory: cooperative games and non-cooperative games. A cooperative game is a game where groups of players enforce cooperative behaviour, and hence the game is a competition between coalitions of players, rather than between individual players. A non-cooperative game is a game in which players make decisions independently, for example, auctions and strategic voting [65]. A Nash equilibrium is a solution of a non-cooperative game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only their own strategy [66].

During the P2P bidding for a single energy exchange time period, the interaction among peers is modelled as a non-cooperative game, due to the assumptions made at the beginning of this section. The solution of the game, in which no peer is able to increase the benefit by modifying only its own placed orders, is the Nash equilibrium, which is considered as the result of P2P bidding through Elecbay.

1. Formulation of P2P Bidding as a Non-cooperative Game

Players of the game are energy consumers and prosumers with flexible demand. Denote $N = \{1, 2, \ldots, i \ldots, n\}$, where n is the number of players in the game, and N is the set of players in the game.

Strategies of a player are the decided status of flexible demand, which directly affect the amount of electricity to be injected to (positive value) or absorbed from (negative value) the Microgrid and are denoted by $s^i_{j^i}$, $j^i = 1, 2, \ldots, m_i$, where m_i stands for the number of strategies that player i can choose. S^i is denoted as the set of strategies of player i. In this chapter, $m_i = 2$, which means that the flexible demand of each consumer or prosumer is scheduled either ON or OFF during the 30-minute energy exchange time period.

A strategy combination is the combination of strategies chosen by the players in the game, which is denoted as $s \in \{(s^1_1, s^2_1, \ldots, s^n_1), \ldots, (s^1_{m_1}, s^2_{m_2}, \ldots, s^n_{m_n})\}$. Each strategy combination consists of n elements. Denote S to be the set of all the possible strategy combinations in the game.

The total number of strategy combinations in the game is

$$M = \prod_{i=1}^{n} m_i \tag{3.1}$$

The payoff function is a mathematical function describing the award obtained by a single player at the outcome of a game, which motivates the player to adopt certain strategy and thus is the key to simulate the behaviour of the player [67]. The payoff function used in this chapter is defined as follows:

$$u^i_k = \frac{(L + E_{out-i-k}) \times C^i_k}{\left|E_{mgout-k}\right|} \tag{3.2}$$

where $k \in [1, M]$. k denotes one of the strategy combinations in S; u^i_k denotes the payoff value of player i in strategy combination k; $E_{out\text{-}i\text{-}k}$ denotes the amount of electrical energy injected to (positive value) or absorbed from (negative value) the Microgrid by player i in strategy combination k; L is an arbitrary constant that levels up the u_k^i to always be non-negative value; $|E_{mgout\text{-}k}|$ denotes the absolute value of energy exchange between the Microgrid and the utility grid in strategy combination k; C_k^i stands for the comfort index of user i in strategy combination k, which will be explained in details later in this section.

The higher the payoff value u_k^i is, the better the outcome of strategy combination k is recognized by the player i. As introduced in Equation (3.2), the payoff value of player i in strategy combination k is determined by three factors, as explained below.

The first factor is $E_{out\text{-}i\text{-}k}$. The higher $E_{out\text{-}i\text{-}k}$ is, the larger amount of energy is injected to the Microgrid, or the smaller amount of energy is consumed by the player i, and the higher possibility there is that player i is able to sell more energy to, or buy less energy from other players or energy suppliers via the P2P energy trading platform. Therefore, $E_{out\text{-}i\text{-}k}$ is placed in the numerator so that the higher $E_{out\text{-}i\text{-}k}$ is, the higher u_k^i is.

The second factor is $|E_{mgout\text{-}k}|$. This factor is introduced to the payoff function in order to reflect and minimise the energy exchange between the Microgrid and the external utility grid for local energy balancing. Therefore, $|E_{mgout\text{-}k}|$ is placed in the denominator so that the lower $|E_{mgout\text{-}k}|$ is, the higher u_k^i is.

The third factor is the comfort index C_k^i. It is defined to guarantee that the scheduling of flexible demand does not worsen the customer comfort, specifically thermal comfort given that water heaters with tanks are considered in this chapter. The thermal index C_k^i is placed in the numerator as a multiplier and takes a binary value (either 0 or 1) following this principle: if the strategy chosen by a player does not lead to thermal comfort violation from none or does alleviate the existing thermal comfort violation, C_k^i takes the value of 1 to approve the current strategy; otherwise, C_k^i denies the strategy by taking the value of 0, which results in the minimum value of the payoff function u_k^i (equal to 0). Quantitatively, the thermal comfort is measured by the temperature of water in the tank after scheduling, denoted by T_k^i. The detailed logic on how C_k^i takes values is described as the following equation:

$$C_k^i = \begin{cases} 0, & if\ T_k^i > T_{max}^i\ and\ the\ heater\ is\ ON, or\ if\ T_k^i < T_{min}^i\ and\ the\ heater\ is\ OFF \\ 1, & if\ \ T_k^i < T_{min}^i\ and\ the\ heater\ is\ ON, or\ if\ T_k^i > T_{max}^i\ and\ the\ heater\ is\ \ OFF, \\ & or\ if\ T_{min}^i \leq\ T_k^i \leq T_{max}^i \end{cases} \tag{3.3}$$

where T_{min}^i and T_{max}^i stand for the lower and the upper limits of the water temperature in the tank owned by player i.

The relationship between C_k^i and T_k^i is further explained in Table 3.1.

Table 3.1. Relationship between the Comfort Index of a Player and the Water Temperature in the Tank after Scheduling

	$\boldsymbol{T_k^i < T_{min}^i}$	$\boldsymbol{T_{min}^i \leq\ T_k^i \leq T_{max}^i}$	$\boldsymbol{T_k^i > T_{max}^i}$
Strategy 1 (Flexible Demand ON)	$\boldsymbol{C_k^i}$ = 1	$\boldsymbol{C_k^i}$ = 1	$\boldsymbol{C_k^i}$ = 0
Strategy 2 (Flexible Demand OFF)	$\boldsymbol{C_k^i}$ = 0	$\boldsymbol{C_k^i}$ = 1	$\boldsymbol{C_k^i}$ = 1

If $T_{min}^i \leq\ T_k^i \leq T_{max}^i$, which means the water temperature in the tank after scheduling is within the temperature limits, the comfort index C_k^i equals to 1 whenever the flexible demand is ON or OFF. In this case, both strategies are approved because the thermal comfort will always be guaranteed.

If $T_k^i < T_{min}^i$, which means the water temperature in the tank after scheduling is lower than the lower temperature limit, the value of comfort index C_k^i depends on the strategy taken. The Strategy 1 (ON) is helpful to increase the water temperature (although still lower than the lower limit), so it is approved, i.e. C_k^i equals to 1. On the other hand, the Strategy 2 (OFF) will further decrease the water temperature, which worsens the thermal comfort, so it is denied by setting C_k^i as 0. The situations where $T_k^i > T_{max}^i$ are similar to those where $T_k^i < T_{min}^i$, so the corresponding explanation will not be presented for conciseness.

With the payoff function (3.2), the associated payoff value of player i given a strategy combination s can be calculated, donated as $u^i(s)$.

2. Calculation of the Nash Equilibrium in a Non-Cooperative Game

This subsection describes the method used to calculate the Nash equilibrium of the non-cooperative game established in the previous sub-section, before which the definition of the Nash equilibrium needs to be given first. In the chapter, each player is considered to be able to not only adopt pure strategies (consistently choosing either ON or OFF strategy) but also adopt mixed strategies (stochastically choosing ON or OFF strategy following certain probability distribution). That is, it is assumed that for any player i, the probability of adopting one pure strategy $s^i_{j^i} \in S^i$ is $\sigma^i_{j^i}$. The mixed strategy of player i is defined as $\{\sigma^i_{j_i} | j_i = 1, 2, \dots, m_i\}$, donated as σ^i, and the following equation holds:

$$\sum_{j_i=1}^{m_i} \sigma^i_{j^i} = 1 \tag{3.4}$$

A mixed strategy combination of all the players is donated as $\sigma = (\sigma^{-i}, \sigma^i)$, where σ^{-i} represents the set of the mix strategies of all the players except player i. The payoff value of player i given a mix strategy combination σ is calculated by

$$u^i(\sigma) = \sum_{s \in S} \left[u^i(s) \cdot \prod_{i \in N} \sigma^i_{j^i} \right] \tag{3.5}$$

where $s = (s^1_{j^1}, s^2_{j^2}, \dots, s^n_{j^n})$.

Given all the above, the definition of Nash equilibrium is able to be derived. A mixed strategy combination σ^* is a Nash equilibrium if

$$u^i(\sigma^*) \geq u^i\left(\sigma^{*-i}, \sigma^i\right), \forall i \in N, \forall \sigma^i \in \Sigma^i \tag{3.6}$$

where Σ^i denotes the set of all the mixed strategies of play i.

According to [67], the calculation of this Nash equilibrium is equivalent to solving the following optimization problem:

$$\begin{aligned} &\min \sum_{i \in N} \left[\beta^i - u^i(\sigma)\right] \\ &s.t.\ u^i\left(\sigma^{-i}, s^i_{j^i}\right) - \beta^i \leq 0 \quad \forall j^i = 1, \dots, m_i, \forall i \in N \\ &\sum_{j_i=1}^{m_i} \sigma^i_{j_i} = 1 \qquad \forall i \in N \\ &\sigma^i_{j^i} \geq 0 \qquad \forall j^i = 1, \dots, m_i, \forall i \in N \end{aligned} \tag{3.7}$$

where β^i is the ancillary variable, which represents the optimal payoff to player i. By solving the optimization problem presented as Equation (3.7), the Nash equilibrium of the non-cooperative game is found.

3.3.3 Simulation of Multiple Time Periods Considering Time-Coupled Constraints of Water Temperature

This section illustrates the consideration for simulating the P2P bidding for multiple energy exchange time periods through the P2P energy trading platform Elecbay. In any energy exchange time period t, the initial water temperature needs to be given for each player to calculate the payoff value. For a water heater of any player, the initial water temperature of time period t is determined by the initial temperature and the strategy of the previous time period t-1. The quantitative relationship is specified as follows:

$$T_t = \theta_{t-1} - (\theta_{t-1} - T_{t-1})e^{\left[-\frac{\Delta t}{RC}\right]} + c_{t-1} \cdot QR(1 - e^{\left[-\frac{\Delta t}{RC}\right]}) \tag{3.8}$$

where T_t and T_{t-1} are the initial water temperature in tank of time periods t and t-1; θ_{t-1} is the ambient temperature in time period t-1; c_{t-1} is the actual ON/OFF status of the water heater during time period t-1; Δt is the length of an energy exchange time period; Q, R and C are heater capacity, thermal resistance and thermal capacitance of the water heater respectively. The higher Q is, the more quickly the water is heated. The higher RC is, the more slowly the temperature of water changes. When hot water is consumed, the water temperature changes by

$$T_t = \frac{[T_{cur,t} \cdot (V - d_{t-1}) + \theta_{t-1} \cdot d_{t-1}]}{V} \tag{3.9}$$

where $T_{cur,t}$ is the initial water temperature of time period t before considering the consumption during time period t-1; V is the mass of water in full storage; d_{t-1} is the demand of hot water drawn during time period t-1.

With Equations (3.8) and (3.9), the multiple energy exchange time periods are linked and the water temperature change is simulated throughout the time line. The procedure of the multi-time period simulation is summarized in Fig. 3.4.

Note that if the strategies at the calculated Nash equilibrium are pure strategies, the pure strategies can directly be taken as the adopted control strategies, c, between the Nash equilibrium calculation and water temperature update blocks in Fig. 3.4.

However, if the strategies at the calculated Nash equilibrium are mixed strategies, the adopted control strategies need to be decided by sampling from the probability distribution in the mixed strategies, e.g. using Monte Carlo sampling, and in this case the multi-time period simulation needs to be conducted many times to get results with statistical significance.

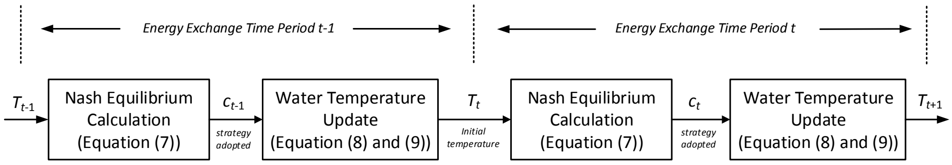


Fig. 3.4. The Procedure of the Multi-time Period Simulation

3.4 Case Study

3.4.1 Case Study in a Benchmark LV Microgrid

A Benchmark LV Microgrid, as shown in Fig. 3.5, was used for the case study to test the bidding through the proposed P2P energy trading platform "Elecbay" [68].

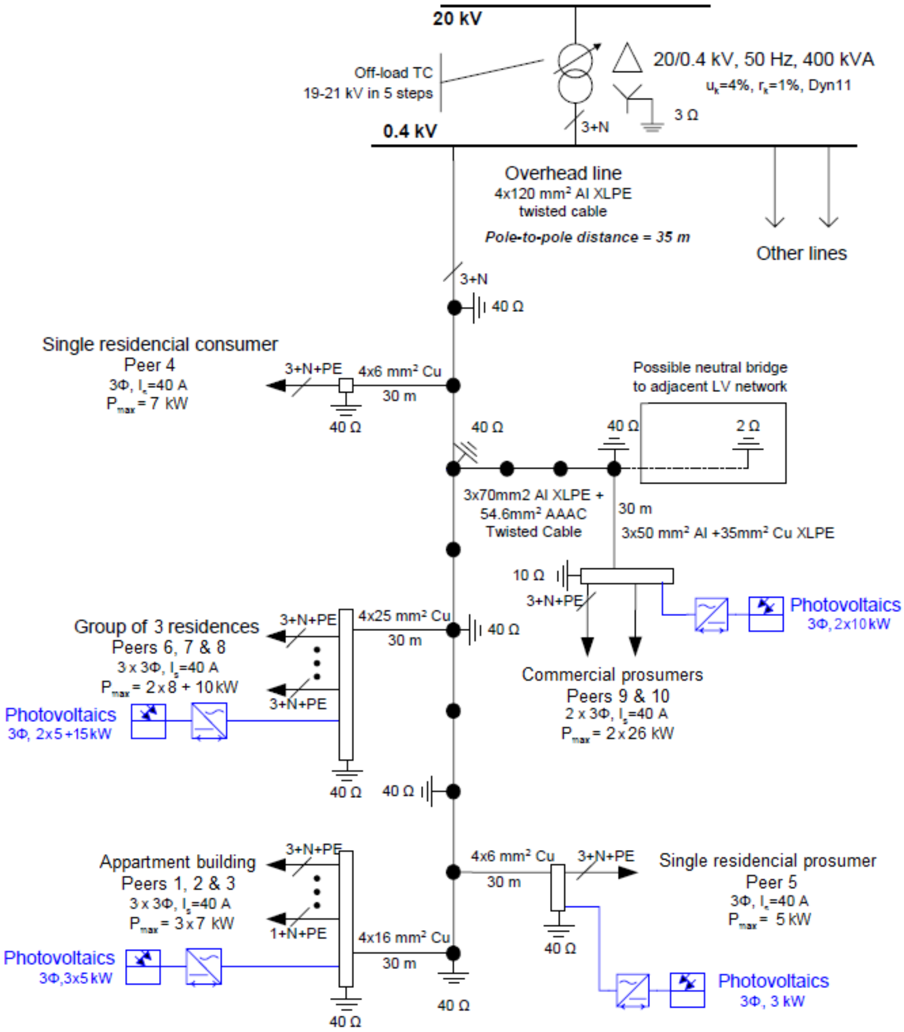
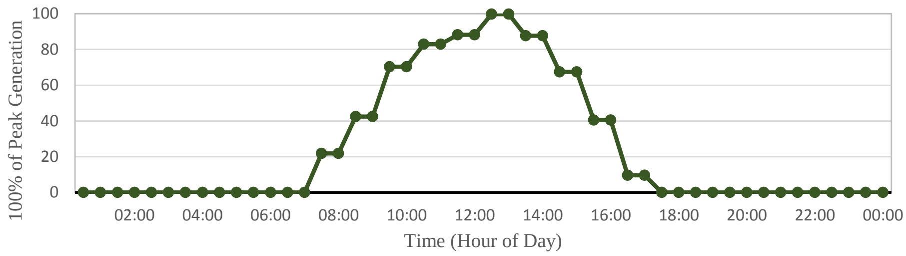


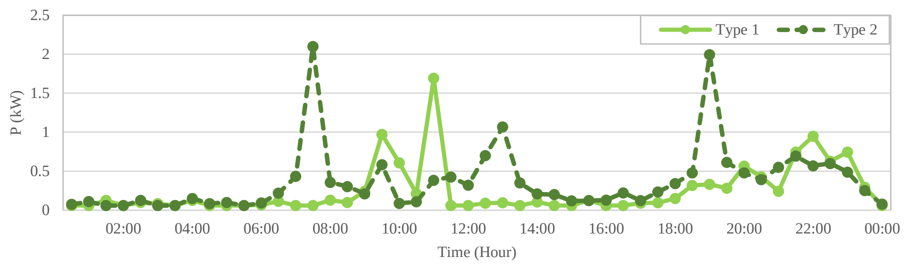
Fig. 3.5. The Benchmark LV Microgrid Adapted from [68]

There are 10 peers in the benchmark LV Microgrid in total. It was assumed that 1) all of the peers have both non-flexible and flexible demands in their premises; 2) all of the flexible demands are electric water heaters with tanks; 3) all of the peers except Peer 4 have DGs connected to their premises; and 4) all of the DGs are considered to be PV panels in this case study.

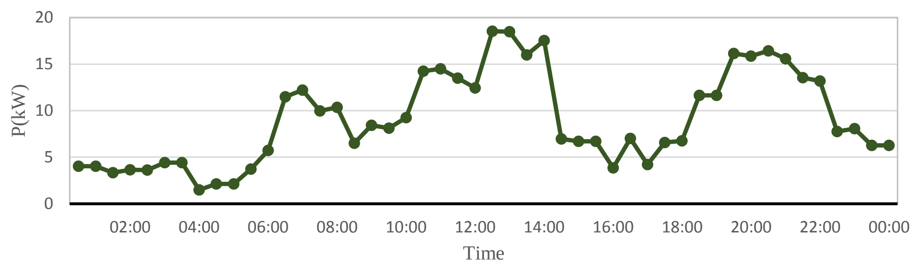
The input data, including the PV generation profiles, and the load profiles of the non-flexible demand (both Types 1, 1-person residential premise and Type 2, 2-person residential premise), were produced by the CREST (Centre for Renewable Energy Systems Technology) demand model [69]. The inputs of Peers 1 and 2 are taken as examples that are shown in Fig. 3.6 (a) and (b) and Table 3.2. The overall power consumption of non-flexible demands in the Microgrid is shown in Fig. 3.6(c).



(a) PV Generation Profile [69]



(b) Load Profiles of Non-flexible Demand [69]



(c) Total Power Consumption of Non-flexible Demands in the Microgrid

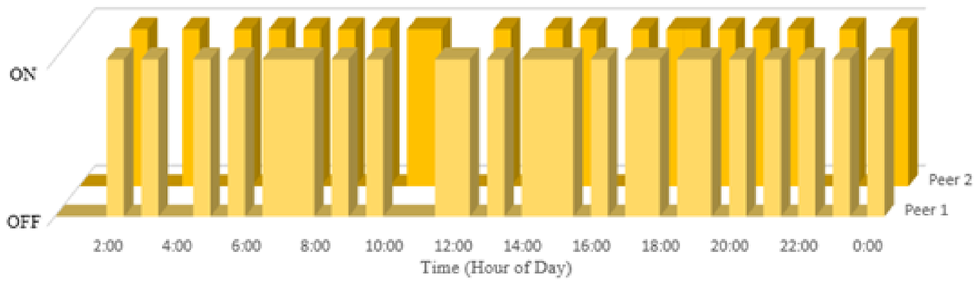
Fig. 3.6. Input Data of Peers 1 and 2, and the Total Non-flexible Demands of the Microgrid in Case Study 3.4.1

As shown in Fig. 3.5, Peers 1 and 2 are both located in the same residential apartment building. Moreover, as listed in Table 3.2, their maximum PV generation, flexible demand and non-flexible demand are also the same. Therefore, they were chosen as examples throughout the case study to demonstrate and compare the impact of P2P energy trading on the residential energy prosumers of the same scale but with different power consumption patterns.

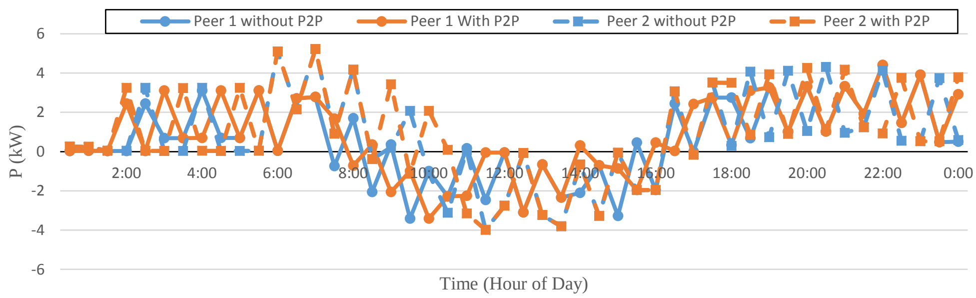
Table 3.2. Key Parameters of Peers 1 and 2 in Case Study 3.4.1

Parameters	Peer 1	Peer 2
Maximum PV generation	5 kW	5 kW
Maximum flexible demand	3 kW	3 kW
Maximum non-flexible demand	4 kW	4 kW
Non-flexible load profile	Type 1	Type 2

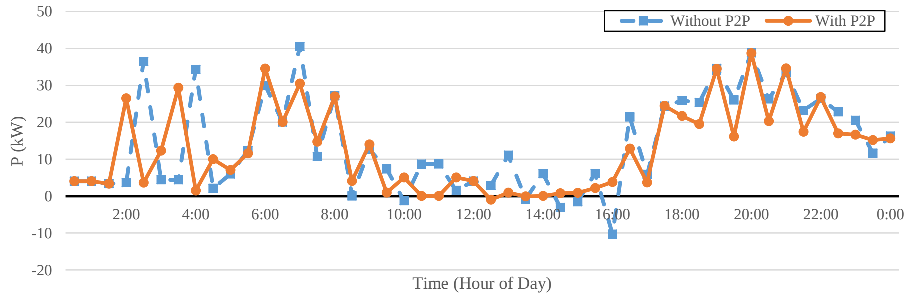
Simulation results are presented in Fig. 3.7 and Table 3.3.



(a) ON/OFF Status of Flexible Demand of Peers 1 and 2



(b) Total Power Consumption of Peers 1 and 2 without and with P2P



(c) Net Load of the Microgrid

Fig. 3.7. Simulation Results of Peers 1 and 2, and the Microgrid in Case Study 3.4.1

Table 3.3. Comparison of Energy Exchange between the Microgrid and the Utility Grid Over One Day and Peak Load of the Microgrid in Case Study 3.4.1

	Energy Consumption (kWh)	Reduction of Energy Exchange	Peak Load (kW)	Reduction of Peak Load
Without P2P	339.34	N/A	40.51	N/A
With P2P	308.15	9.19%	38.73	4.41%

Fig. 3.7(a) shows that with P2P energy trading, the flexible demand owned by peers of different non-flexible load profiles are scheduled to be ON during different time periods of the day. The flexible demand is less likely to be turned ON or OFF simultaneously, even given that they are assumed to have very similar types of water heater, water usage pattern and initial water temperature in tank. Fig. 3.7(b) further illustrates the power consumption of those peers with or without P2P energy trading over a day. The peaks of their power generation and consumption appear at different time periods of the day.

Fig. 3.7(c) and Table 3.3 show that with P2P energy trading, the overall energy exchange between the Microgrid and the utility grid is reduced. However, the local generation and demands are not well balanced due to the relatively low variety of peers and their DGs. The reduction of the peak load of the whole Microgrid after adopting P2P energy trading is only 4.41%.

3.4.2 Case Study in a LV Microgrid with Higher Peer Variety

Based on Case Study 3.4.1, another case was designed with higher peer variety. The DGs owned by peer 3, 8 and 10 were changed to wind turbines with the same generation capacity. The generation profiles of the wind turbines was shown in Fig. 3.8. Other relevant inputs were illustrated in Fig. 3.6(b), Fig. 3.6(c) and Table 3.4.

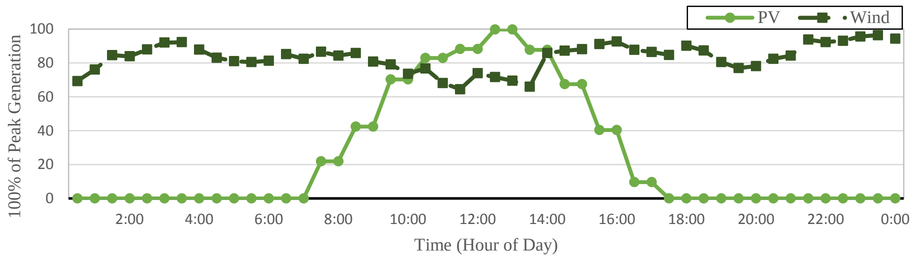
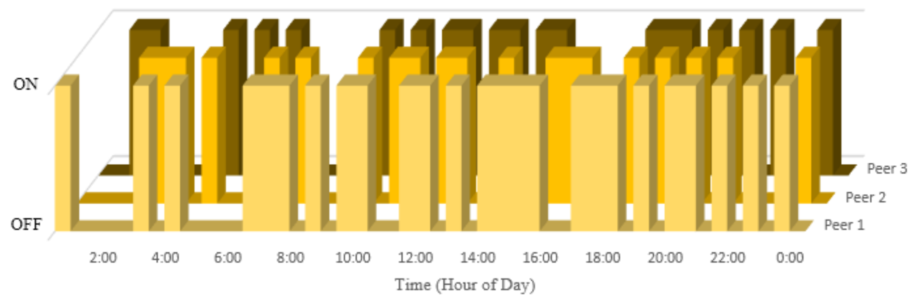


Fig. 3.8. PV and Wind Generation Profiles in Case Study 3.4.2

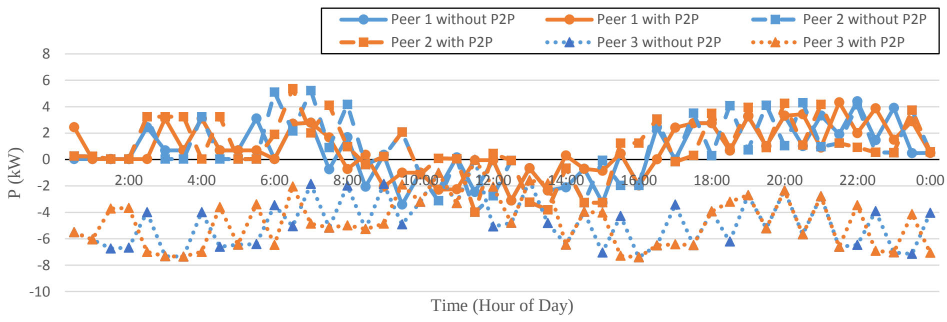
Table 3.4. Key Parameters of Peers 1, 2 and 3 in Case Study 3.4.2

Parameters	Peer 1	Peer 2	Peer 3
Maximum PV generation	5 kW	5 kW	N/A
Maximum wind generation	N/A	N/A	5 kW
Maximum flexible demand	3 kW	3 kW	3 kW
Maximum non-flexible demand	4 kW	4 kW	4 kW
Non-flexible load profile	Type 1	Type 2	Type 1

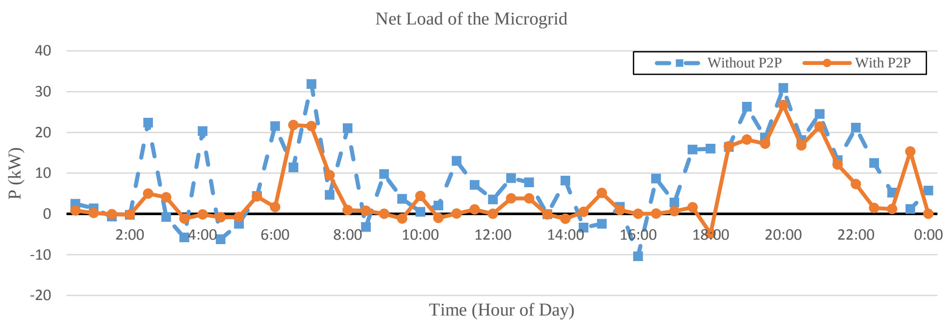
Simulation results are presented in Fig. 3.9 and Table 3.5.



(a) ON/OFF Status of Flexible Demand of Peers 1, 2 and 3



(b) Total Power Consumption of Peers 1, 2 and 3 without and with P2P



(c) Net Load of the Microgrid

Fig. 3.9. Simulation Results of Peers 1, 2 and 3, and the Microgrid in Case Study 3.4.2

Table 3.5. Comparison of Energy Exchange between the Microgrid and the Utility Grid Over One Day and Peak Load of the Microgrid in Case Study 3.4.2

	Energy Consumption (kWh)	Reduction of Energy Exchange	Peak Load (kW)	Reduction of Peak Load
Without P2P	204.31	N/A	31.87	N/A
With P2P	117.49	42.49%	26.26	17.60%

Fig. 3.9(a) shows that with P2P energy trading, the flexible demand owned by peers of different non-flexible load profiles and different type of DGs are scheduled to be ON during different time periods of the day. The flexible demand is less likely to be turned ON or OFF simultaneously. Especially for Peer 3 whose DG is a wind turbine, its flexible demand is scheduled in a very different pattern compared with Peers 1 and 2. Fig. 3.9(b) illustrates the power consumption of those peers with or without P2P energy trading over a day. The peaks of their power generation and consumption appear at different time periods of the day.

Fig. 3.9(c) and Table 3.5 show that with P2P energy trading, the overall energy exchange between the Microgrid and the utility grid is significantly reduced. The local generation and demands are also more balanced compared with the simulation results in Case Study 3.4.1. The reduction of the peak load of the whole Microgrid has increased to 17.60%, compared with 4.41% in Case Study 3.4.1. This is due to the increased variety of peers in the Microgird.

Table 3.6. Comparison of Results in Case Study 3.4.1 and Case Study 3.4.2.

	Reduction of Energy Exchange with P2P	Reduction of Peak Load with P2P
Case Study 3.4.1	9.19%	4.41%
Case Study 3.4.2	42.49%	17.60%

Compared the results of Case Studies 3.4.1 and 3.4.2, as shown in Table 3.6, it is concluded that with high peer variety, P2P energy trading is able to better reduce the energy exchange between the Microgrid and the utility grid, and better balance local generation and demand.

3.5 Conclusions

P2P energy trading is one of the promising paradigms of future smart grids, which enables the direct energy trading among energy consumers and prosumers in local power networks. A P2P energy trading platform “Elecbay” was designed for a grid-connected LV Microgrid. The simulation of P2P bidding among energy consumers and prosumers through the energy trading platform “Elecbay” was developed. Roles of flexible demand and storage in P2P energy trading were demonstrated. Simulation of a single energy exchanging time period was developed using game theory. The P2P bidding was formulated as a non-cooperative game. Nash equilibrium of the non-cooperative game was calculated in order to simulate the most possible P2P bidding results. The simulation of multiple energy exchanging time period was developed by considering the time-coupled constraints of water temperature of the flexible demand (electric water heaters with tanks) owned by peers.

Case studies were carried out based on the EU benchmark Microgird. Simulation results showed that P2P energy trading was able to reduce the energy exchange between the Microgrid and the utility grid and balance local generation and demand, and therefore, had the potential to facilitate a large penetration of renewable energy resources in the power grid. The increased variety of energy consumers and prosumers in the Microgrid was able to further improve the benefits of P2P energy trading.

In this chapter, for the first time, a business model and an associated bidding system are introduced for the P2P energy trading among consumers and prosumers in a grid-connected Microgrid. The methodology of modelling the P2P bidding among consumers and prosumers with electric water heaters with tanks as flexible demands using game theory is proposed. However, energy storage systems are also able to provide significant amount of flexibility for P2P energy trading in practice. The use of energy storage for P2P energy trading and the relevant modelling methodology are to be investigated in the future research.

Chapter 4

Control of a LV Microgrid with Peer-to-Peer Energy Trading

This chapter focuses on the control of the local distribution network with P2P energy trading in the control layer before and during the exchanging time period. Two necessary control systems are proposed for the P2P energy trading arrangement based on “Elecbay”. A bid acceptance/rejection system is considered for the period after Gate Closure and before the start of energy exchange. A voltage control system which combines droop control and OLTC control is designed and simulated. Case studies are carried out in order to demonstrate the impact of P2P energy trading on the voltage control system of a grid-connected LV Microgrid. Simulation results show that the proposed voltage control system is sufficient for supporting the P2P energy trading in the Microgrid based on “Elecbay”. The total number of operation times of the OLTC is reduced with P2P energy trading compared to the reference scenario.

4.1 Introduction

In a LV Microgrid, voltage is sensitive to active power [70]. With the integration of P2P energy trading, the changes of active power generation and consumption in the Microgrid become even more frequently.

There are a number of actions that the DSOs are able to take before and during each Settlement Period. These control methods are categorised into two separate control systems and introduced in this chapter.

4.2 Control of a grid-connected LV Microgrid with P2P energy trading

According to the P2P energy trading platform "Elecbay" proposed in Chapter 3, for each Settlement Period, the control systems are designed to be operated between the gate closure and the end of that Settlement Period by the DSOs.

There are two separate control systems which are necessary for "Elecbay". They are demonstrated in Fig. 4.1.

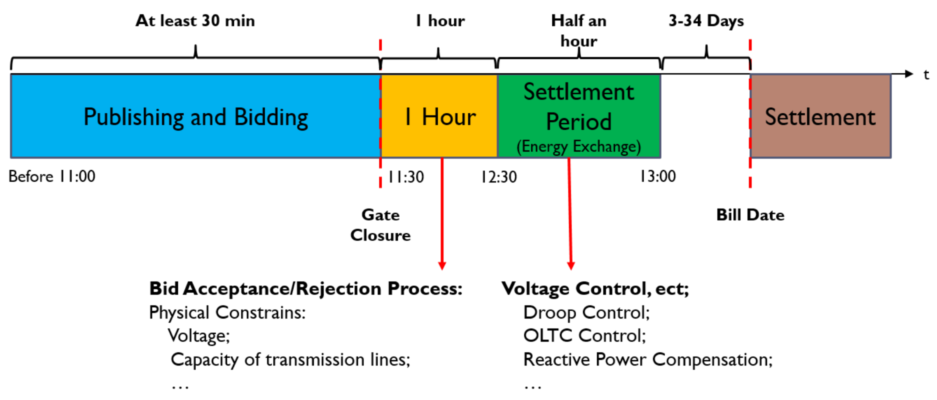


Fig. 4.1. Two Control Systems for "Elecbay"

The first control system is Bid Acceptance/Rejection System. It is operated between the gate closure and the start of each Settlement Period. The DSOs evaluate if there is going to be a network constraint violation, e.g. voltage excursion, thermal overloading, etc., when all the placed orders are accepted. Once a network constraint violation is identified, DSOs are the only entities which have the permission to modify or cancel orders after the gate closure. The rules for order modification or cancellation are various. For example, with the last on first off principle, the orders placed at a later time (i.e. closer to the gate closure) have a higher possibility to be cancelled. The Bid Acceptance/Rejection System will not be discussed in details in this chapter, but is an important part of the future work for the research reported in this thesis.

The second control system is voltage control. It is operated during each half-hourly Settlement Period. Two control methods are considered including droop control of generators and OLTC control. The following sections in this chapter focus on the design and simulation of the voltage control system for a Benchmark LV grid-connected Microgrid with P2P energy trading.

4.3 Voltage control of a grid-connected LV Microgrid with P2P energy trading

Voltage control in LV distribution networks has been widely investigated. [71] – [73] reviewed current voltage control in LV distribution networks. [74] – [79] discussed the voltage control methods with DGs. [80] proposed a voltage regulation strategy by controlling smart loads. In [81] reactive power flow control mechanisms were illustrated. [82] – [84] demonstrated the use of storage system in voltage control. And in [85] - [90], different coordinated control strategies were proposed and examined. Simulation parameters for examining voltage control strategies were mentioned in [91].

Droop control of DGs and OLTC control are used in the proposed voltage control system introduced in this thesis, and are developed as illustrated in the following sub-sections.

4.3.1 Droop control

Voltage / reactive power droop control of DGs is designed and simulated as follows.

1. Determining the droop

Voltage / reactive power droop control is used for reducing the voltage excursions [92]. A typical droop characteristic of a DG is shown in Fig. 4.2.

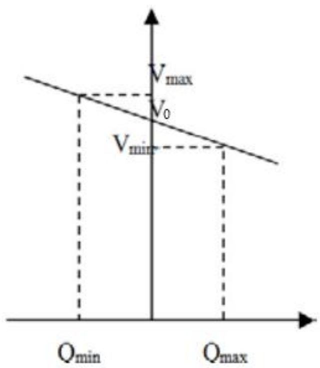


Fig. 4.2. A typical voltage / reactive power droop characteristic

The droop characteristic is described by:

$$Q_{DG} = -k_{DG}(V_{DG} - V_0) \tag{4.1}$$

where Q_{DG} is the reactive power output of DG, V_{DG} is its terminal voltage, V_0 is 1 p.u., and k_{DG} is called gain, which is a constant.

The value of k_{DG} is calculated by:

$$k_{DG} = \frac{Q_{DG-max}}{\Delta V_{max}}$$

(4.2)

where ΔV_{max} is the maximum permissible voltage deviation, and Q_{DG-max} is the rated reactive power of the DG.

2. Simulation of DGs with the droop control when connected to the Microgrid

The simulation of the droop control is developed by mimicking DGs' behaviours when they are first connected to the Microgrid, as illustrated in Fig. 4.3.

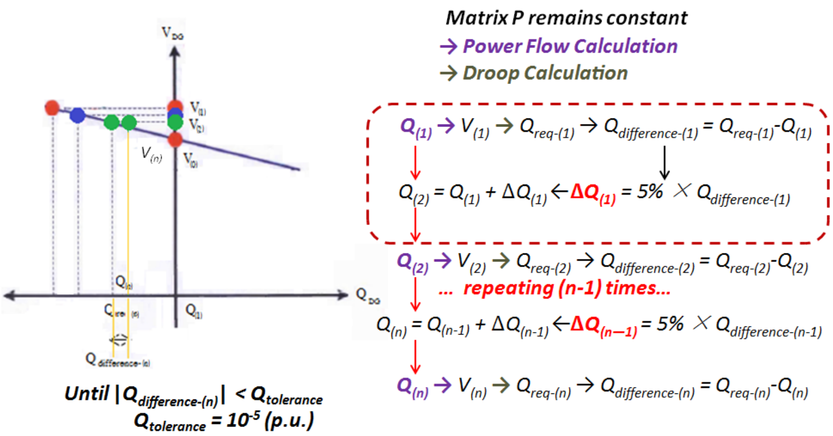


Fig.4.3. Simulation of Droop Control by Mimicking DGs' Behaviours when Connected to the Microgrid

The simulation is carried out in MATLAB by iterating power flow calculation and droop calculation. For the power flow calculation, Newton-Raphson method is used [93] [94]. The main feeder is considered as the slack bus, while all the other buses are considered as P-Q buses. A matrix containing reactive power output of all DGs are updated during the iteration process until the difference between the new matrix and the previous one ($|Q_{difference-(n)}|$) is smaller than a tolerance value ($Q_{tolerance}$, 10^{-5} *p.u.* is used here). Until then, the system is considered to be in a stable status. The voltage level at each bus is achieved.

4.3.2 On-Load-Tap-Changer control

Transformers can regulate the voltage at all voltage levels. With an OLTC transformer, by triggering proper tap actions, reactive power produced by all DGs is able to be reduced. Therefore, the conditions for triggering a tap change action need to be addressed.

The OLTC control is developed in two steps:

- Determining the monitoring bus;
- Defining the conditions for triggering tap actions.

1. Determining the monitoring bus

The monitoring bus is determined by finding the most voltage-sensitive bus in the Microgrid over a day. The voltages of all buses over a day without OLTC control are calculated. Standard deviation of the voltages at each bus is then obtained. The bus with the highest standard deviation value is chosen as the monitoring bus.

2. Defining the conditions for triggering tap actions

The OLTC controller tries to maintain the voltage at the monitoring bus (V_m) within a certain range ($[1-\Delta V_{trigger}, 1+\Delta V_{trigger}]$). In order to get V_m monitored and controlled, the voltage measurements at the monitoring bus are recorded by sensors and sent to the OLTC controller in real-time via a communication link. Once the voltage measurement falls outside the range, certain tap action is to be trigger by the OLTC controller so that the voltage at the monitoring bus is able to move back within the range again.

Since droop control is in operation, the range for the voltage at the monitoring bus ($[1-\Delta V_{trigger}, 1+\Delta V_{trigger}]$) is able to be transferred as the range for the reactive power output of the DG connected to the monitoring bus ($[-Q_{trigger}, Q_{trigger}]$).

The process is illustrated in Fig.4.4.

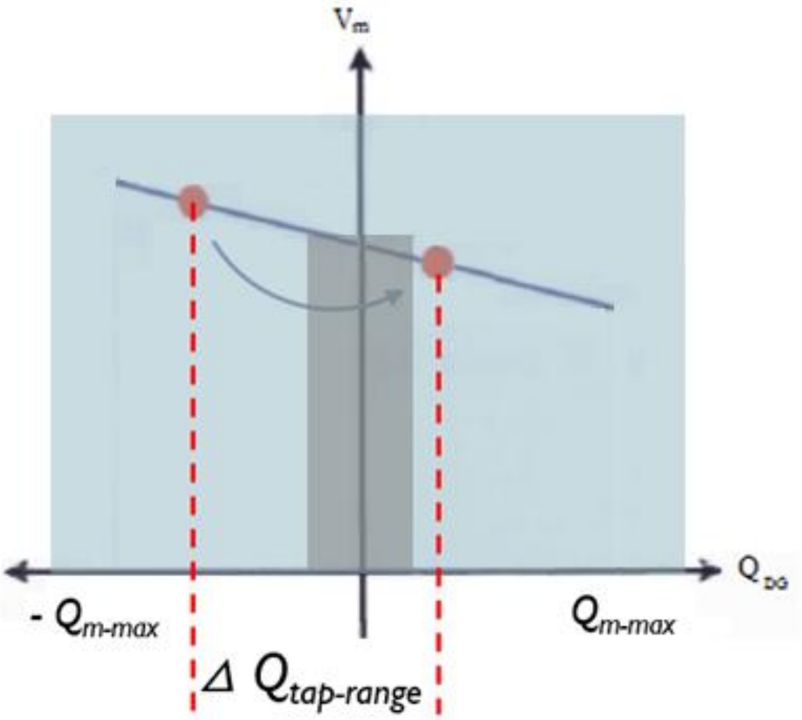


Fig. 4.4 Conditions for Triggering Tap Actions

According to Fig.4.4, it is concluded that the range for the reactive power output should be larger than the difference of reactive power output caused by one tap action, and smaller than that caused by two tap actions. Besides, it should not be larger than the rated reactive power of the DG, either. These are illustrated in Equations (4.3), (4.4) and (4.5).

$$2Q_{trigger} \geq \Delta Q_{tap-range} \tag{4.3}$$

$$2Q_{trigger} < 2\Delta Q_{tap-range}$$

(4.4)

$$Q_{trigger} < Q_{m-max}$$

(4.5)

Therefore, the value of $Q_{trigger}$ is able to be determined by Equation (4.6).

$$\frac{1}{2}\Delta Q_{tap-range} \leq Q_{trigger} < \Delta Q_{tap-range} < Q_{m-max}$$

(4.6)

4.4 Case study

The case studies carried out in Chapter 3 are used as the basis of the case study in this section. The same benchmark Microgrid is considered. The simulation results of the P2P bidding of all 10 peers are used directly here. The generation profiles and the load profiles of all peers remain the same. These are provided in Fig. 3.5, Fig. 3.6, Fig. 3.7, and Table 3.2.

For simplicity, the demand or generators connected to the same bus are all integrated as single ones. The benchmark Microgrid model is then updated and as shown in Fig. 4.5.

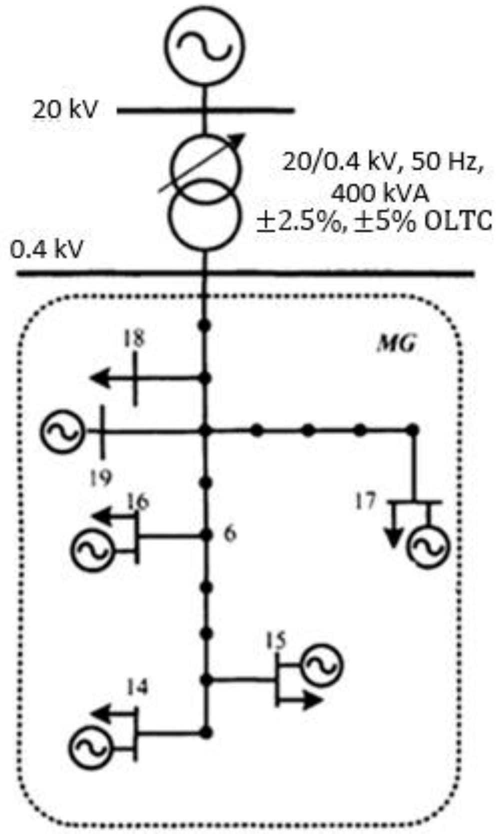


Fig. 4.5. Benchmark Microgrid Model for Voltage Control

Power factor of the load is considered to be 0.95. The allowed maximum voltage change in the Microgrid is assumed to be ± 0.06 p.u..

For droop control, the values of the droop are calculated as demonstrated in Table 4.1.

Table 4.1. Determination of the Gain and Droop of DGs at Major Buses

DG No.	$P_{DG\text{-}max}$	$Q_{DG\text{-}max}$	k_{DG} (p.u.)	Droop
14	15kW	3kVAr	**50.00**	**2.00%**
15	3kW	0.6kVAr	**10.00**	**10.00%**
16	25kW	5kVAr	**83.33**	**1.20%**
17	20kW	4kVAr	**66.67**	**1.50%**
19	30kW	6kVAr	**100**	**1.00%**

For OLTC control, in order to determine the monitoring bus, the standard deviation of the voltages at each bus over a day is calculated as displayed in Table 4.2.

Table 4.2. Determination of the Monitoring Bus by Calculating Standard Deviation

Bus No	00:00	00:30	…	23:30	σ
1	0.997751	0.999166		0.997008454	0.000664027
…					…
14	0.991159	1.014988		0.99599036	0.010505365
15	0.990513	1.012454		0.99696233	0.009527802
16	0.99124	1.010633		0.998870703	0.00872727
17	0.975624	0.997727		0.997491402	0.009609464
18	0.991025	1.001777		0.994992805	0.004233057
…					…
20	1	1		1	0

Bus 14 has the highest standard deviation, which means that it is the most voltage-sensitive bus in the Microgrid. Therefore, it is chosen to be the monitoring bus for the OLTC control.

The conditions for triggering tap actions are then determined based on Table 4.3.

Table. 4.3. Determining the Conditions for Triggering Tap Actions

Tap Ratio at Transformer	$V_{bus\text{-}14}$	Q_m (Q_{14})	$\Delta Q_{tap\text{-}range}$	$0.5\Delta Q_{tap\text{-}range}$
95%	1.0201	-1.6495	2.0875	1.0438
97.5%	0.9947	0.4380	1.9787	0.9894
100% (20:0.4)	**0.9706**	**2.4167**	/	/
102.5%	0.9477	4.2947	1.8780	0.9390
105%	0.9260	6.0797	1.7850	0.8925

It is concluded that $Q_{trigger}$ is expected to be any value between 1.0438 p.u. and 1.7850 p.u.

In this case study, the following values are used:

$$Q_{trigger} = 1.4\, p.u. \tag{4.7}$$

$$\Delta V_{trigger} \approx 0.028\, p.u. \tag{4.8}$$

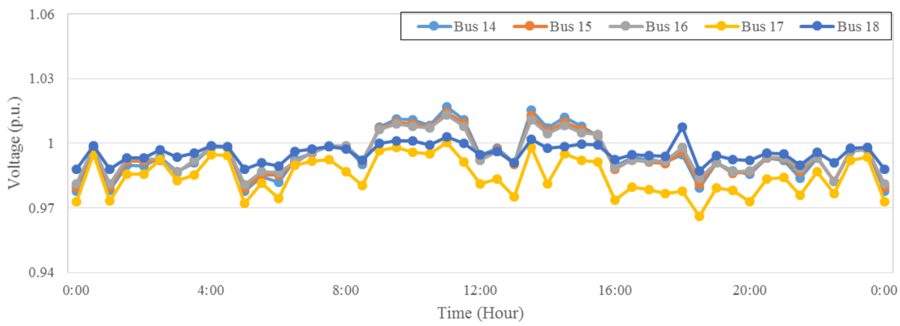
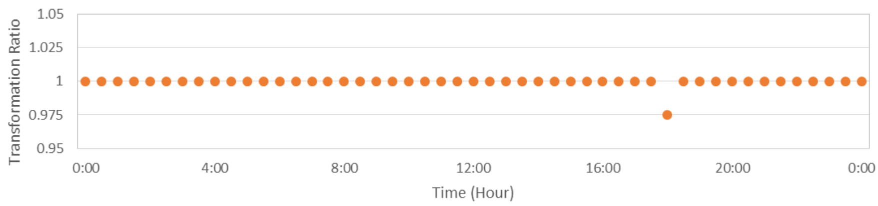
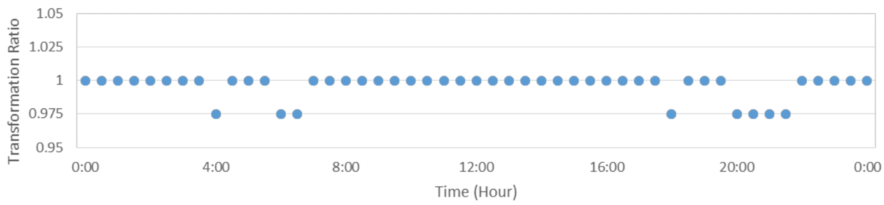


Fig. 4.6. Voltage at Major Buses with Voltage Control (with P2P)



(a) Tap Settings of OLTC with P2P Energy Trading



(b) Tap Settings of OLTC without P2P Energy Trading

Fig. 4.7. Tap Settings of OLTC with Voltage Control (with and without P2P)

The simulation results are displayed in Fig. 4.6 and Fig. 4.7.

According to Fig. 4.6, it is concluded that the voltage control system is sufficient for supporting the P2P energy trading based on the platform "Elecbay". The voltage at all major buses in the Microgrid remain within the tolerance ($\pm$0.06 p.u.). In addition, the voltage at the monitoring bus (Bus 14) remains within the range [0.972 p.u., 1.028 p.u.], which is defined in the OLTC controller.

Fig. 4.7(a) further demonstrates the tap settings of the OLTC. Only 2 tap actions are taken over a day. This number of tap actions is much smaller than that in another scenario without P2P energy trading as shown in Fig. 4.7(b), where 8 tap actions are taken over a day. It is concluded that P2P energy trading is able to reduce the number of tap actions for the OLTC control in the voltage control system. This has a positive impact on the operating life of the OLTC transformer.

4.5 Conclusion

Two necessary control systems for implementing the P2P energy trading platform "Elecbay" in the distribution networks were proposed – the bid acceptance/rejection system and the voltage control system. The former was designed to operate after the gate closure and before the start of energy exchange, while the latter was designed to operate during the energy exchanging time period.

The voltage control system was further developed in details. Droop control and OLTC control were used in the voltage control system. For droop control, the method of determining the droop for DGs was illustrated. The simulation by iterating power flow calculation was explained. For OLTC control, the method of determining the monitoring bus was demonstrated. The conditions for triggering different tap actions at the OLTC were discussed.

The case study was carried out on the basis of the case studies in Chapter 3. The proposed voltage control system was tested on the benchmark LV grid-connected

Microgrid. Two scenarios were developed with or without P2P energy trading separately. Simulation results illustrated that the voltage control system was sufficient for supporting the P2P energy trading platform “Elecbay”. The number of operation times of the OLTC was even reduced with P2P energy trading compared to the reference scenario.

In this chapter, for the first time, the complete control systems for P2P energy trading in a grid-connected Microgrid are introduced. The voltage control system is further developed and tested. It is proved that the existing voltage control methods, including droop control and OLTC control, are sufficient for supporting P2P energy trading. However, their further coordination and the relevant benefits to DSOs are to be discussed in the future research.

Chapter 5

ICT Infrastructures for Peer-to-Peer Energy Trading

This chapter investigates the requirements of ICT infrastructures for the P2P bidding platform and the control system in the ICT layer during the bidding time period and exchanging time period respectively: The information exchange among peers and other parties (Elecbay, DSOs, etc.) is designed based on TCP/IP protocol. Existing and private communication networks with different communication medium, bandwidths, etc., are modelled in OPNET. The performances of the networks are compared and analysed in the case studies in order to verify the technical feasibility of existing ICT infrastructures for supporting P2P energy trading platform and its relevant control systems. Simulation results show that the existing ICT infrastructures (e.g. wired broadband networks, GPRS Smart Metering networks, etc.) are sufficient for supporting both the P2P energy trading platform and the voltage control system. Therefore, there are no large amount of additional investments required in order to facilitate P2P energy trading.

5.1 Introduction

Both the P2P energy trading platform proposed in Chapter 3 and the voltage control system proposed in Chapter 4 require communication systems.

In [95] – [100], the requirements of ICT infrastructures for Smart Grids and their applications were demonstrated. [101] - [105] proposed a number of wired or wireless ICT solutions which were suitable for facilitating Smart Grids. [106] – [111] proposed different simulation methods for evaluating the performance of ICT infrastructures and the impact on electric power grid.

Implementing private ICT infrastructures for the P2P energy trading platform is not a cost-effective option. That is because each peer requires a separate connection to the server which hosts the platform. The investment is expected to be very high especially when the total number of peers is large. Therefore, two existing communication networks are considered for integrating the trading platform. They are:

- The wired broadband network;
- The GPRS smart metering network.

In the voltage control system proposed in Chapter 4, only OLTC control requires communication. That is to say, only one connection between the OLTC transformer and the monitoring bus is needed. On the other hand, some of the existing communication networks (e.g. GPRS smart metering networks) are not sufficient because of their higher latency and lower reliability for information exchange. Therefore, private networks are considered. They are able to provide high reliability, but require additional costs for installation and maintenance at the same time. The following communication networks are considered for integrating the voltage control system:

- The wired broadband network;
- Private wired network;
- Private wireless network.

The sections below introduce the modelling of the communication networks mentioned above.

5.2 Modelling of TCP/IP- based information exchange

TCP/IP means Transmission Control Protocol and Internet Protocol. Because the Internet and most communications use the Internet Protocol, the TCP/IP model is technically more commonly used for modern network implementations. Similar to the seven-layer OSI network model, the structure of the TCP/IP network model is illustrated in Fig. 5.1.

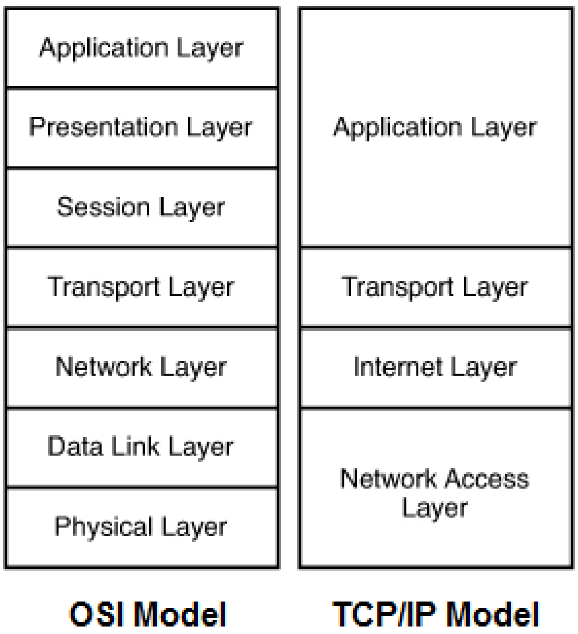
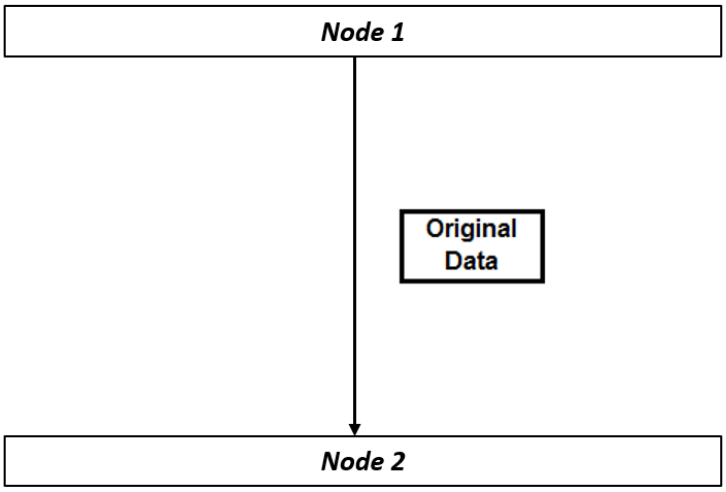


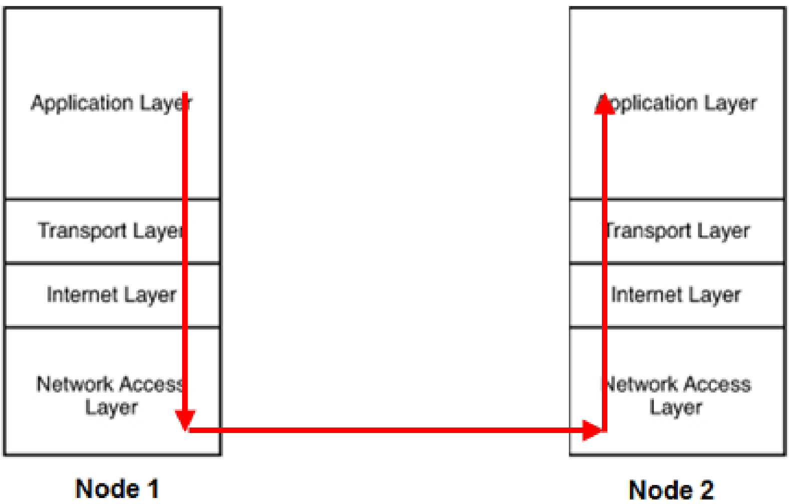
Fig. 5.1. TCP/IP Network Model and OSI Network Model [112]

The TCP/IP –based information exchange between two nodes can be illustrated as follows:

If the "original data" is expected to be transmitted from Node 1 to Node 2, it needs to be passed on layer by layer within or between both of the two nodes, as shown in Fig. 5.2.



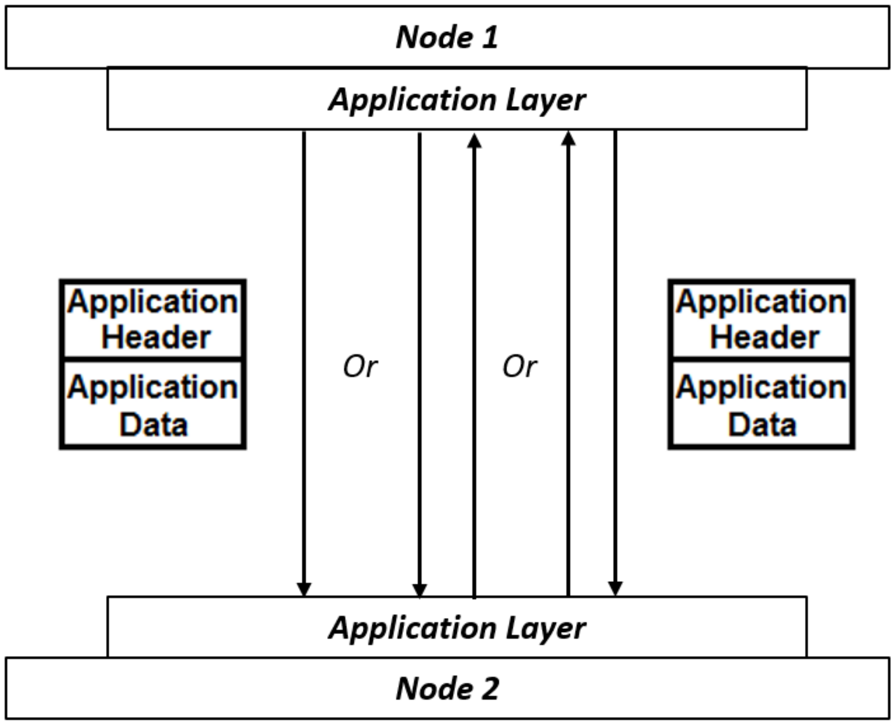
(a)



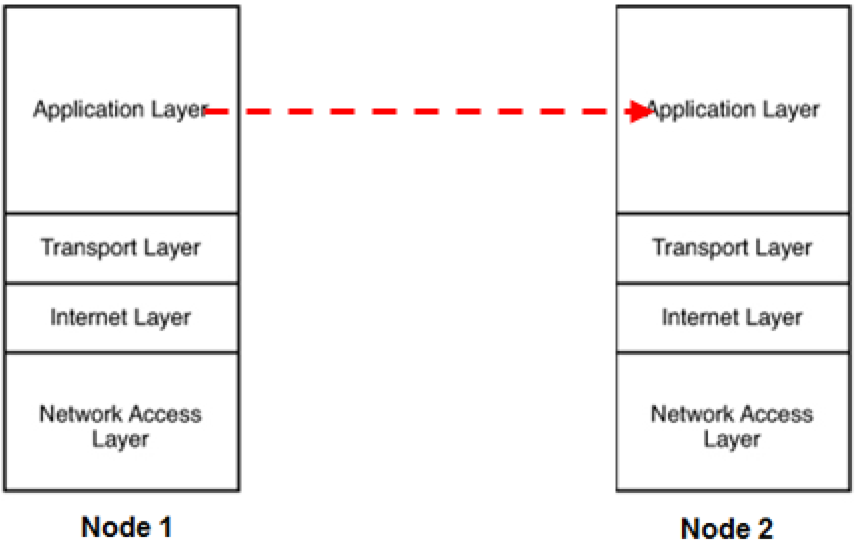
(b)

Fig. 5.2. TCP/IP-based Information Exchange from Node 1 to Node 2

Over the application layer, the original data is transformed as one or several pieces of application data with an application header in front of each piece of application data, as shown in Fig. 5.3. One or more times of data transmission between Node 1 and Node 2 are necessary in order to guarantee the successful information exchange of the original data.



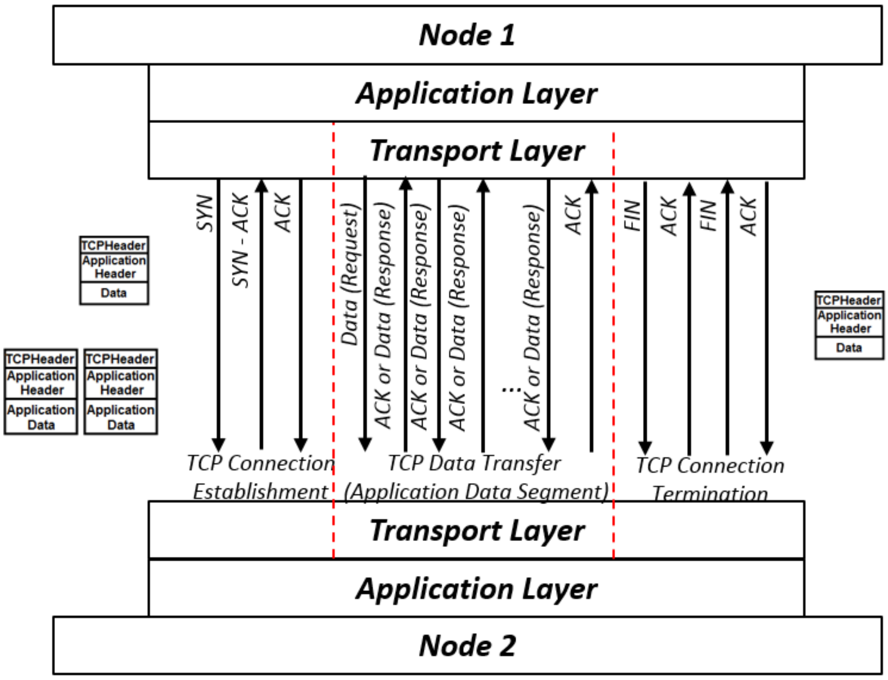
(a)



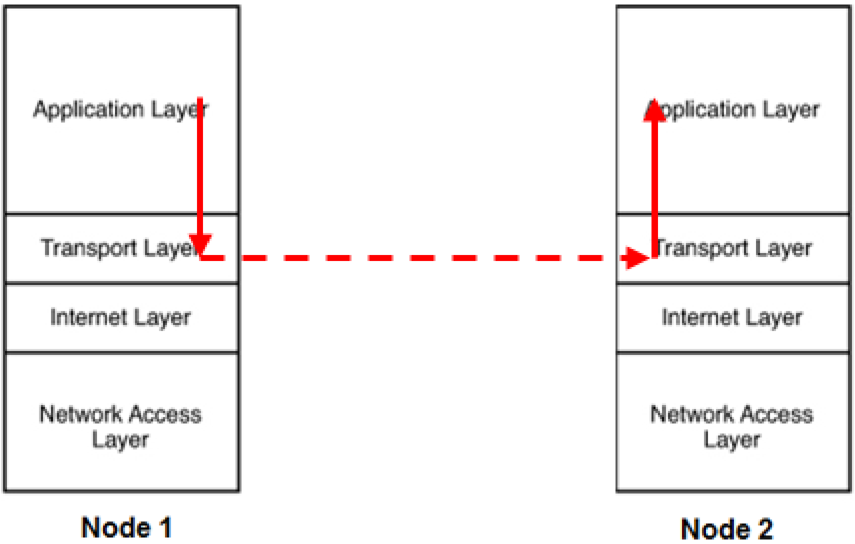
(b)

Fig. 5.3. TCP/IP-based Information Exchange from Node 1 to Node 2 over Application Layer

Over the transport layer, the application data with application header is segmented. A TCP header is attached in front of each segmented piece of data. Each segmented data with a TCP header is transmitted via a TCP connection established between the transport layers of the two nodes. A TCP connection is established and terminated following handshake processes as illustrated in Fig. 5.4.



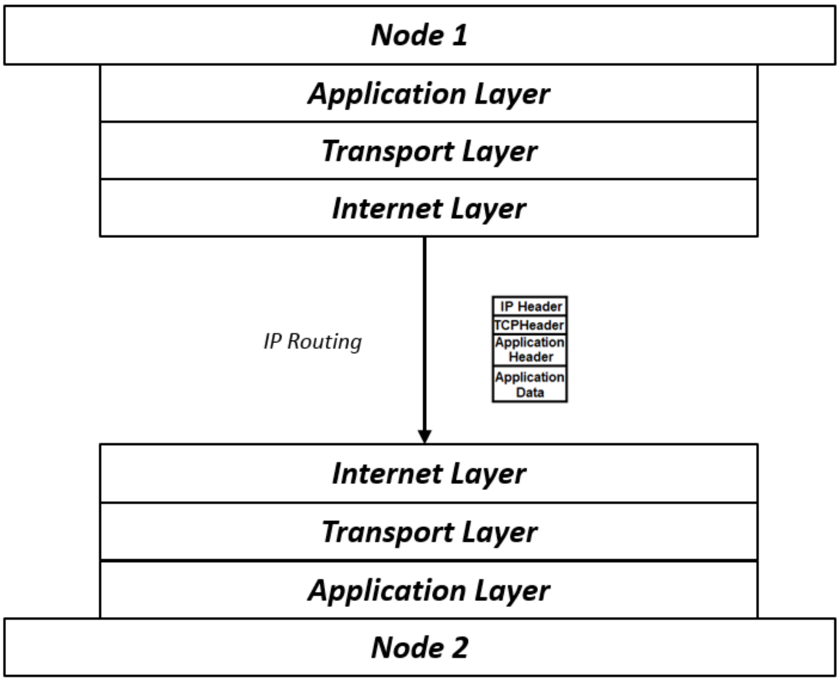
(a)



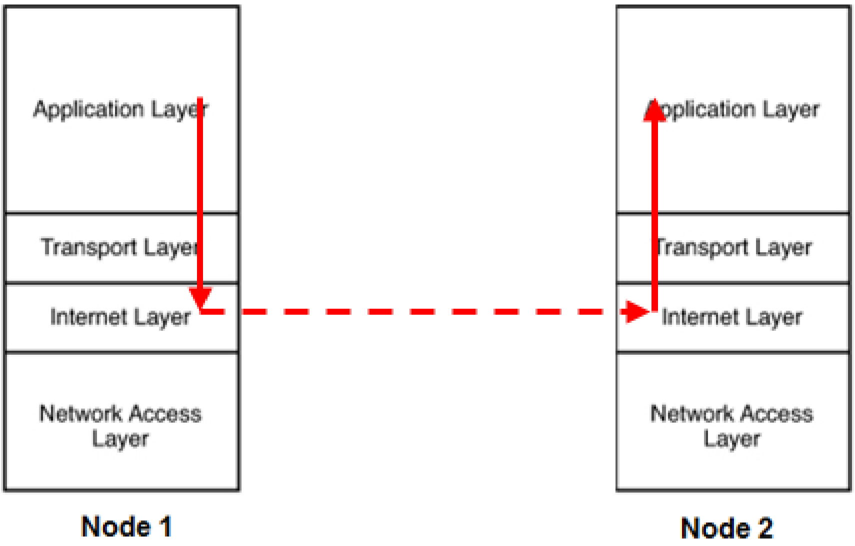
(b)

Fig. 5.4. TCP/IP-based Information Exchange from Node 1 to Node 2 over Transport Layer

Finally, over the Internet layer, each segmented piece of data from the TCP layer is further attached with an IP header, which contains information for routing, to form a packet, as shown in Fig. 5.5. Only with an IP header can a package be sent to the correct destination.



(a)



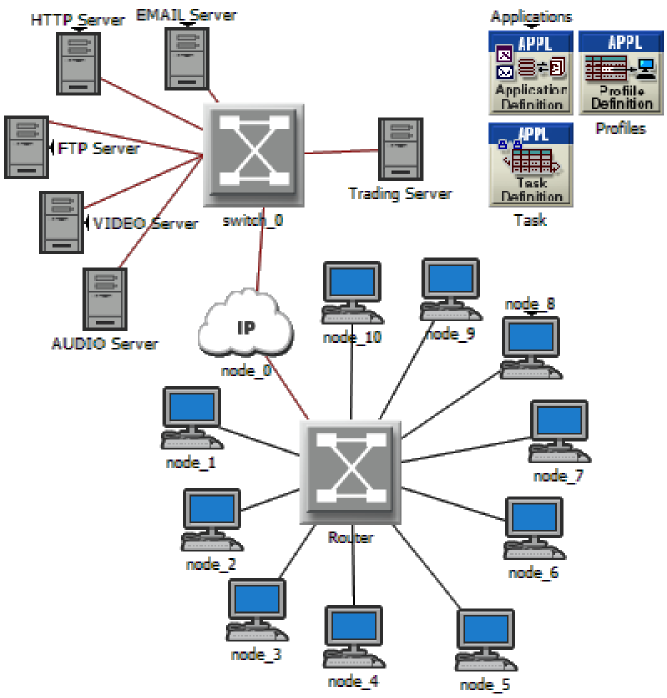
(b)

Fig. 5.5. TCP/IP-based Information Exchange from Node 1 to Node 2 over Internet Layer

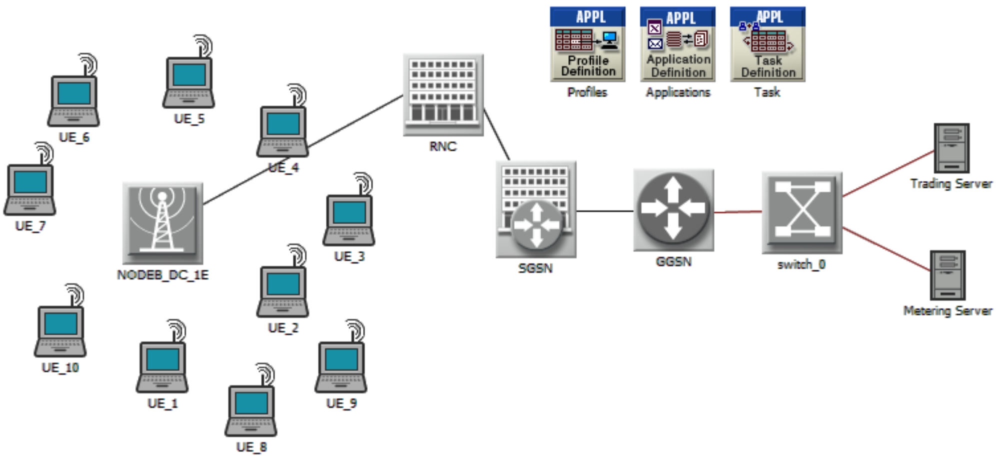
The TCP/IP-based information exchange model illustrated in this section is used to simulate the data flow of the P2P energy trading platform and the voltage control system in OPNET.

5.3 ICT infrastructures for the peer-to-peer energy trading platform

The network topologies of the communication networks integrated with the P2P energy trading platform are developed in OPNET, as demonstrated in Fig. 5.6.



(a) A wired broadband network integrated with the P2P energy trading platform



(b) A GPRS Smart Metering network integrated with the P2P energy trading platform

Fig. 5.6. Examples of existing communication networks for integrating the P2P energy trading platform

A general communication model of GPRS is provided in Fig. 5.7. The GPRS core network is the central part of GPRS which allows 2G mobile networks to transmit IP packets to external networks such as the Internet. The gateway GPRS support node (GGSN) is responsible for the internetworking between the GPRS network and external packet switched networks, such as the Internet. A serving GPRS support node (SGSN) is responsible for the delivery of data packets from and to the mobile stations within its geographical service area. Its tasks include packet routing and transfer, mobility management, logical link management, authentication and charging functions. The base station is connected to an antenna that receives and transmits the signals in the cellular network to cellular devices. [113]

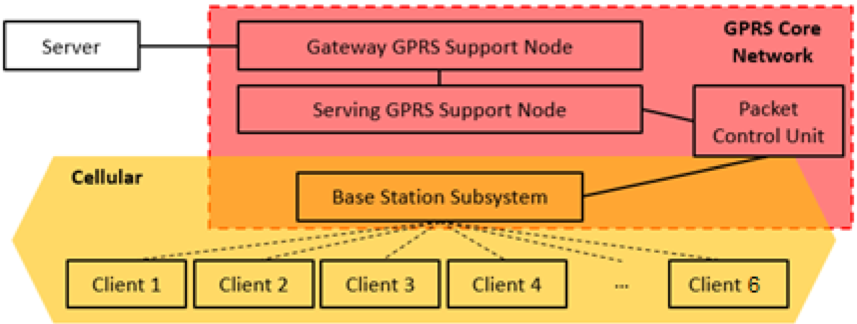


Fig. 5.7. The simplified communication model of GRPS [113]

The data flows in the P2P energy trading platform is modelled as follows:

Application 1: Listing items / placing orders

The minimum components and sizes of the original data from each peer to the server of the trading platform is shown in Table 5.1.

Table 5.1. Minimum Components and Sizes of the Original Data for Listing Items / Placing Orders

Data	Size of Data
ID of Peer	6 bytes
ID of Target	6 bytes
Date	8 bytes
Time	8 bytes
Energy Amount	8 bytes
Energy Price	8 bytes
Total	**44 bytes**

The minimum sizes of the packets transmitted between the peers and the server for listing items/placing orders is displayed in Table 5.2.

Table 5.2. Minimum Sizes of the Packets for Listing Items / Placing Orders

Transport	IP Header Size	TCP Header Size	Data Size	Packet Size
SYN →	20	24	0	44
SYN – ACK ←	20	24	0	44
ACK →	20	20	0	40
Data (Request) →	20	20	44	84
Data (Response) ←	20	20	0	40
ACK →	20	20	0	40
FIN →	20	20	0	40
ACK ←	20	20	0	40
FIN ←	20	20	0	40
ACK →	20	20	0	40

The time interval of the application is once per 5 to 10 min during simulation time period 0min – 20 min, and then become as frequent as once per 0 to 2 min during simulation time period 20min – 30 min.

<u>Application 2: Browsing existing items</u>

The minimum size of the original data from the server to peers is calculated by

$$\text{Number of peers} \times 44 \tag{5.1}$$

The minimum sizes of the packets are further adjusted based on (5.1) and Table 5.2.

The time interval of the application is the same with Application 1.

As the existing GPRS Smart Metering network is also considered for the research, the background data flows in the Smart Metering network is modelled as follows:

Application 3: Meter readings collection

The minimum components and sizes of the original data from each peer (smart meter) to the server of the smart metering data centre is shown in Table 5.3.

Table 5.3. Minimum Components and Sizes of the Original Data for Meter Reading Collection

Data	**Size of Data**
ID of Meter	8 bytes
Time	16 bytes
Reading	8 bytes
Total	**32 bytes**

The minimum sizes of the packets transmitted between the peers (smart meters) and the server for meter reading collection is displayed in Table 5.4.

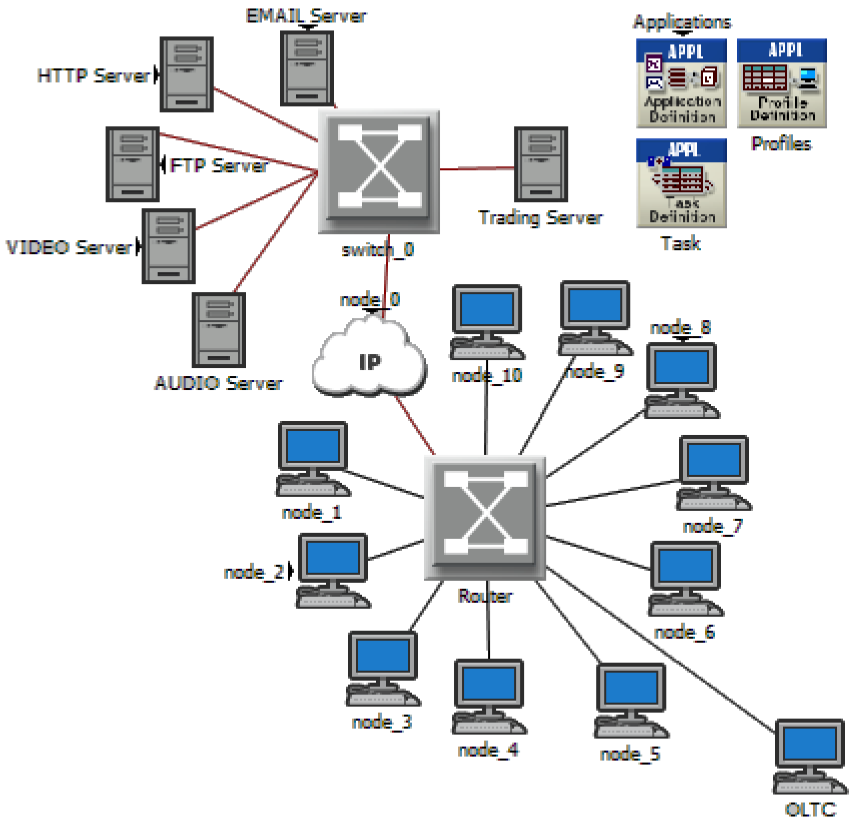
Table 5.4. Minimum Sizes of the Packets for Meter Reading Collection

Transport	IP Header Size	TCP Header Size	Data Size	Packet Size
SYN →	20	24	0	44
SYN – ACK ←	20	24	0	44
ACK →	20	20	0	40
Data (Request) →	20	20	0	40
Data (Response) ←	20	20	32	72
ACK →	20	20	0	40
FIN →	20	20	0	40
ACK ←	20	20	0	40
FIN ←	20	20	0	40
ACK →	20	20	0	40

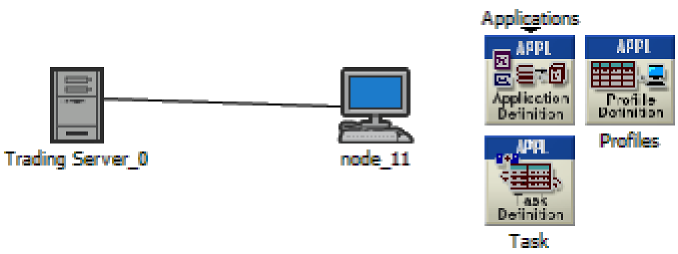
The time interval of the application is once per 30 min.

5.4 ICT infrastructures for the voltage control systems of LV Microgrids with P2P energy trading

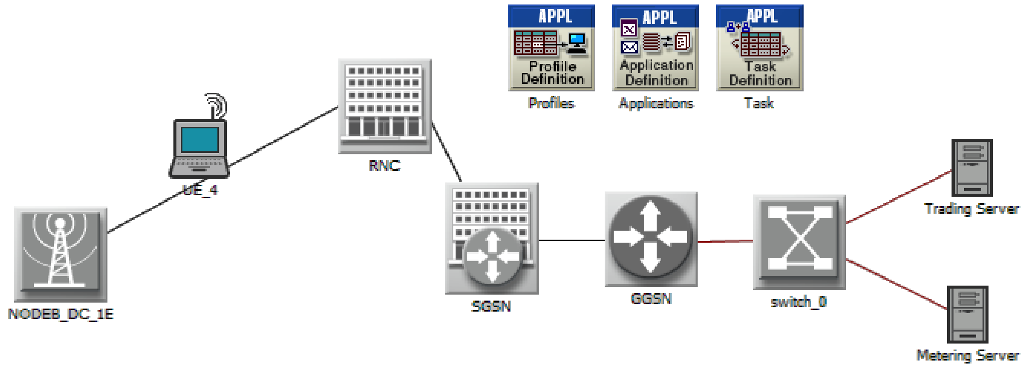
The network topologies of the communication networks integrated with the voltage control system are developed in OPNET, as demonstrated in Fig. 5.8.



(a) A wired broadband network integrated with the voltage control system



(b) A private wired network integrated with the voltage control system



(c) A private wireless network (GPRS) integrated with the voltage control system

Fig. 5.8. Examples of existing and private communication networks for integrating the voltage control system

The data flows in the voltage control system is modelled as follows:

Application: Sending voltage measurements:

The minimum components and sizes of the original data from the sensor at the monitoring bus to the controller of OLTC are shown in Table 5.5. The voltage measurements used for sampling here are considered to be the phase voltage.

Table 5.5. Minimum Components and Sizes of the Original Data for Sending Voltage Measurements

Data	Size of Data
Voltage Measurement	8 bytes
Total	**8 bytes**

The minimum sizes of the packets transmitted between the sensor at the monitoring bus and the controller of OLTC for the application are displayed in Table 5.6.

Table 5.6. Minimum Sizes of the Packets for Sending Voltage Measurements

Transport	IP Header Size	TCP Header Size	Data Size	Packet Size
SYN →	20	24	0	44
SYN – ACK ←	20	24	0	44
ACK →	20	20	0	40
Data (Request) →	20	20	8	48
ACK ←	20	20	0	40
FIN →	20	20	0	40
ACK ←	20	20	0	40
FIN ←	20	20	0	40
ACK →	20	20	0	40

The time interval of the application is variable from once per 1 sec to once per 1 min.

5.5 Case Study

To investigate the feasibility of integrating the P2P energy trading platform and the voltage control system to existing or private communication networks, the following case studies were carried out. Explanations of the summary of simulation results were attached in Appendix I.

5.5.1 ICT infrastructures for the P2P energy trading platform

The case studies in this section are developed based on the network topologies shown in Fig. 5.6. The processing time within the Trading Server was not considered here.

<u>Case Study 1: Different Amount of Background Traffic for Wired Broadband Networks</u>

There are three models with different amount of background traffic developed as shown in Table 5.7. The application models mentioned in the table (e.g. High HTTP, High FTP, etc.) are all default models defined in OPNET

Table 5.7. Scenarios of Case Study 1

Background Traffic Scenarios	**Scenario Settings**
High Traffic	All peers: High HTTP; High FTP; High Email; High Quality Video; High Quality Audio;
Medium Traffic	All peers: Medium HTTP; Medium FTP; Medium Email; Low Quality Video; Low Quality Audio;
Low Traffic	All peers: Low HTTP; Low FTP; Low Email; No Video; No Audio;

The network topology is as shown in Fig. 5.6 (a).

The simulation results are summarised in Table 5.8.

Table 5.8. Simulation Results of Case Study 1

Background Traffic	Applications Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Placing Orders" Applications (s)	Maximum Latency of "Browsing" Applications (s)
High	100%	0.36	0.61	0.63
Medium	100%	0.31	0.57	0.57
Low	100%	0.000058	0.00012	0.00013

It is concluded that with the increase of background traffic, the maximum latency increases. The application successful rates of the three scenarios are all 100%. The maximum latencies of the trading applications with high background traffic are still lower than 1 sec, which is not considered to have any negative impact on the P2P trading platform. That is to say, the wired broadband network is sufficient for integrating the P2P energy trading platform even when the amount of background traffic is high.

Case Study 2: Multiple / Single Server(s) for Wired Broadband Networks

There are two models developed as shown in Table 5.9.

Table 5.9. Scenarios of Case Study 2

No. of Server(s) Scenarios	Scenario Settings
6	1 HTTP Server, 1 FTP Server, 1 Email Server, 1 Video Server, 1 Audio Server, and 1 "Trading" Server; high traffic of peers
1	1 "All-in-One" Server; high traffic of peers

The network topology of the model with single server is as illustrated in Fig. 5.9.

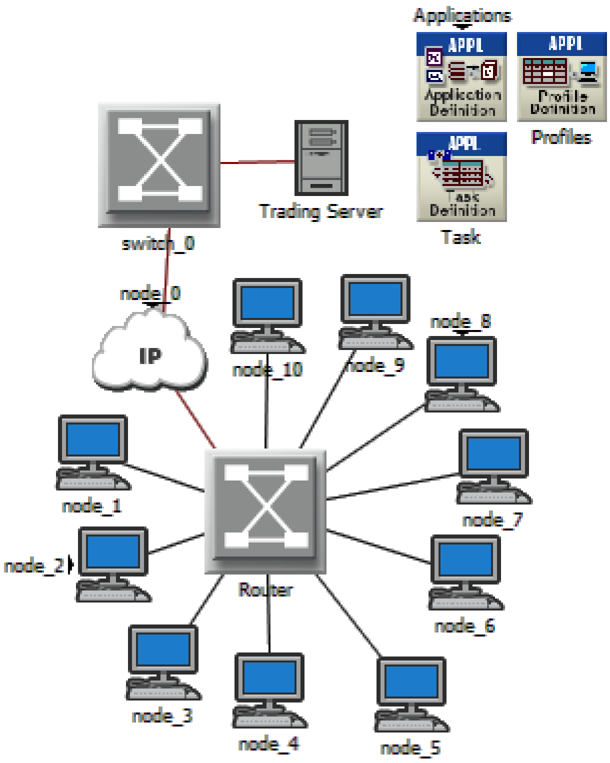


Fig. 5.9. A wired broadband network with single server

The simulation results are summarised in Table 5.10.

Table 5.10. Simulation Results of Case Study 2

No. of Server(s)	Applications Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Placing Orders" Applications (s)	Maximum Latency of "Browsing" Applications (s)
6	100%	0.36	0.61	0.63
1	100%	0.42	0.68	0.78

It is concluded that with the decrease number of servers, the maximum latency of P2P trading applications increases. The application successful rate are both 100% in the two scenarios. That is to say the wired broadband network is sufficient for integrating the P2P energy trading platform even when the number of servers is limited.

Case Study 3: Different Amount of Peers for Wired Broadband Networks

There are 20 models with different amount of peers developed as shown in Table 5.11. The number of routers used in the scenarios increases as the total number of peers increase.

Table 5.11. Scenarios of Case Study 3

No. of Peers	Scenario Settings
10; 20	1 Router; high traffic of peers
30; 40; 50	2 Routers; high traffic of peers
60; 70	3 Routers; high traffic of peers
80; 90; 100	4 Routers; high traffic of peers

No. of Peers	Scenario Settings
110; 120	5 Routers; high traffic of peers
130; 140; 150	6 Routers; high traffic of peers
160; 170	7 Routers; high traffic of peers
180; 190; 200	8 Routers; high traffic of peers

The simulation results are summarised in Table 5.12.

Table 5.12 Simulation Results of Case Study 3

No. of Peers	Application Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Placing Orders" Application	Maximum Latency of "Browsing" Application
10	100%	0.36	0.61	0.63
50	100%	0.37	0.61	0.69
100	100%	0.42	0.62	0.77
150	100%	0.43	0.65	0.86
200	100%	0.49	0.67	0.91

It is concluded that with the increase number of peers, the maximum latency increases. The highest latency of the P2P energy trading application in the network with 200 peers is still lower than 1 sec. The application successful rates remain 100% in all of the scenarios. That is to say the wired broadband network is sufficient for integrating the P2P trading platform even when the number of peers is high.

Case Study 4: Different Data Rate of Transmission Links for Wired Broadband Networks

There are 6 models with different transmission link data rates between peers and their routers developed in this case study. The background traffic is "high traffic" as defined in Table 5.7. The 200-peer topology network is used as defined in Table 5.11 and shown in Fig. 5.10.

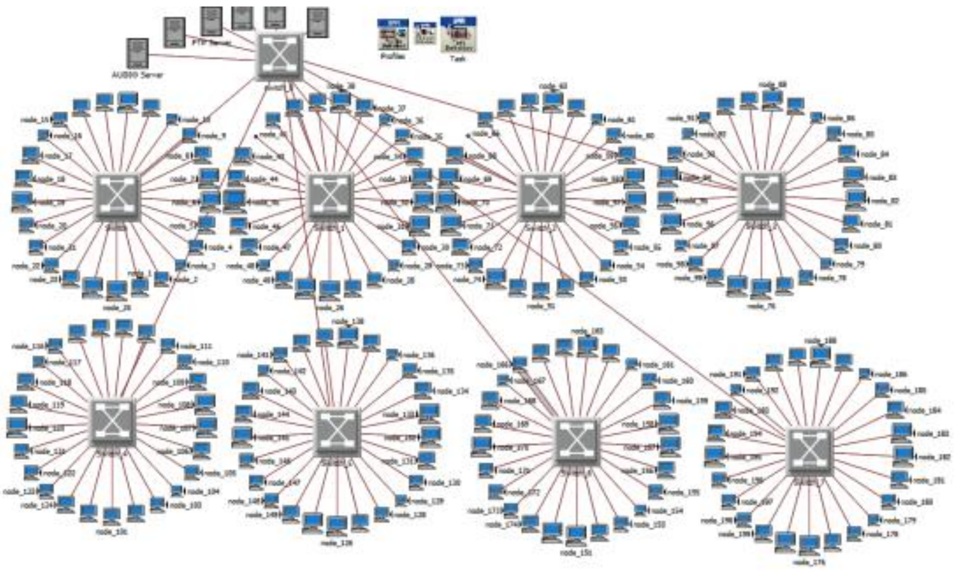


Fig. 5.10. A wired broadband network with 200 peers

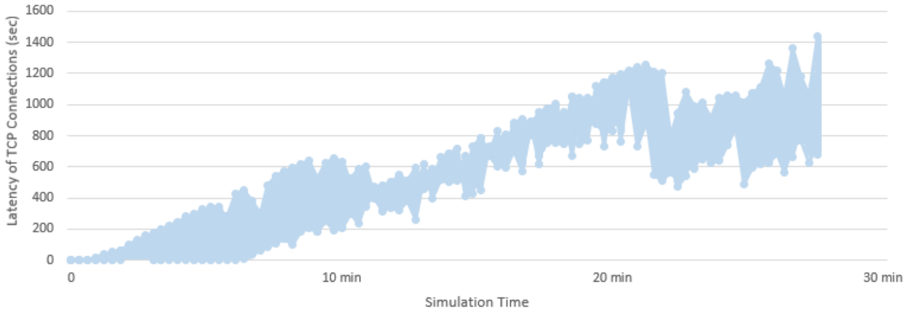
The simulation results are summarised in Table 5.13 and Fig. 5.11.

Table 5.13 Simulation Results of Case Study 4

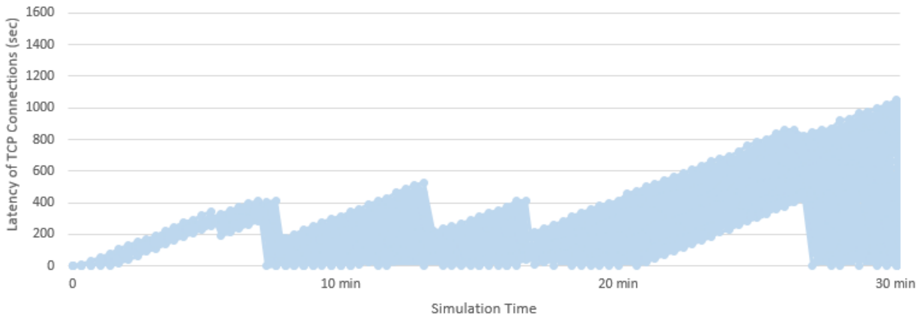
Data Rate of Transmission Links	Applications Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Placing Orders" Applications (s)	Maximum Latency of "Browsing" Applications (s)
1 kbps	0.10%	8.63	15.51 (Successful);20 (Failed)	20 (Failed)
10 kbps	0.40%	482.05	3.87 (Successful); 20 (Failed)	19.20 (Successful); 20 (Failed)
100 kbps	88.00%	1421.63	9.21	18.74 (Successful); 20 (Failed)
1 Mbps	100.00%	1078.82	2.97	3.27
10 Mbps	100.00%	45.21	0.89	1.06
100 Mbps	100.00%	0.36	0.61	0.63

It is concluded that the data rate of the communication link between peers and routers has a significant impact on the performance of the P2P energy trading platform. When the data rates is lower than 1Mbps, the P2P trading application successful rate is lower than 100%, which is considered as infeasible to support the platform. However, when the data rate is higher than 1Mbps, the application successful rate becomes 100%, and the maximum latencies of the applications keep decreasing while the data rate increases

It can be noticed that in scenarios where the application successful rates are lower than 100%, the maximum latency of TCP connection increases while the data rate increases. This is because the latency of the failed TCP connections is not recorded by OPNET, and therefore cannot be shown in Table 5.13. To illustrate this, two figures in Fig. 5.11 are provided.



(a)Latency of TCP Connections of All Peers (Connection Link Data Rate: 100 kbps)



(b) Latency of TCP Connections of All Peers (Connection Link Data Rate: 1 Mbps)

Fig. 5.11. Simulation Results of Case Study 4 for data rates 100 kbps and 1 Mbps

In Fig. 5.11 (a), between time period 28min-30min, there are no TCP connection latency results collected because all of those TCP connections have failed during that time period. While in Fig. 5.11 (b), the results are different. All of the TCP connection latency results are recorded.

Case Study 5: Different Amount of Peers for GPRS Smart Metering networks

There are 20 models with different number of peers developed for this case study, and their network topologies are defined in a similar way as shown in Table 5.11. The routers used in the wired broadband networks are replaced with base station here. The background traffic here is only the “meter reading collection” application defined in Table 5.3 and Table 5.4.

The simulation results are summarised in Table 5.14.

Table 5.14. Simulation Results of Case Study 5

No. of Peers	Application Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of “Placing Orders” Application	Maximum Latency of “Browsing” Application
10	100%	1.78	3.27	3.40
50	100%	1.82	3.33	3.52
100	100%	1.92	3.35	3.61
150	100%	1.97	3.39	3.75
200	100%	2.05	3.40	3.92

It is concluded that with the increase number of peers, the maximum latency increases. The highest latency of the P2P energy trading application in the network with 200 peers is lower than 4 sec, which is not very high considering the network is based on GPRS. The application successful rates remain 100% in all of the scenarios. That is to say the GPRS Smart Metering network with light traffic is sufficient for integrating the P2P trading platform even when the number of peers is high.

Case Study 6: Different Background Traffic for GPRS Smart Metering networks

“Meter reading collection” is the most essential application in the GPRS Smart Metering networks. However, it should not be the only one considering the rapid implementation and development of Smart Metering technology. There are expected to be the occasions when there are data flow congestions in the GPRS Smart Metering networks.

There are two scenarios defined in this case study, as demonstrated in Table 5.15.

Table 5.15. Scenarios of Case Study 6

Background Traffic Scenarios	**Scenario Settings**
High Traffic	Software Update and Smart Metering; 200 peers
Normal Traffic	Smart Metering Only; 200 peers

The information exchange for the application “Software Update” is as defined in Table 5.16.:

Table 5.16. Minimum Components and Sizes of the Original Data for “Software Update”

Data	**Size of Data**
Software Update	1 Mb
Total	**1 Mb**

The repeat times of application is only once.

The network topology of the models is developed in OPNET as illustrated in Fig. 5.12.

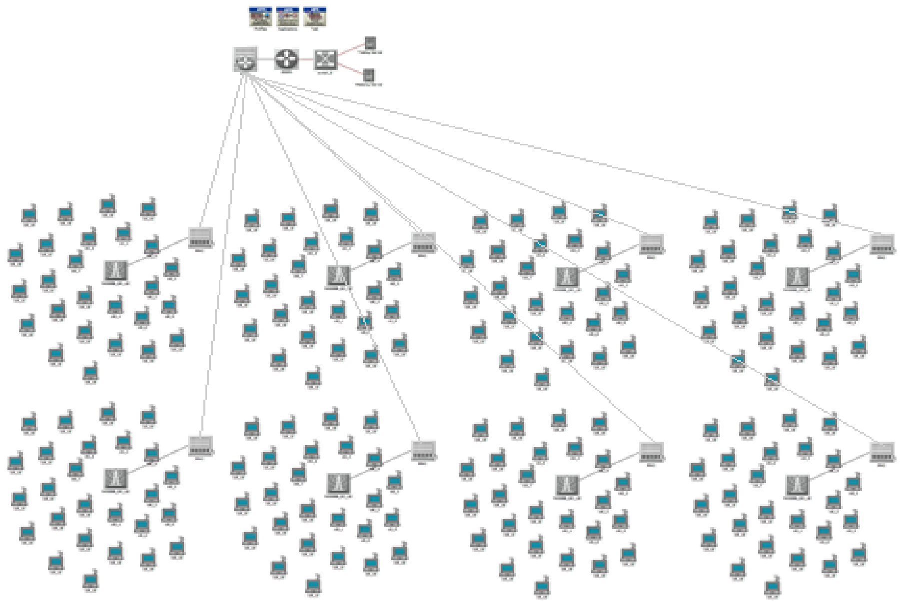


Fig. 5.12. A GPRS Smart Metering network with 200 peers

The simulation results are summarised in Table 5.17.

Table 5.17. Simulation Results of Case Study 6

Background Traffic	Applications Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Placing Orders" Applications (s)	Maximum Latency of "Browsing" Applications (s)
High Traffic	8.10%	761.07	14.14 (Successful);20 (Failed)	18.74 (Successful);20 (Failed)
Normal Traffic	100.00%	2.05	3.40	3.92

The results demonstrates that then the background traffic volume in the GPRS Smart Metering network is high, the successful rate of the P2P trading applications decreases significantly. The maximum latencies of the TCP connections and the P2P trading applications are also much higher than the reference scenario.

It is concluded that the GPRS Smart Metering networks are not sufficient for integrating the P2P energy trading platform when the background traffic volume in the network is high.

5.5.2 ICT infrastructures for the control systems

The case studies in this section are developed based on the network topologies shown in Fig. 5.8.

Case Study 7: Different Time Intervals of Application for Wired Broadband Networks

There are six models with different time intervals of the application “sending voltage measurements”. The network topology of the models is as defined in Fig. 5.8 (a), and the background traffic of the wired broadband network is the same with the “high traffic” scenarios defined in Table 5.7.

The simulation results are summarised in Table 5.18.

Table 5.18. Simulation Results of Case Study 7

Time Interval of Application	Application Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of “Sending measurements” Applications
1s	100%	0.000068	0.000068
5s	100%	0.000063	0.000063
10s	100%	0.000062	0.000062
15s	100%	0.000060	0.000060
30s	100%	0.000060	0.000060
1min	100%	0.000060	0.000060

It is concluded that with the increase of the time interval between two continuous applications “sending voltage measurements”, the maximum latency of the application decreases very slightly. In all the scenarios, the application successful rates are all 100%, and the maximum latencies of the application are all very low. That is to say, the time interval doesn’t have an impact on the performance of the voltage control system.

Case Study 8: Different Data Rates of Transmission Links for Wired Broadband Networks

There are 6 models with different transmission link data rates between the sensor at the monitoring bus and the controller of OLTC developed in this case study. The network topology of the models is as defined in Fig. 5.8 (a), and the background traffic is "high traffic" as defined in Table 5.7. The time interval of the application "sending voltage measurements" is 1 sec.

The simulation results are summarised in Table 5.19.

Table 5.19. Simulation Results of Case Study 8

Data Rate of Transmission Links	Application Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Sending measurements" Applications
1 kbps	100%	1.37	1.37
10 kbps	100%	0.135	0.135
100 kbps	100%	0.0134	0.0134
1 Mbps	100%	0.00143	0.00143
10 Mbps	100%	0.00024	0.00024
100 Mbps	100%	0.000068	0.000068

It is concluded that with the increase of the data rate of transmission links, the maximum latency decreases. However, because the amount of data transmitted between the sensor and the OLTC controller is very small, the application successful rate is not affected. This is different compared to the case studies for the P2P trading platform.

<u>Case Study 9: Comparison of Existing and Private Networks</u>

In private wired / wireless networks, there is no background traffic. Besides, the number of routers and servers in the network is also smaller than that in existing networks.

There are two new models developed for this case study. The network topologies of the networks are as illustrated in Fig. 5.8 (b) and (c). The time interval of the application "sending voltage measurements" is still 1 sec.

The simulation results are summarised in Table 5.20.

Table 5.20. Simulation Results of Case Study 9

Network	Application Successful Rate	Maximum Latency of TCP Connections (s)	Maximum Latency of "Sending measurements" Applications
Wired Broadband	100%	0.000068	0.000068
Private Wired	100%	0.000068	0.000068
Private GPRS	100%	1.67	1.67

It is concluded that the private wired network has better performances compared with the private GPRS network. However, compared to the wired broadband network, the improvement by implementing a private wired network is not significant and can even be neglected. That is to say, it is not very necessary to invest on a private wired network.

However, private networks have their own advantages. There is no background traffic and other unnecessary equipment deployed in the private networks, which make the networks more secure and reliable especially when cyber security is concerned.

5.6 Conclusions

The ICT infrastructures for the P2P energy trading platform and the voltage control system proposed in previous chapters were developed. The TCP/IP-based information exchange for the two systems was modelled based on the OSI and TCP/IP network model. Various network topologies for the two systems were modelled in OPNET.

Six case studies were carried out for the ICT infrastructures of the P2P energy trading platform. Different amount of background traffic, number of servers, amount of peers and data rates of transmission links were tested based on the existing wired broadband networks. Different number of peers and amount of background traffic were tested based on the existing GPRS Smart Metering networks. Simulation results illustrated that both the existing wired broadband network and the existing GPRS Smart Metering network with normal amount of background traffic were sufficient to support the P2P energy trading platform. However, there were still a number of limitations. First of all, in the wired broadband networks, the data rate of the transmission links had to be higher than 1Mbps in order to guarantee the performance. Secondly, in the GPRS Smart Metering network, during the peak traffic time periods (software update, etc.), the performance of the P2P energy trading platform was significantly affected.

Three case studies were carried out for the ICT infrastructures of the voltage control system. Different time intervals between two continuous applications ("sending voltage measurements"), data rates of transmission links and types of private network were tested. Simulation results demonstrated that the existing wired broadband network is sufficient to support the voltage control system. The data rate of transmission links has an impact on the latency of the control system. The private wired network provides a much better performance compared to the private GPRS network. When reliability and cyber security is concerned, private networks are better options.

Chapter 6

Conclusions

The conclusions drawn from the research work in previous chapters are summarised. Contributions of the thesis are outlined. Possible future work is suggested. Publications are listed.

6.1 Conclusions

P2P energy trading is one of the promising paradigms of future smart grid, which enables the direct energy trading among energy consumers and prosumers in local distribution networks. A four-layer system architecture of P2P energy trading was proposed to identify and categorize the key elements and technologies involved in P2P energy trading. A P2P energy trading platform “Elecbay” was designed for a grid-connected LV Microgrid. A voltage control system was developed in order to facilitate P2P energy trading platform “Elecbay” in the distribution network. The necessary ICT infrastructures for the P2P trading platform and the voltage control system were investigated.

The thesis also demonstrated the possibilities and potential benefits of integrating P2P energy trading in local distribution networks from the technical perspectives. The P2P energy trading arrangements was able to balance local generation and consumption. The proposed voltage control system was proved to require a smaller amount of tap actions at the OLTC transformer after facilitating the P2P trading platform. The existing ICT infrastructures (e.g. wired broadband networks, GPRS Smart Metering networks, etc.) were sufficient for supporting both the P2P energy trading platform and the voltage control system, which meant that no large amount of additional investments were required in order to facilitate P2P energy trading in the distribution networks.

6.1.1 Design of a P2P Energy Trading Platform

A P2P energy trading platform “Elecbay” was designed for a grid-connected LV Microgrid. The simulation of P2P bidding among energy consumers and prosumers through the energy trading platform “Elecbay” was developed using game theory.

Case studies were carried out based on the EU benchmark Microgird. In the base case, the peers with P2P energy sharing had very different load schedules from each other, and from the ones in the reference case without P2P energy sharing, resulting in 9.19% reduction in energy exchange with the utility grid and 4.41% reduction in peak power. This result showed that P2P energy trading was able to reduce the energy exchange between the Microgrid and the utility grid and balance local generation and demand, and therefore, had the potential to facilitate a large penetration of renewable energy resources in the power grid. In a further case with higher peer variety, the reduction in energy exchange and peak power increase significantly to 42.49% and 17.60% respectively. This result demonstrated that the increased diversity of energy consumers and prosumers in the Microgrid was able to further improve the benefits of P2P energy trading.

6.1.2 Control of a LV Microgrid with Peer-to-Peer Energy Trading

Two necessary control systems for implementing the P2P energy trading platform “Elecbay” in the distribution networks were proposed – the bid acceptance/rejection system and the voltage control system. The voltage control system was further developed in details. Droop control and OLTC control were used in the voltage control system.

A case study was carried out on the basis of the case studies in Chapter 3. The proposed voltage control system was tested on the benchmark LV grid-connected Microgrid. Two scenarios were developed with or without P2P energy trading separately. Simulation results illustrated that the voltage at the monitoring bus and other major buses were all regulated into the voltage tolerance range with P2P energy trading, proving that the proposed voltage control system was sufficient for supporting the P2P energy trading platform “Elecbay”. Moreover, the total number of tap actions was reduced from 8 times to 2 times in the scenario with P2P energy trading, showing that P2P energy trading contributed to the reduced number of operation times of the OLTC, which benefited the operation life of the transformer.

6.1.3 ICT Infrastructures for Peer-to-Peer Energy Trading

The ICT infrastructures for the P2P energy trading platform and the voltage control system proposed in previous chapters was developed. The TCP/IP-based information exchange for the two systems was modelled based on the OSI and TCP/IP network model. Various network topologies for the two systems were modelled in OPNET.

A series of case studies were carried out for the ICT infrastructures of the P2P energy trading platform. Four cases with different amount of background traffic, number of servers, number of peers and data rates of transmission links were tested based on the existing wired broadband networks. Simulation results illustrated that for the P2P energy trading platform, the application successful rates were mostly 100% for wired broadband networks apart from the scenarios in which the data rate of the connection was low. Also, the latency of TCP connections and P2P energy trading applications were all relatively low for wired broadband networks unless the data rate of the connection was too low.

Two cases with different number of peers and amount of background traffic were tested based on the existing GPRS Smart Metering networks. Simulation results showed that the application successful rates were mostly 100% for GPRS Smart Metering networks apart from the scenarios in which the traffic in the network was high. Moreover, the latency of TCP connections and P2P energy trading applications were acceptable unless the traffic in the network was high.

From the above results it is concluded that both the existing wired broadband network and the existing GPRS Smart Metering network with normal amount of background traffic were sufficient to support the P2P energy trading platform. In spite of this, there were still a number of limitations. First of all, in the wired broadband networks, the data rate of the transmission links had to be higher than 1Mbps in order to guarantee the performance. Secondly, in the GPRS Smart Metering network, during the peak traffic time periods (software update, etc.), the performance of the P2P energy trading platform was significantly affected.

Three case studies were carried out for assessing the ICT infrastructures of the voltage control system. Different time intervals between two continuous applications ("sending voltage measurements"), data rates of transmission links, and types of private network were tested. Simulation results demonstrated that the application successful rates were all 100% and the latency of TCP connections and the "Sending measurements" application was all low, for the wired broadband networks, the private wired networks and the private GPRS networks. In conclusion, existing wired broadband network was sufficient to support the voltage control system so that no additional investment on ICT infrastructures was needed. When cyber security was concerned, private networks were a good option.

6.2 Contributions of the thesis

The contributions of the thesis are listed:

(a) A four-layer system architecture of P2P energy trading was proposed.

The system architecture was proposed in order to categorise the key elements and technologies involved in P2P energy trading based on the roles they play. It was developed based on the Smart Grid Architecture Model proposed by the European Standardization. It contained three dimensions. The research reported in this thesis was carried out on the basis of it.

(b) A P2P energy trading platform "Elecbay" was designed.

A P2P energy trading platform was a software platform, which enables the information exchange among peers, and also assists the system regulators (e.g. DSOs) to monitor and control the distribution network with P2P energy trading. “Elecbay” was proposed as one of the platforms. Its design was inspired by the concept of “sharing economy” and the current trading arrangements in the GB electricity wholesale market.

(c) The P2P bidding among peers was modelled using game theory.

The simulation process was illustrated in details in this thesis. The P2P bidding was formulated as a non-cooperative game. The most possible bidding results were found by calculating the Nash equilibrium of the non-cooperative game. Simulation results demonstrated that P2P energy trading was able to balance local generation and consumption, and therefore had the potential to facilitate a large penetration of renewable energy resources in the power grid.

(d) A voltage control system was proposed and developed for facilitating P2P energy trading in distribution networks.

Droop control and OLTC control were used in the voltage control system. The methods of determining the key characteristics for the control mechanisms were illustrated in details. Simulation results showed that the proposed voltage control system was sufficient for facilitating P2P energy trading in the distribution networks. The total number of tap actions of the OLTC was reduced after implementing P2P energy trading.

(e) ICT infrastructures for both the P2P energy trading platform and the voltage control system were studied and modelled.

The information exchange for the two systems was modelled using TCP/IP protocol. The network topologies of both existing and private networks were developed in OPNET. Simulation results illustrated that the existing ICT infrastructures (wired broadband networks and GPRS Smart Metering networks) were sufficient for supporting both the P2P energy trading platform and the voltage control system. No large amount of additional investments were required in order to facilitate P2P energy trading.

6.3 Future work

The following future work is proposed:

(a) Use of energy storage in the simulation of P2P bidding

In this study, energy storage was not considered for the simulation of P2P bidding. However, it is able to provide significant amount of flexibility for P2P energy trading in practice. The main concern is that some of the prosumers may become able to take advantage of the P2P energy trading arrangements in order to maximise their own profits by scheduling their energy storage in a way that does harm to the balance of local generation and consumption. This situation needs to be addressed when energy storage is added to the current simulation.

(b) Development of the bid acceptance/rejection system

The bid acceptance/rejection system was proposed to operate after the gate closure and before the start of energy exchanging time period in this research. However, it has not been developed in details. A potential design was mentioned, which was to use the last on first off principle. It will be a strong support to the study in this area if the system can be developed and tested in some critical scenarios.

(c) Development of mechanisms to deal with the inaccurate generation prediction of RESs

In practice, RESs are considered to be intermittent and very difficult to predict. Both the trading platform and the control systems proposed in this study can be improved by adding additional mechanisms to deal with the situation when the generation prediction of RESs is inaccurate. The methods used in the GB electricity wholesale market can be considered, such as bid-offer pairs, contingency balancing reserve, demand control, etc.

(d) Further development of the proposed voltage control system

A voltage control system with droop control and OLTC control has been developed in Chapter 4, and it has been proved to be sufficient for supporting P2P energy trading. However, the voltage control system is able to be further improved with additional control targets. For example, by controlling the reactive power generation and consumption, the power loss in the Microgrid is able to be minimised. By coordinating the droop control and OLTC control, the total number of tap-changing actions is able to be further reduced. All of those potential control mechanisms are able to be introduced to and tested in the voltage control system for P2P energy trading. Moreover, their benefits to DSOs in scenarios with P2P energy trading can be further discussed.

6.4 Publications

1. C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-Peer Energy Trading in a Microgrid", Applied Energy. (Under Review)

2. C. Zhang, J. Wu, M. Cheng, Y. Zhou, and C. Long, "A Bidding System for Peer-to-Peer Energy Trading in a Grid-connected Microgrid", Energy Procedia, Vol. 103, December 2016, pp. 147-152. (Applied Energy Symposium and Forum: REM2016, Maldives.)

3. C. Zhang, J. Wu, C. Long, and M. Cheng, "Review of Existing Peer-to-Peer Energy Trading Projects", Energy Procedia, Vol. 105, 2017, pp. 2563-2568. (8th International Conference on Applied Energy, ICAE 2016, Beijing.)

4. S. Sahoo, C. Zhang, D. Pullaguram, S. Mishra, J. Wu, and N. Senroy, “Investigation of Distributed Cooperative Control for DC Microgrids in Different Communication Medium”, 9th International Conference on Applied Energy, ICAE 2017, Cardiff.

5. C. Long, J. Wu, C. Zhang, M. Cheng, and A. Al-Wakeel, “Feasibility of Peer-to-Peer Energy Trading in Low Voltage Electrical Distribution Networks”, Energy Procedia, Vol. 105, 2017, pp. 2227-2232. (8th International Conference on Applied Energy, ICAE 2016, Beijing.)

6. Y. Zhou, J. Wu, C. Long, M. Cheng and C. Zhang “Performance Evaluation of Peer-to-Peer Energy Sharing Models”, World Engineers Summit 2017, WES-CUE 2017, Singapore.

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Appendix I Summary of simulation results for cases studies in Chapter 5

OPNET was used for the simulation in Chapter 5. OPNET is a powerful event-based simulation tool. The result tables displayed in the case studies were not achieved directly after the simulation, but required a lot of manual work. In this sections, an example has been provided in order to demonstrate the process.

In Case Study 4 (pp. 115), 6 models of 200-peer wired broadband network with different transmission link data rates between peers and their routers were developed for the P2P bidding platform. According to the simulation results, significant difference of the network performance was discovered when the data rate rose from 100kbps to 1Mbps. Fig. 5.11 was used to illustrate the difference of those two models.

During the simulation, there were results achieved from all of the 200 peers, servers, routers, etc. Fig. I.1 and Fig. I.2 showed the Latency of Application “Listing Items / Placing Orders” at Peer 1 in the two models (100kbps and 1Mbps). Fig. I.3 and Fig. I.4 showed the Latency of TCP connections at Peer 1 in the two models.

It was concluded that the latencies of P2P bidding applications and TCP connections in the 100kbps model were both much higher than that in the 1Mbps model. This also happened at most other peers. Maximum values of the latencies were found after the results from all peers were reviewed. Application successful rates were also calculated manually based on those simulation results and figures. The summarized results were able to be finally demonstrated in Table 5.13.

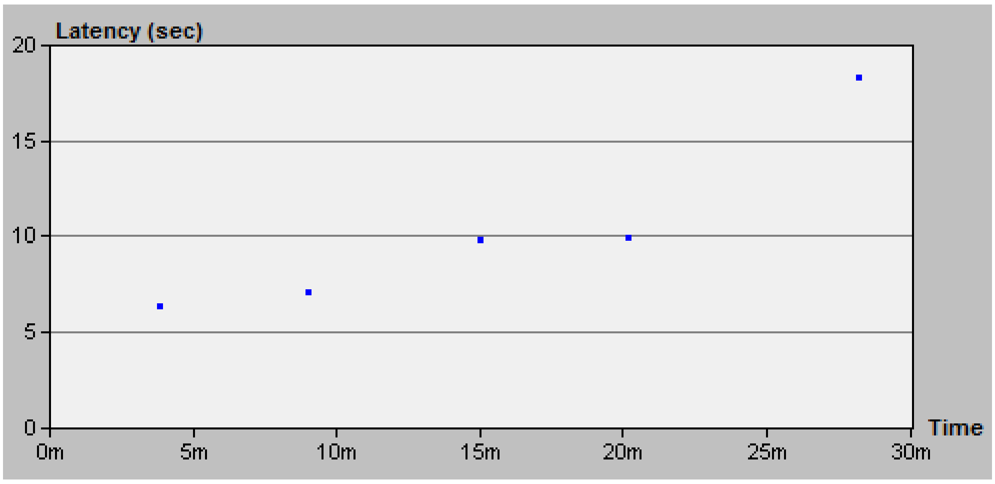

Fig. I.1. Latency of Application “Listing Items / Placing Orders” at Peer 1 (100kbps Data Rate Model)

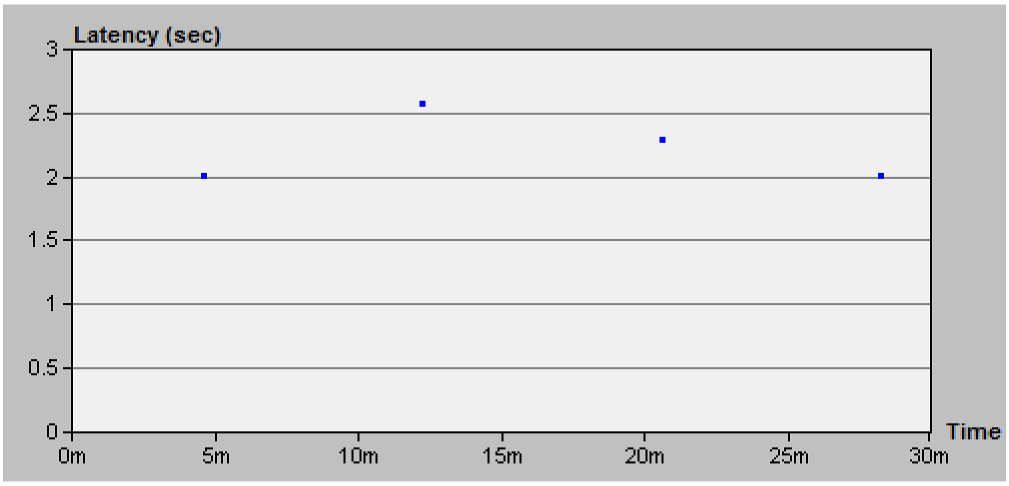

Fig. I.2. Latency of Application “Listing Items / Placing Orders” at Peer 1 (1Mbps Data Rate Model)

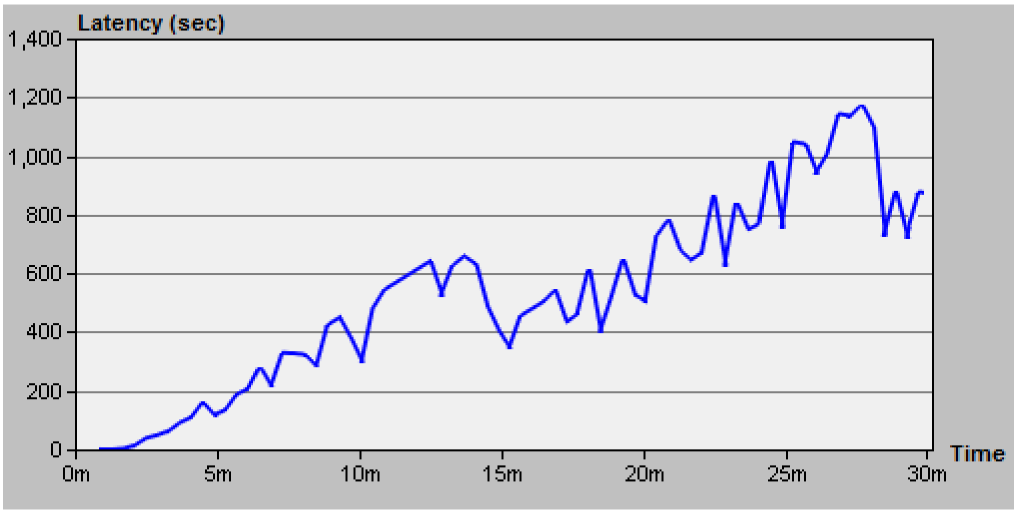

Fig. I.3. Latency of TCP Connections at Peer 1 (100kbps Data Rate Model)

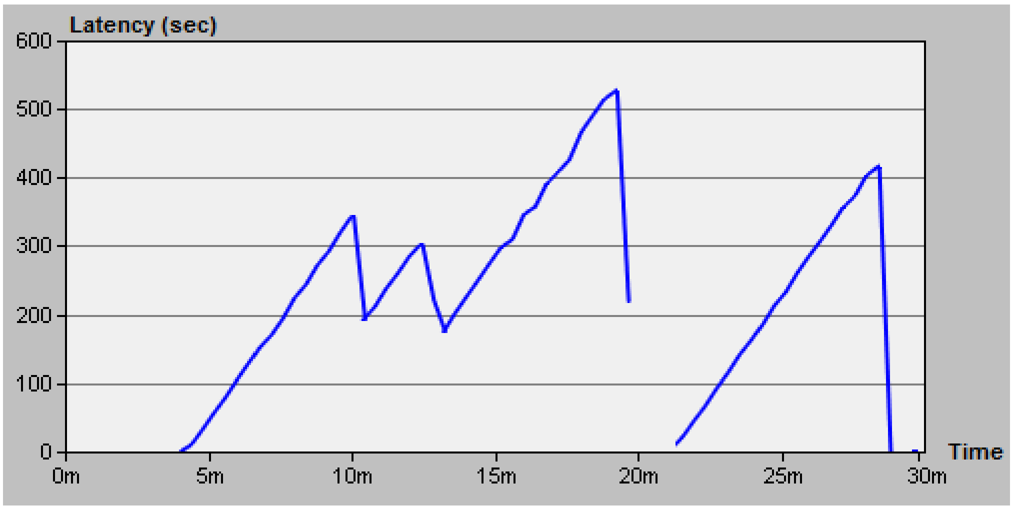

Fig. I.4. Latency of TCP Connections at Peer 1 (1Mbps Data Rate Model)

Because the full results were too many and not possible to be displayed in full, the summary tables were used. Similar methods were used for processing the simulation results achieved from all of the case studies illustrated in Chapter 5.