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Electric losses balancing through integrated storage and power electronics towards increased synergy between railways and electricity distribution networks

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Terms and Abbreviation

DG	Distributed Generation
EV	Electric Vehicle
EU	European Commission
LV	Low Voltage
PV	Photo voltaic
RES	Renewable Energy systems
SOP	Soft open point

1 Introduction

The E-LOBSTER project aims in developing an innovative, economically viable and easily replicable electric transport-Grid interconnection system that will establish synergies between power distribution networks, electrified transport networks and charging stations for EVs.

European distribution networks and light-railway networks have been developed as independent networks, relying on the resilience and robustness of existing power supplies. However, with the increased use of renewable energy systems (RES) there are new challenges that need to be addressed. There is now a need for integrated solutions that will reduce electricity losses, increase grid stability in areas of high local RES penetration and accommodate the needs of EVs, local electrical storage and prosumers.

The losses in the distribution systems in the EU member states range from 1% to 13.5%[1] and are shown in Figure 1-1.

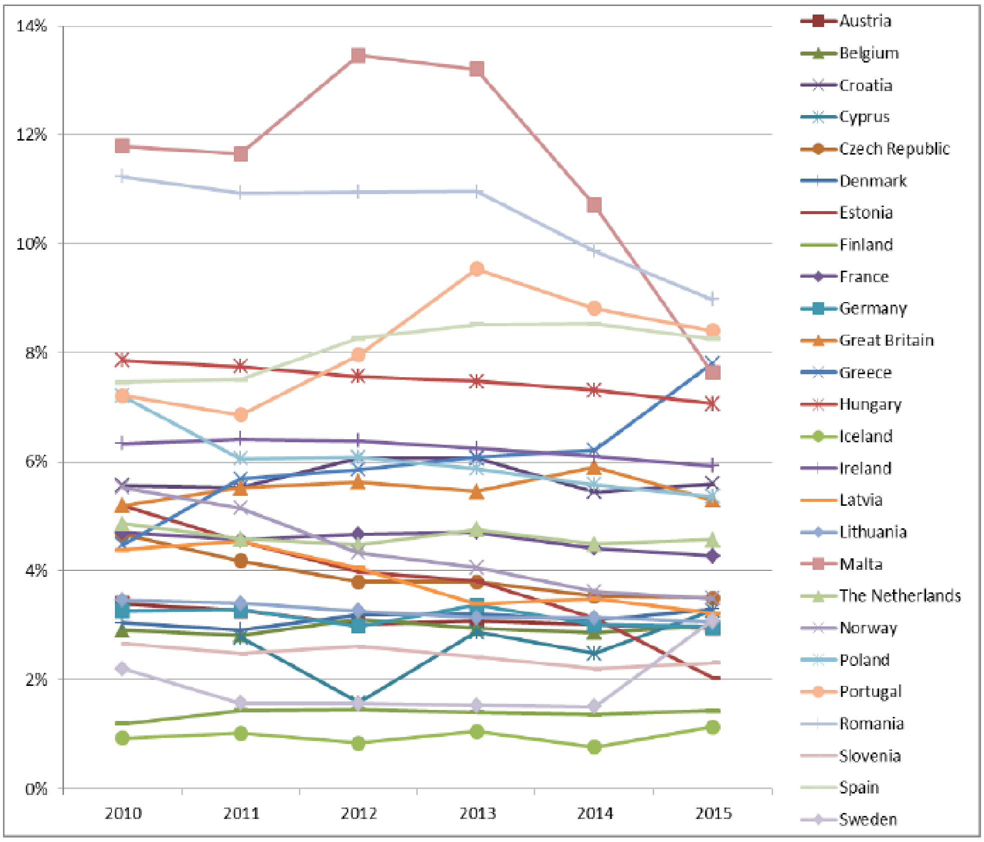

Figure 1-1: Loss in Distribution network of the EU member states as percentage of total injected energy[1]

The objective of E-LOBSTER task T1.2 is to investigate the connection of storage and RES, e.g. photovoltaics, and a dispatchable EV charging facility at the SOP to analyse numerically the possibilities of reducing power losses within the power distribution grid. This report analyses the losses on the distribution and the transported networks and the impacts due to the connection of distributed generation (DG) technologies.

[1] CEER Report on Power Losses, Ref: C17-EQS-80-03

The report further presents simulation results of power flow analysis in a typical metro electrical network.

In particular, chapter 2 provides an overview of general architecture of distribution networks.

Chapter 3 deals with strategies to mitigate energy losses in distribution network.

Chapter 4 presents the general architecture of railway power supply systems whereas chapter 5 illustrated energy efficiency solutions for railway networks and power flow analyses through simulations by using real data from a typical metro electrical network.

The conclusions are reported in chapter 6.

2 General architecture of distribution networks & future roadmaps

Electrical power systems usually share a common architecture illustrated in Figure 2-1. The transmission grid has typically a national scale and is the “backbone” of the electrical systems. Its design and operation are oriented to bulk distribution of the energy; it is usually a meshed grid in which the highest obtainable voltages are typically used. The distribution grid has normally a regional or local scale. Its design and operation are oriented to detail distribution of the energy; it is usually a radially operated grid, using lower voltages and reaching final customers.

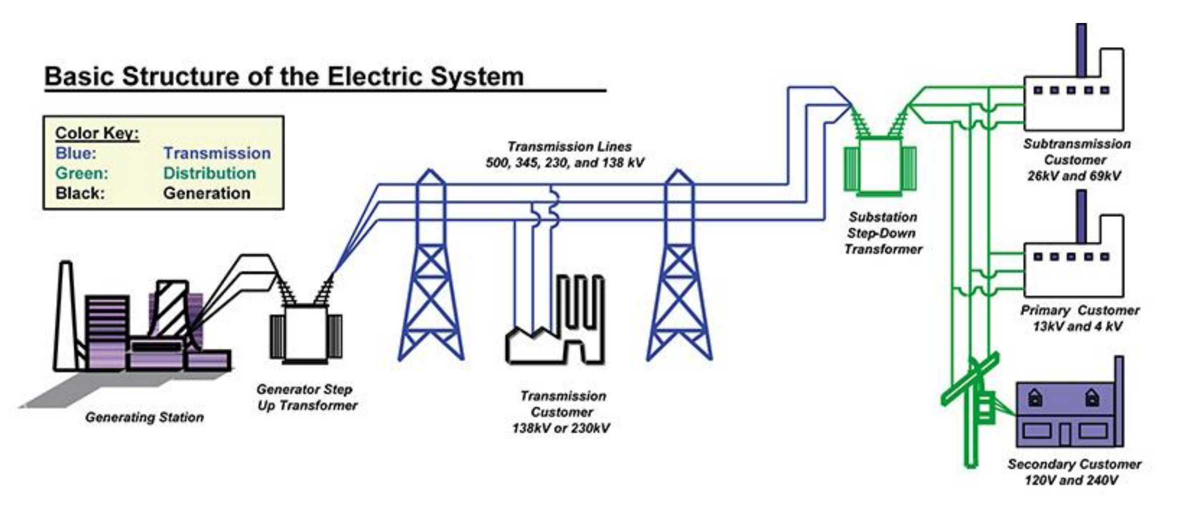

Figure 2-1:General architecture of electrical power systems

Typical voltage levels of the distribution system are 132 kV, 33 kV, 11 kV and 400/230 V networks. From the losses point of view, the bulk of the power losses occur in the 11 kV and 400/230 V LV networks. A typical voltage levels in power systems and a typical part of LV network are presented in Figure 2-2.

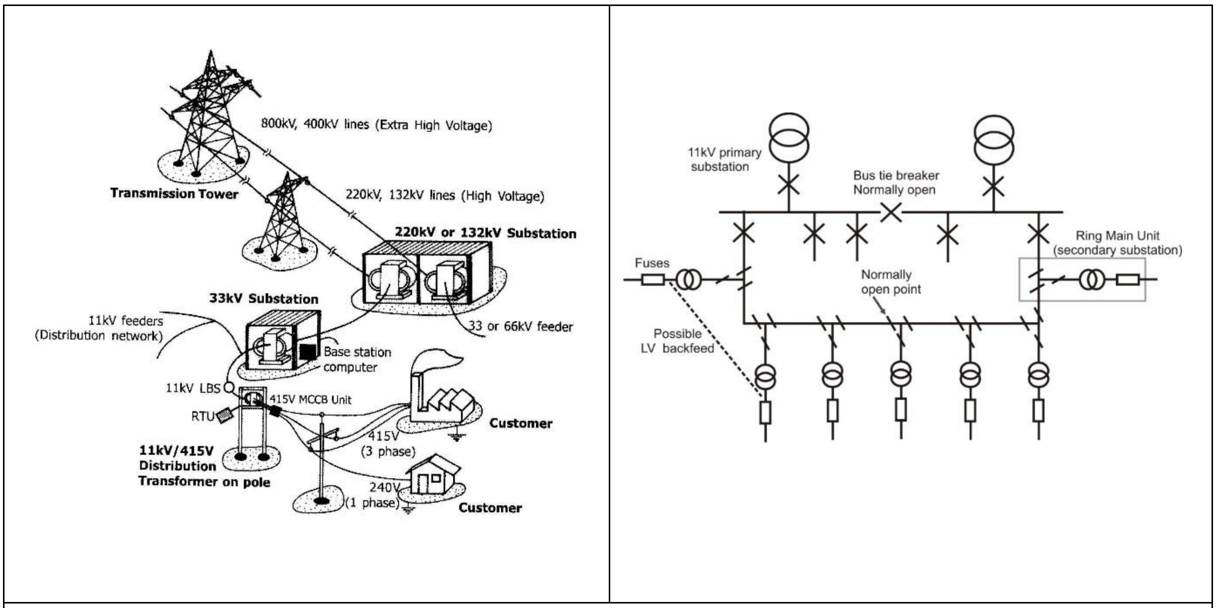

Figure 2-2:- A typical voltage levels in power systems and a typical LV network distribution system

The network is continuously evolving and key technologies are commercially available and have already been trialled on many networks. These technologies allowed customers to get connected to network quickly with respect to the past where they would have had to wait on significant reinforcement works to connect. New types of production units have been introduced to the distribution network. Some of the terms to refer to the new types of production are: renewable energy sources (RES), distributed generation (DG), distributed energy resources (DER), embedded generation, small-scale generation, etc. The integration of these production units requires investments at different voltage levels. The new types of production introduce new challenges which require new types of solutions. Small production units are usually connected to the low or medium voltage distribution system, where traditionally only consumption was connected. The introduction of large numbers of them requires investments not only at the voltage level where the units are connected but also at higher voltage levels. The shift from large production units connected at higher voltage levels to small units connected at lower voltage levels also impacts the design and operation of transmission networks. New structure of power systems is generally illustrated in Figure 2-3 representing the future grids.

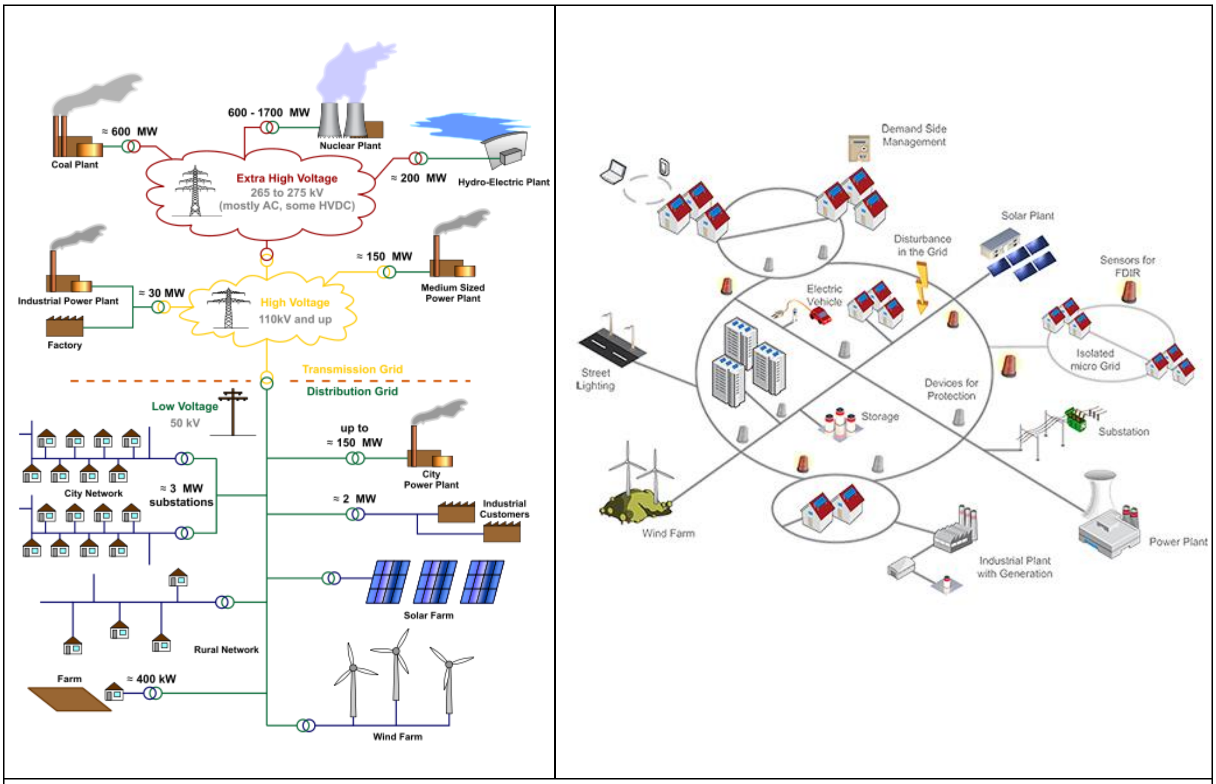

Figure 2-3:- New structure of future grids

In this context, customers are playing a key role and they are expected to be actively engaged in all aspects of energy efficiency as prosumers (i.e. consuming and producers of electricity). Network operators need to adapt to meet these challenges by maintaining at the same time low costs and reliable energy distribution. They also need to facilitate a fair market for the services that they could provide. The future power system is expected to make extensive use of communications technologies to support a flexible, secure and cost-effective decarbonized electrical power.

2.1 Smart Grids

According to the European Technology Platform Smart Grid (ETPSG)[2], a Smart Grid is an electricity network that can intelligently integrate 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 uses innovative products and services together with intelligent monitoring, control, communication and self-healing technologies[3] in order to:

- Better facilitate the connection and operation of generators of all sizes and technologies;
- Allow electricity consumers to play a part in optimizing the operation of the system;
- Provide consumers with greater information and options for choice of supply;
- Significantly reduce the environmental impact of the whole electricity supply system;
- Maintain or even improve the existing high levels of system reliability, quality and security of supply;
- Maintain and improve the existing services efficiently;
- Foster market integration towards a European integrated market.

The definition provided by the Energy Networks Association (ENA)[4] is:

The Smart Grid is everything from generation through to home automation with a smart meter being an important element, with every piece of network equipment, communications technology and processes in between contributing to an efficient and smart grid.

A completely Smart Grid of the future will enable appliances in the home to communicate with the smart meter and enable the networks to ensure efficient use of infrastructure, demand response and energy management. These are all critical to making the most of intermittent renewables and keeping the lights on in an affordable low-carbon energy future.

2.1.1 The role of DSOs in a smart grid environment

From DSOs perspective[5], smart grids are a tool for efficient system management. Generally speaking DSOs recognize the positive effects of smart meters as enabling better network planning and control. However, not many DSOs look forward to have completely new roles in a smart grid environment, although they envisage their existing tasks to become more complex in the current market structure. They see their role being gradually adapted to the new scenario. However, only a few DSOs see a possibility of providing new services and activities, such as advance network supervision and promoting energy efficiency awareness. Furthermore, local balancing (to be provided in close cooperation with the TSOs) is seen by several DSOs becoming more relevant. From the point of view of DSOs, among their relevant tasks there are to maintain the grid operation, secure the supply, connect and give access to the network, and collect and provide data (from smart metering) to third parties[7].

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[2] European Commission. European Technology Platform for the Electricity Networks of the Future. [2015-12-02]. http://www.smartgrids.eu/ETPSmartGrids

[3] J. Ekanayake, K. Liyanage, J. Wu, A. Yokoyama, N. Jenkins. *Smart Grid: Technology and Applications*. Chic hester: John Wiley & Sons, Ltd., 2012

[4] Energy Network Association. Electricity—Smart networks overview.[2015-08-16]. http://www.energynetworks.org/electricity/smart-gridportal/ overview.html

5 The role of DSOs in a Smart Grid environment, ECORYS

In the following, some potential future services in smart grid are summed up:[6] [7]

Flexibility Services

As mentioned above, among the tasks of DSOs, there are network planning and network operation. They provide voltage control and load curtailment in case of local congestion. Because of the high RES penetration, network flows become more variable and network operation becomes more important for DSOs. In this context, the new technologies as well as smart grids constitute new options for network operation and system management by providing flexibility in generation, demand and storage. Flexibility can be supplied by system users or by intermediaries such as aggregators.

Energy efficiency services

Smart grids in combination with smart metering can provide information on usage and tariffs in order to inform consumers as well as to help identify cost effective solutions for energy savings.
Among the different actors that can provide energy efficiency services there are: DSOs, electricity suppliers, independent firms, such as electrical installation companies etc. Concerning local balancing, DERs are seen as being able to deliver reliable capacity and congestion management to DSOs.

Infrastructure provision for electric vehicles

The electric vehicles requires the availability of charging points to become attractive. In this context, several actors could play a role in the provision of EV charging infrastructure, such as DSOs or suppliers who can use the charging points to sell electricity. Other commercial actors may also provide access to EV infrastructure, such as private investors and independent emobility providers who may provide electricity bundled with other services.

2.1.2 Provision and procurement of flexibility services

The increasing share of RES, determined an increasing need for flexibility in the power system value chain to maintain competitiveness and security of supply. The variability of network flows increases peak demand for network capacity and lowers average network utilization, making network investments less profitable and requiring flexibility to keep network operation in control. In this context, the lower predictability of power supply increases demand for system balancing as well as demand for ancillary services (e.g. voltage control). DSOs may deploy flexibility services for congestion management in network operation in order to save on network reinforcements that would be used only occasionally. Furthermore, DSOs may need flexibility services to fulfil some operation tasks at the distribution network level such as balancing, which are currently only performed at the transmission level.

Generally speaking, 5 types of flexibility services can be distinguished[7]:

1. **Portfolio optimization** is used by market players to meet their load obligations at minimum costs by arbitrating between generation and demand response on different time horizons[8]. The responsibility of portfolio optimization is sometimes assigned to balancing responsible parties (BRP) by TSOs in the framework of imbalance settlement.

2. **Preventive congestion management** relates to congestion management that takes place before gate closure of wholesale markets.

6 CEER Conclusion Paper on New Services and DSO involvement, 22 March 2019, Ref. C18-DS-46-08.

[7] The role of DSOs in a Smart Grid environment, ECORYS

[8] He, X, L. Hancher, I. Azevedo, N. Keyaerts, L. Meeus, and J-M. Glachant (2013), Shift, Not Drift: Towards Active Demand Response and Beyond, Final report, Topic 11 FP7 THINK report.

3. **Curative congestion management** is near real-time resolving of local network overload through network operation after gate closure of wholesale markets.

4. **System balancing** refers to procurement of balancing reserves (capacity) and balancing energy by the TSO to perform balancing (i.e, actions by TSOs to maintain the system frequency within a predefined stability range[9]).

5. **Ancillary services** relate to a range of functions to guarantee system security. These include black start capability, frequency response, fast reserve, the provision of reactive power and various other services[10] .

2.2 Smarter Energy Storage

The generation mix is evolving in response to policy goals to pursue decarbonisation of the energy sector and to increase the share of electricity generated from RES. The share of generation provided by wind and solar capacity is increasing and this trend is expected to continue. As a result, flexibility will be needed to manage the unpredictability and variability of intermittent generation. Electricity storage is one possible source of flexibility. More in detail, flexibility could be provided by four sources: flexible generation, interconnection, demand side response and electricity storage. These four options and their ability to provide flexibility are illustrated[11] in Figure 2-4.

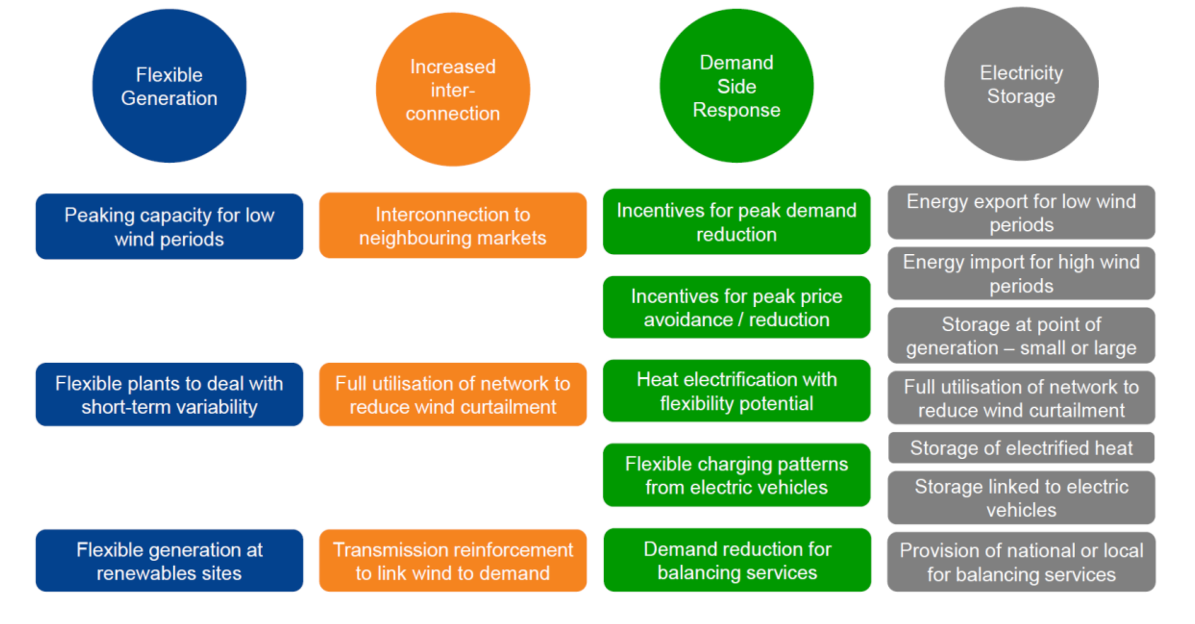

Figure 2-4- Sources of flexibility[11]

However, it is worth to specify that whether and how the flexibility offered by these options will be provided depends on the market and regulatory structure available to incentivise new capacity to enter the market, including storage.

[9] ENTSO-E (2013a), ENTSO-E Network Code on Electricity Balancing v1.19 (draft 24 April 2013).

[10] ENTSO-E (2013b), Overview of transmission tariffs in Europe: Synthesis 2013, Brussels, June.

[11] Smarter Network Storage-LCNF-Interim-Report-Regulatory Legal Framework, 2015

2.2.1 Future role of Energy storage in Electricity Grid

Energy storage will play a key role in enabling the EU to develop a low-carbon electricity system. Energy storage can supply more flexibility and balancing to the grid, providing a backup to intermittent renewable energy.

Energy storage can be integrated at different levels of the electricity system[12]:

- Generation level: Arbitrage, balancing and reserve power, etc.
- Transmission level: frequency control rtc
- Distribution level: voltage control, capacity support, etc.
- Customer level: peak shaving, time of use cost management, etc.

In a future low-carbon energy system, storage will be needed at all points of the electricity system and will support a variety of functions as illustrated in Figure 2-5. The different locations in the power system will involve different stakeholders and will have an impact on the type of services to be provided. Different energy storage systems will have to be considered (centralised and decentralised) and specific business models have to be identified.

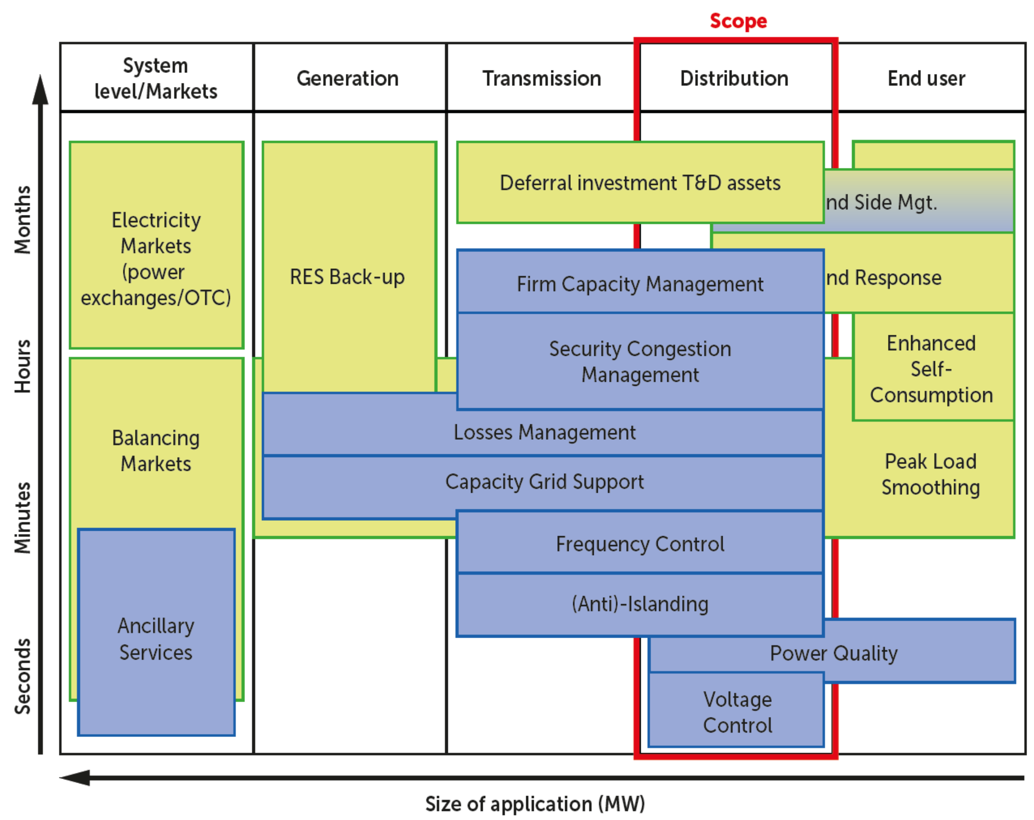

Figure 2-4:- Overview of the electricity storage functions[12]

[12] DG ENER Working Paper - The future role and challenges of Energy Storage

2.3 Renewable resources integration into distribution network

Traditionally the distribution networks were designed to facilitate the flow of electricity in one direction, from transmission network to customer demand. They were generally passive networks, with simple voltage control designed to counter the induced voltage drops along circuits.
With the increased penetration of the distributed generation, many aspects of the distribution system operation, design and implementation have changed. Distributed generation sources (DERs) are typically defined as small-scale generation sources that connect to the electrical distribution network. The small scale generation technologies varies significantly in their operation and potential impacts. Some of them use technologies already developed to generate electricity as wind turbines, PV solar, small hydro, cogeneration units etc. Other techniques are more recent as fuel cells, solar thermal, micro-turbines, biomass, and marine renewable technologies.
Cogeneration, micro-hydro and bioenergy generally have limited weather-related dependencies and hence offer relatively constant and predictable energy output by comparison with wind and solar technologies.
Photovoltaics (PV) is increasing the use in many countries and the amount of energy produced by a PV module is proportional to the module area as well as the solar irradiance. The rated power generated by a module is limited and it is worth to highlight that the maximum output voltage corresponds to open circuit which is usually reduced with respect to the mains voltage. Thus, to increase the voltage of the plant several PV modules are connected in series, composing strings and several strings can be connected in parallel to form an array.
Figure 2-5 shows a general diagram of a PV plant to be connected to a distribution network. As it can be seen in the figure, the output of a panel string can be connected to the dc bus by means of a dc/dc converter in order to adjust to the proper voltage levels. Then a dc/ac inverter converts the dc voltage to the appropriate ac voltage level of the distribution network[13].

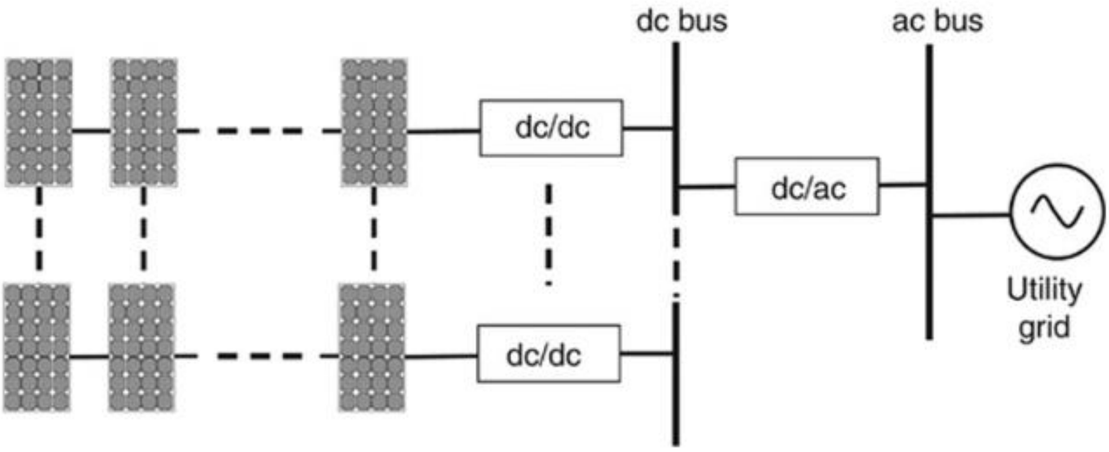

Figure 2-5: Typical PV plant

The magnitude of the power supplied by PV systems depends on the weather therefore, if there are changes in the sun irradiance, the output power of the PV system will fluctuate significantly. In this context, there is a low predictability of the PV output. PV technology itself has almost no inherent

[13] Active Power Line Conditioners: Design, Simulation and Implementation for improving power quality. By Patricio Salmeron Revuelta, Salvador Pérez Litrán, Jaime Prieto Thomas

energy storage. As such, it can have significant negative power quality impacts at high penetrations if appropriate measures are not implemented. PV inverters normally operate with unity power factor, not generating reactive power, so they do not take part in the voltage control of the system.

Currently wind energy is the renewable technology that is growing most rapidly worldwide. The improvement in the turbines and the design of power converters has led to a significant drop in the cost. Currently wind energy is the second largest energy renewable resource behind the hydroelectrics.

Variable speed turbines with permanent magnet synchronous generators are often used in small wind turbines. The output is ac of variable frequency, so it includes an ac/dc converter and an inverter as coupling interface to the voltage and frequency of the distribution network.

2.3.1 Impacts of distributed generation

Electricity network grids must have standard conditions of supply to safe and effective operations. These conditions are usually referred as power quality requirements and are defined in standards and/or by regulating authorities.

Distributed generation resources can reduce the need for investment in the transmission and distribution infrastructure. The transmission and distribution losses will also reduce as the network flow is reduced.
However, these introduces many challenges to the distribution network operator[14]:

- Inadvertent islanding where a section of a distribution network is split from the transmission network and is still energised by its local generation.
- Flow reversal which means that existing directional protection cannot be used and the need to install a new protection system.
- Increased fault levels and the need to install new circuit breakers (expensive).
- Need for more sophisticated voltage and reactive control schemes for 'active distribution networks' of the future.
- The random fluctuations of the power generated by large wind farms can result in network voltage dips and rises if either the wind farm or the network is not providing support to the system with some form of voltage control.
- Voltage control and power quality problems can arise when generators embedded within the distribution networks start or stop generating power. If not properly regulated this may even cause other network users to suffer voltage fluctuations outside the acceptable statutory limits, and inject unwanted harmonics into the voltage waveform.

1. Voltage fluctuation and regulation

Voltage fluctuation is a change or swing in the voltage. It can be problematic if it fluctuates outside the statutory limits set for the distribution network. Actually, voltage fluctuation affects the performance of many household appliances. Effects on loads are usually noticed when the voltage fluctuates more than 10 % above or below the nominal voltage, and the severity of the effects depend upon the duration of the change.

[14] A. O. Ekwue, and O. A. Akintunde "The impact of distributed generation on distribution networks" Nigerian Journal of Technology (NIJOTECH) Vol. 34 No. 2, April 2015, pp. 325 – 331

In the traditional distribution networks, voltage control and regulation typically relies on the action of the On-Load Tap Changer (OLTC) installed at the primary substations transformers and additionally the off-load tap changers provided the choice of an appropriate tap position for the secondary substation transformers. This method relies on the fact that the voltage profile decreases along the feeder and that the feeder voltage drop is proportional to the load currents that flow along the feeders. Actually, the regulation parameters are chosen under the assumption that the feeder is passive, which does not correspond to the real scenario with the embedded generation in the distribution network. When generators are connected to the feeder, voltage profile is likely to increase.

In a typical Distributed Generation connection,

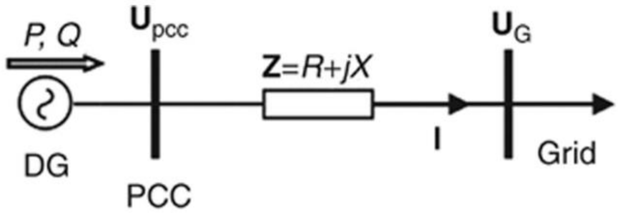

Figure 2-6: Typical equivalent circuit with DG connected

The line current can be obtained through the following formula:

$$I = \frac{P - jQ}{U_{PCC}}$$

Where, U_{PCC} is the voltage at the point of common coupling, P and Q is the output active and reactive power of the DG. Voltage between the connection points of the Distributed generation DG the utility grid is the voltage is given by;

$$\Delta U = U_G - U_{PCC}$$

$$\Delta U = \frac{RP + XQ}{U_{PCC}} + j\frac{XP + RQ}{U_{PCC}}$$

As the X/R ratio of the LV line is small, neither RP nor XQ is negligible. The XQ term may be positive or negative, depending on whether the generator is exporting or importing reactive power. However, as the magnitude of the reactive power will be small compared to that of the power (unless some compensations are used), the RP+XQ term will tend to be positive. Therefore, the voltage at the point of connection of the generator to the Low Voltage system will rise above that of the primary substation. As the inverter pushes power to the grid, the voltage at the PCC rises, and has impacts on the neighbouring circuits.

With high penetration of the PVs, which produces power during the day when the load is not high, could potentially increase the voltages above the statutory limits.

From the above equations, it can be deduced that the variations in the power or reactive power injected into the network can cause voltage fluctuations in the grid. Distributed Generation produced by solar and wind are examples of systems with the output power that varies randomly.

As example, during a hot summer day, a local distribution network is heavily loaded, and it mainly comprises room air conditioners. PV panels can input a great amount of power to the grid under intensive sun irradiation with a high penetration level, therefore the voltage regulator does not detect a large load current and the tap changers are kept in relatively low positions. If clouds sweep over this network within a short time, PV power contribution will drop quickly. This will cause a large load increase for the upstream network and voltage drop will follow PV power decrease. A voltage regulator can observe a current increase; however, the tap changer control scheme and mechanism stop it from responding immediately, so voltage drop cannot be compensated for until the tap changing delay exceeds a preset value. During this short period, voltage drop of some remote buses may have already developed to an unacceptable low level at which voltage stability cannot be maintained.

With 40% of PV penetration levels, the voltage stability problem arises in the network due to cloud cover[15].

Therefore, to guarantee the safety and stability in PV systems, it is necessary to use an appropriate voltage/reactive power control strategy to mitigate these rapid voltage fluctuations.

2. Reverse Power Flow

The massive integration of Distributed generation in the distribution network introduces new challenge to the operators, the reverse power flow from the Low Voltage (LV) to Medium Voltage (HV). Reverse flow can cause problems for the protection system and AVC scheme in place.

The voltage profile in the conventional distribution system is stable. When generators are connected to the distribution system, the power flow and the voltage profiles are affected as well as the system is no longer passive but active. In order to export power, a generator is likely to have to operate at a higher voltage as compared to the other nodes where it is supplied power.

If$\Delta U = U_{PCC} - U_G > 0$, power will flow from the generator bus (PCC) to the substation (Grid). The exiting directional protection used in the feeder cannot be used and would require to install new protection system. With the high variability of the renewable sources like, solar and wind devising a protection strategy is difficult.

The Traditional AVC schemes have been developed assuming the power flows in one direction and the voltage drops along the line.

3. Harmonic Injections

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. The standard frequency is 50 or 60 Hz depending on the country (50 Hz in the UK and Europe. Therefore harmonics in a 50 Hz country could be 100, 150, 200 Hz, etc. Electrical appliances and generators all produce harmonics and are regulated under the International Electrotechnical Commission (IEC) Electromagnetic Interference (EMI) standards. However in large volumes, these harmonics can add up to cause interference that can result in vibration of elevators/ motors , flickering of TV monitors and fluorescent lamps, heating of the transformers, degradation of sound quality, malfunctioning of control devices and in the worst case even fires.

Several of the forms of DGs are connected to the distribution network via an interfacing inverter (e.g.: PVs, fuel cells, micro-turbines. The inverter is a very versatile unit and while its main function will be to control the export of real power. it may also be called upon to provide reactive power support as an ancillary service to the DNO or as a condition of connection.in the UK, the ENA's ER G99 clarifies these requirements. On the other hand, harmonic distortion that arises from the increased use of nonlinear electronic devices such as inverters, power electronic devices etc.. may degrade the grid power quality.

Furthermore, due to the widely used LC filters in the grid connected converters, harmonic resonances resulting from the aggregated shunt-connected capacitors for a number of LC filters, the capacitive loads, as well as the power factor correction capacitors are becoming a power quality

[15] T. K. S. Ruifeng Yan, "Investigation of Voltage Stability for Residential Customers Due to High Photovoltaic Penetrations," vol. 27, no. 2, MAY 2012

challenge. On the other hand, the LC filter resonances between the paralleled converters coupled through the grid impedance degrade the performance of converters in the micro grid system.

In the UK, the allowable harmonic distortion is outlined by the Energy Networks Association's Engineering recommendation G5/4-1 Planning Levels for harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom.

In simple terms this means that the harmonic output of the loads to be connected to the DNO must be assessed and verified if the Total Harmonic Distortion (THD) and individual harmonic levels (up the 50th harmonic) are within the guidelines given in the G5/4 standard.

4. Operational and control

Due to large penetration of DG, there is a risk of control and stability issues. If a circuit breaker in a distribution system opens, it could result in an islanding of a DG unit. If loss-of-mains is not detected by the DG unit, this last one will continue to operate. If the DG unit is able to match the active and reactive power of the load of the island system precisely, then the island system could continue to operate without any problem. It is however, very unrealistic that DG will exactly match the load, so large frequency or voltage variations will occur when DG unit tries to supply load. So most interconnection rules devised by the regulators and the DNOs requires a loss-of-main detection which automatically disconnect the DG unit in case of a loss of main and the unit remains disconnect until the grid is restored.

Islanding operation has following drawbacks:

1. Line worker safety can be compromised by the DG sources feeding a system after primary sources have been opened and tagged out for maintenance.
2. The voltage and frequency may not be maintained within a standard permissible level as the DG might not be capable of the controlling the power depending on the variation in the loads
3. The islanded system may be inadequately grounded by the DG interconnection.
4. Instantaneous reclosing could result in out of phase reclosing of DG.(synchronisation may not be achieved and the protections on the grid might trip)

Due to these reasons, it is very important to detect the islanding quickly and accurately and open the DGs in the island.

2.3.2 Potential Solutions

Over the years, many research work has been done on solving the voltage stability problems related to the PV power fluctuations and voltage rise. First, the energy can be stored. This approach should be effective since the voltage instability addressed previously is caused by real power drop from the PV. Installing distribution static compensators (DSTATCOM) can also mitigate the voltage problem.

1. Battery/storage

Various types of storage including batteries (e.g. lithium-ion batteries (popular), lead-acid batteries, flow batteries), super conducting Magnetic Energy Storage (SMES), compressed air, pumped hydro and flywheels can be used to regulate power output. The pumped hydro is effective however it requires appropriate storage facilities for water. The battery technologies are available in the market and the efficiency of them are improving at a rapid rate. The large battery banks are being deployed in the grid network, which are still on experimental level. In addition to reducing the amount of voltage rise on feeders, storage can be used to provide services such as peak shaving, load shifting, demand side management and outage protection. Storage can help defer upgrades of transmission and distribution systems, and can help with 'blackstarts' after a system failure. It can also help provide several ancillary services, including contingency reserves (spinning reserve, supplemental reserve, replacement reserve), and voltage and frequency regulation.

2. PV-STATCOM

Another attractive approach of solving the voltage problem is reactive power support through PV inverters. Usually, PV produces less real power than the rated capacity of its inverter, which leaves space for reactive power generation. Especially when grid voltage drops are caused by loss of PV real power, there will be more room for reactive power support. Over the years, many reactive power generation schemes have been proposed. The concept of utilising PV solar inverters as dynamic STATCOM, termed PV-STATCOM, could be used to improve the voltage stability issues. The PV inverter could provide reactive power as required by the grid during critical times to ensure the stability. During night time, the PV inverter could utilise its full capacity to runs as STATCOM, while during the day this will depend on the spare capacity available[16].

3. Electric vehicles

Electric vehicles (EV) are increasing worldwide, as the countries moving towards low carbon solutions. This increase the demand in Low Voltage grids. EVs can work as a storage device when connected to the grid and may be able support the grid by discharging when required. Many studies are being conducted to exploit the chances of using the EVs to support the grid by charging and discharging when required. As demonstrated in paper "Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks" [17] and studies performed in "Voltage rise mitigation for solar PV integration at LV grids"[18], EV charging, which first may appear as an additional load to the grid, can be used as an effective storage solution. In the grids with PV, EVs represent a unique opportunity, as not only they can locally consume part of the produced PV energy, yet this energy reduces the charging energy from the grid and gives additional travel range for EV drivers. For an average size EV with a 24 kWh battery, the charging process can show an additional demand of about 3.7 kW with a single–phase charging option. EV charging, with coordination to PV generation, can help to mitigate the voltage issues.

If we consider a public charging station, with the possibility to accommodate the parallel charging of several vehicles, this can be ideally seen as a grid-connected battery; the charging load due EV parallel charging can cope with high PV generation, by activation from a centralized position. The study performed in "Improvement of Local Voltage in Feeders With Photovoltaic Using Electric Vehicles" [19], shows that an example Belgian radial feeder may be able to accommodate more PV without the need of grid reinforcement, but only with coordinated EV charging. With the increasing number of Electric vehicle, which is boosted by the low carbon policies, this could be implemented in the public car parks.

The network islanding issue is a well-known problem. The present day grid inverter technology has developed to include anti-islanding features as required by the local regulations and standards. The

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[16] E. M. S. Rajiv K. Varma, "PV-STATCOM:A New Smart Inverter for Voltage Control in Distribution Systems," vol. 9, no. 4, OCTOBER 2018.

[17] P. F. C. A. F. M. F. Pedro M. S. Carvalho, "Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks," vol. 23, no. 2, May 2008.

[18] Guangya YANG, Francesco MARRA, Miguel JUAMPEREZ, Søren Bækhøj KJÆR, Seyedmostafa HASHEMI, Jacob ØSTERGAARD, Hans Henrik IPSEN, Kenn H. B. FREDERIKSEN, "Voltage rise mitigation for solar PV integration at LV grids, Studies from PVNET". dk

[19] F Marra, GY Yang, YT Fawzy, C.Traeholt, E Larsen, R Garcia-Valle, M M Jensen "Improvement of Local Voltage in Feeders With Photovoltaic Using Electric Vehicles"IEEE Transactions on power systems ,vol. 28, no. 3, August 2013.

main idea of detecting an islanding situation is to monitor and decide whether or not an islanding situation has occurred from change in these parameters. Islanding detection techniques can be divided into remote and local techniques. Local techniques can further be divided into passive, active and hybrid techniques.

1. Remote islanding detection techniques

Remote islanding detection techniques are based on communication between utilities and DGs. Although these detection techniques may have higher reliability compared local techniques, they are very expensive to implement and hence uneconomical. Some of the remote islanding detection techniques are:

- Transfer trip scheme
- Power line signalling scheme

2. Local detection techniques

It is based on the measurement of system parameters at the DG site, like voltage, frequency, power etc. It can be further classified as:

I. Passive detection technique: Passive detection methods work on measuring system parameters such as variations in voltage, frequency, harmonic distortion, etc. These parameters vary greatly when the system is islanded. Differentiation between an islanding and grid connected condition is based upon the thresholds set for these parameters. Some of the passive islanding detection techniques are:
    - Rate of change of output power
    - Rate of change of frequency
    - Rate of change of frequency over power
    - Change of impedance
    - Voltage unbalance

II. Active detection techniques: With active detection methods, islanding can be detected even under the perfect match of generation and load, which is not possible in case of the passive detection schemes.
    - Reactive power export error detection
    - impedance measurement method
    - Phase (or frequency) shift method

III. Hybrid Techniques

3 Strategies to mitigate energy losses in distribution network

3.1 Energy Losses in the Distribution network

Distribution network losses can be broadly defined as the difference between the electrical energy entering the distribution network and the electrical energy exiting the distribution network and can be classified as technical losses and non-technical losses.

Technical losses

Technical losses arise from the physical reasons and depends on the energy flowing through the network, the parameters of the transmission lines and transformers. Technical losses can be classified as fixed losses and variable losses. Fixed losses are losses that are independent of the load but arises from the functioning of the network, i.e. energy is dissipated by network components and equipment such as transformers or conductors as a result of being connected to the network and being energised. Although fixed losses do not change with the current, they depend on the applied voltage.

The load dependent variable loss may be impacted by the power factor, network imbalance and the effects of the harmonics.

Following are some technical losses that present in the distribution network.

1. Distribution line losses
2. Transformer losses
3. Losses due to harmonics
4. Losses due to power factor

Non-technical losses

Non-technical losses, sometimes called commercial losses, incorporate measurement errors, recording errors, theft, and timing differences.

Losses represent an important amount of energy flows in transmission and distribution networks. In this context, reduction of losses plays a relevant role for reasons of financial sustainability as well as for improving the reliability of the system and its quality. It is worth to highlight that there is a major environmental benefit in losses reduction. On high and extra high voltage levels, most countries assess losses by measurement as energy flows on these voltage levels are usually metered. On medium and low voltage levels, losses are in principle calculated. However, in some countries (i.e. Germany, Great Britain, Poland and Romania), losses on certain voltage levels are either metered or calculated, depending on availability of meters in a specific location [20]. In Spain, where the E-LOBSTER demonstrator will be based, losses are not monitored at individual voltage levels because it is not required in the country the legal framework. Obviously, the measurements determine certain costs: metering points, smart meters for all consumers etc.

It is worth to underline that losses are one of the key contributors to operational expenditures in power networks. Actually, Council of European Energy Regulators (CEER)[20] recommends that system operators aim to find the right balance between the managing the costs of losses and costs of investing in more efficient technologies.

[20] Council of European Energy Regulators, CEER report on Power Losses, C17-EQS-80-03

CEER makes the following recommendations for reducing electricity network losses[20]:

Overall:
1) Harmonise definitions for improved benchmarking
2) Make more data available (e.g. the availability of energy injected into distribution grids). This will allow the calculation of distribution system losses as a percentage of energy injected into distribution grids
3) Incentivise system operators to reduce losses instead of passing losses on to consumers
4) Use a life cycle costing approach that includes losses when the investment are decided

Technical losses:
1) Increase voltage levels
2) Apply less transformational steps to deliver electricity to consumers
3) Utilise new and improved equipment
4) Use distributed generation in a more efficient manner (combination with local storage)
5) Optimise network flows (peak reduction)
6) Network architecture and management enabling highest efficiency

Non-Technical losses:
1) All countries should collect data on these types of losses
2) Focus on more accurate recording of electricity consumptions through improved metering and the use of smart meters
3) Reduce theft and other hidden losses

3.2 Smart Meters

The use of smart meters for the assessment of electricity consumption is essential as it affect the volume of non-technical losses in mainly 2 ways:

1) it help to reduce metering errors and to have more accurate measurement of electricity consumption. Therefore, the estimation/calculation of non-technical losses will be more exact.
2) Real time reading of energy consumption and an establishment of dynamic tariffs might help to reduce the gap between peak demand and the available power at any given time

Basically, a higher penetration rate of smart meters has several advantages. They allow to collect real-time consumption readings, to control the volume of electricity delivered and to detect non-technical losses.

3.3 Technical loss reduction

Technical losses that occurs in the network cannot be eliminated, but can be reduced to an economically optimum level.
Some of the loss reduction techniques are discussed in the following sections.

3.3.1 Power factor correction

Most present day electrical loads not only consumes active power but also consumes reactive power. The power factor is lowered with the increase in the reactive power transported by the distribution network to supply the load requirements. With lower power factor, the current has to increase to deliver the required active power, which results in an increased loss, I^2Z. Traditionally industrial and commercial customers had higher reactive power demand however with the developments of the domestic power electronics, PVs, and heat pumps mean, this issue will be occurring in the LV mains networks.

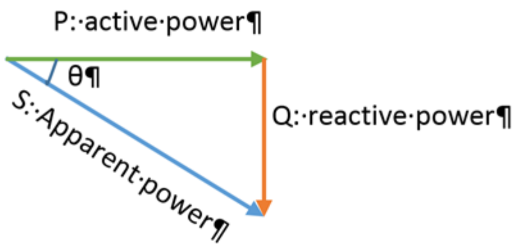

Figure 3-1: Power factor

The Power factor correction is a method to restore the power factor as close as to unity, economically. This is normally achieved by the addition of capacitors to the electrical networks, which compensates the reactive power demand on the inductive load demand (usually the loads are inductive by nature). There are two methods for improving power factor using capacitors, based on where the compensation is achieved: individual load compensation and centralized compensation.

Individual load compensation method is typically achieved with static capacitors applied to the system on linear or no-linear loads. This method eliminates the need for switching the capacitors because they are on when the motor is on and off when the motor is off and avoids having the capacitance on the system while the motor is not presenting the inductive reactance.

Centralized compensation typically occurs with the installation of automatically switched capacitor banks at the feeder or substation. This method commonly has a lower cost per kvar correction compared to individual load compensation.

3.3.2 Voltage regulation

At the load end, the power required by the load, S, can be given by the formula below:

$$Apparent\ Power\ S = VI$$

For a constant power load, as the voltage at the load bus is reduced the current required by the load increases, which increases the current flow in the distribution lines and increases the power losses.

Therefore another strategy for reducing the losses in to control the voltage. The voltage control technology can be implemented at the system level by optimising position of tap changing transformers.

The distribution networks are equipped with Automatic voltage control schemes (AVC) which measures the local voltage and compares this with a target voltage. The tap ratio of the transformer is then adjusted to achieve the target voltage. An AVC may have line drop compensation, using line current and impedance to calculate the voltage drop at the end of the line. The AVC+LDC will then control the tap ratio of the transformer to achieve the target voltage at the end of the line.

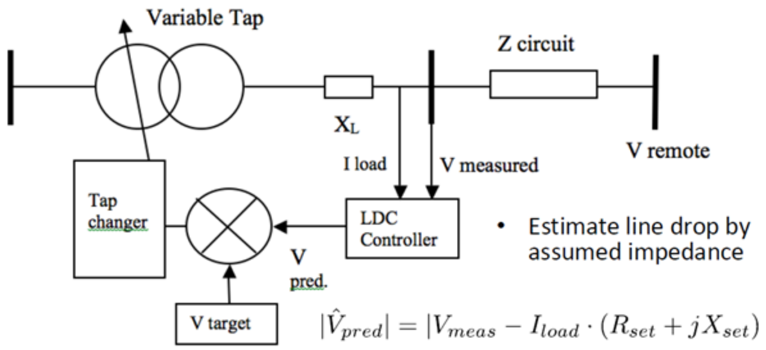

Figure 3-2: Regulating voltage profile

3.3.3 Harmonic compensation

Harmonics injected by the non-linear equipment causes harmonic currents to flow in other loads, such as fixed impedance heating demands/constant load demand and motors. Because of the additional harmonics in the line, the rms value of the current increases, which results in an increase in the copper losses and thus heating. The extent of the overall sensitivity of losses depends upon the extent of the harmonics and also the composition of the demand.
With the increase in the distributed generation, the non-linear equipment connected at the distribution level is significantly higher now than before, and will increase in the future.

1. **Passive filter**

Passive filters are made up of inductors and capacitors, which are tuned to block or absorb particular harmonic content.

2. **Active harmonic filter**

Active harmonic filters are designed using power electronics such that the device either provides variable harmonic impedance to absorb some or all of the harmonic currents or else provides harmonic current of opposite polarity to cancel the harmonic current. These active filter are expensive compare to the passive filters.

Transformer, the widely available network component, can also be used to reduce the harmonics. The delta connected transformer could be used to cancel the triplen harmonics and zig-zag grounding transformer that employs a 3-phase auto transformer to cancel the triplen harmonics.

3.4 Case studies in Spain

In the following, two cases studies in Spain which is particular relevant with respect to E-LOBSTER as the demonstrator will be installed in Metro of Madrid have been reported. The first case is related to **non-technical losses** mitigation strategy whereas the second one to **technical losses**.

1) Power line carrier (PLC) technology has been implemented by Iberdrola (DSO, Spanish) between customer smart meters and supervisory meters located on the secondary side of MV/LV transformer of secondary substation[21]. This allows to send hourly values of the meters of the

[21] "Reduction of Technical and Non-Technical Losses in Distribution Networks" Working Group on Losses Reduction CIRED WG CC-2015-2 Final Report 20-11-2017

customers and the supervisory to the central system from the secondary substations. The scope is to perform the balance between customer energy usage and energy supplied by the secondary substations and therefore to identify secondary substations with high losses for inspection and for determining the cause of the losses. These inspections have discovered in most of the cases high rates of fraud due to illegal connections to the grid. In another Iberdrola innovation project in close collaboration with Ariadna Instruments S.L., advanced supervisory meters on secondary substations are used. These meters allow a high performance supervision enabling the identification of connectivity errors (differences between the customer data in the field and data base information), meter tampering detection and power quality reports.

2) Fixed and variable technical losses produced by PV self-consumption installations have been analyzed in the region of Murcia in Spain for instantaneous self-consumption (ISC) and net-metering (NM) regulatory frameworks[22]. Different regulatory framework will have a different effect on design and dimensions of PV installations and as a consequence on energy losses values. In the specific case, 20 different PV self-consumption scenarios have been investigated to quantify the variation of energy losses due to the presence of a significant number of PV self-consumption. In terms of energy losses, the results of the simulations carried out during the study show that ISC regulatory framework is more efficient, not only at the same adoption level but also at the same quantity of installed power. Moreover, concerning the net-metering regulatory framework, it has to be highlighted that it has a relevant impact on voltage levels, which can exceed the permitted values for LV/MV distribution networks. To minimize these impacts, it is suggested to avoid or minimize energy exports from PV self-consumption installations. In this context, storage systems or Demand Response Scheme could allow a better integration of these installations.

[22] J. García-Villalobos, P. Eguía, E. Torres, A. Etxegarai "Assessing the impact of photovoltaic self-consumption support policies on energy losses" International Conference on Renewable Energies and Power Quality (ICREPQ'17) Málaga (Spain), 4th to 6th April, 2017

4 General architecture of Railway Power Supply Systems

Railway require a large amount of energy for maintenance, renewal and enhancement by including also the production, transportation and installation of materials and products. In this framework, the sector should focus on operating in a more energy efficient way[23].

Electrical power systems normally share a common architecture, from generation to consumers through transmission and distribution grids with power lines and transformers as the primary components of infrastructure in electricity networks as illustrated in Figure 2-1. Electrical power systems in railways have the same structure as other power systems: they may have their own generation (as in Germany), their own transmission grid (as in Germany and in Sweden), their own distribution grid, etc. Depending on the country, railways power systems may be connected to the public grid in different ways.

4.1.1 Description of Electrical Railway Network in Spain

With respect to E-LOBSTER, Spain plays a special role, as the demonstrator of the project will be based in Metro of Madrid. Currently, in Spain, the railway infrastructure network is split into General Interest Railway Network (RFIG), Autonomic Networks and Private Industrial Railways. RFIG (the most important) belongs to the State and comprises ADIF Network, FEVE Network (currently part of the ADIF network) and State Ports. The voltage used in the catenary for each line in the Spanish network are essentially 1500 V DC, 3000V DC and 25kV 50 Hz AC (both 1x25kV and 2x25kV AT-based). Figure 4.1, summarizes how the railway network is interconnected to public grid (transmission and distribution grids) to get the power supply, as the Spanish network does not have its own generation.

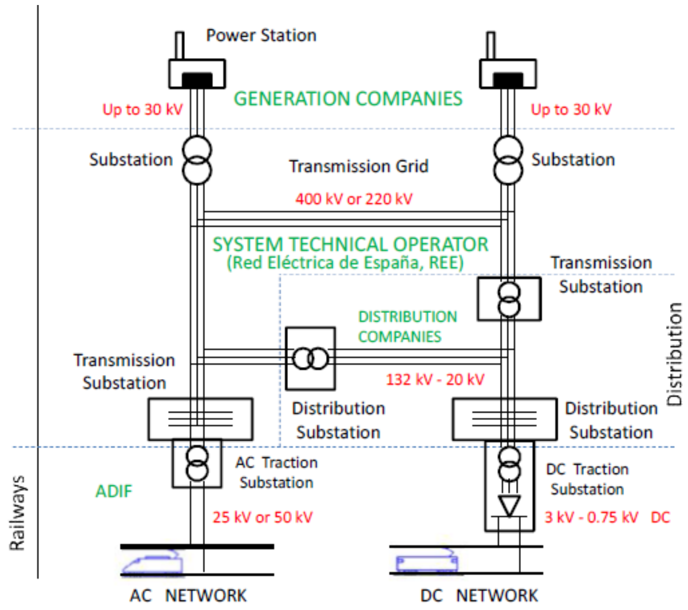

Figure 4.1. Railway electrification (AC and DC) in Spain (ADIF)

Traditionally, railways had been fed with DC (from 600 V to 1500 V), especially in suburban, trams and conventional railway lines. As the speed and traffic density increases, these voltages have been

[23] The future railway - The industry's rail technical strategy 2012

increasing to allow a higher power supply while reducing losses. Moreover, AC systems, which allow higher voltage supply than DC, were adopted for the high-speed lines. Table 4-1 shows typical voltages of each kind of services.

Table 4.1. Nominal feeding voltages to Spanish trains

Nominal feeding voltage	Application Area
600-750 V DC	Underground and trams
1200-1500 V DC	Suburban and Undergrounds
3000 V DC	Conventional lines
25 kV AC 50 Hz (1x25kV and 2x25kV)	High Speed lines

4.1.2 Description on Electrical Railway Network in Great Britain

In UK, Network rail is the infrastructure manager of the national rail network. Actually, they are in charge of track, signalling, bridges, tunnels and stations. A majority of the electrified track kilometres use AC overhead line in either 1x25 kV (Rail Return or Booster Transformer) or 2x25kV (Autotransformer-based) systems. The AC network operates typically from the public power supply, transformed from a source voltage of either 132kV (for 1x25kV) or 400kV (for 2x25kV). There are a few exceptions which vary between 66kV and 275kV. The DC network is also fed from the public power supply, and is distributed along the line to substations at either: 11kV, 22kV, 33kV or 66kV. The Tyne and Wear Metro has a shared section with Network Rail which is electrified with 1500 V DC overhead line which will be discussed in details in this report for better understanding of Metro electrical networks.

The public electricity supply industry is split into the transmission network (operating at between 275kV and 400kV) and the distribution network (operating at between 132kV and 400V). Both of these networks are owned and managed by private companies, and are of fixed geographical nature.

In figure 4.2, topology of electrical power supply of a typical 3rd rail 750 V DC is depicted. Although 750 V DC is normally considered to be a low voltage level to be used for railways, some railway lines are electrified by using this value both in UK and in Europe. The 750V direct current (DC) third-rail network is limited in the amount of power it can provide efficiently for train services.

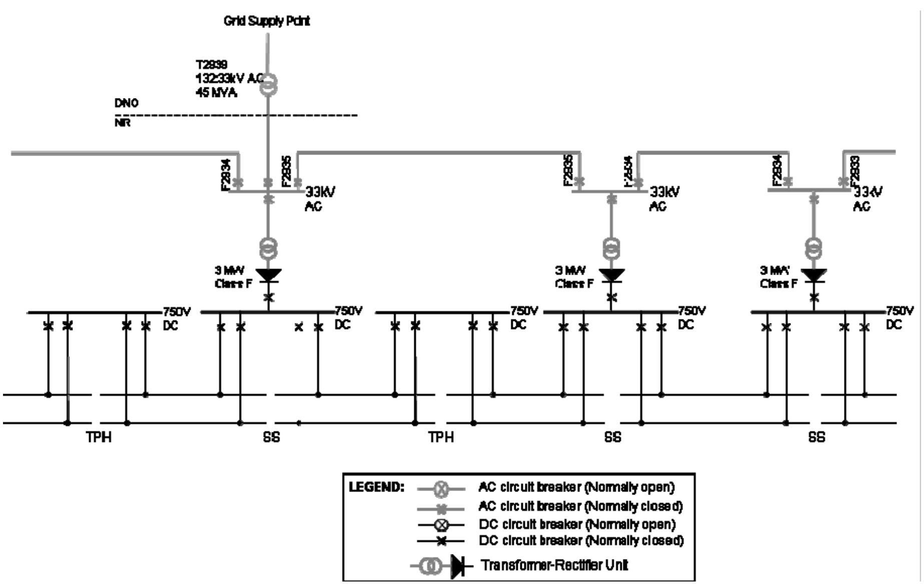

Figure 4.2- Typical rail 750 V DC Traction System configuration

4.1.3 Power supply description of the Tyne & Wear Metro

The Tyne and Wear (T&W) Metro is a light rail system centred on Newcastle upon Tyne in UK. Originally (1980), the metro consisted of 54 km network whereas nowadays, it consists of 78 km network that links the cities of Sunderland, Gateshead and Newcastle with the local airport and coastal regions. After the London Underground, it is the second largest urban rail system in the UK and the only one powered by an overhead 1500 V DC supply network. Other key statistics: 40 million passenger trips per year, 90 trains and 60 stations[24].

The original fleet of 90 twin-section Metro cars remain in service today, and operate services in pairs. They were refurbished between 1995 and 2000, and life extension work was carried in the period 2010-2015. Traction is provided by two 185 kW series-wound DC motors per Metro car. Waste heat is recovered from the resistors for saloon heating, supplemented by an auxiliary heater when required. The peak service pattern provides a train every 10 min on each leg, thus giving a 150 seconds headway in the central section and a 5 min headway on the east-west sections. The typical train configuration consists of two Metrocars (single unit operation is also possible).

Supplying the central area by means of an infeed at 33 kV has advantages of supply security. Individual supplies at 11 kV would require the station interconnectors to be operated with open points under Northern Power Grid control to prevent the bulk transfer of power between 132 kV and 275 kV systems. Also, 415 V station interconnectors would not be allowed because they would bridge the open points and in the event of a supply failure, complex switching would be necessary to restore supplies. The system is electrified using overhead wires at 1500 V DC, fed from ten substations connected to the National Grid. The system has 9 traction substations and one track-paralleling substation. There is an internal 11 kV network that covers the central underground section in Newcastle; this feeds two further traction substations, as well as signalling supplies in the tunnels and seven passenger stations. There are 7 other stations around the network that are connected directly to adjacent traction substations, while the remaining 46 stations are connected directly to local distribution networks. The original electrical network was described in a paper by Prickett[25]; subsequently a second transformer/rectifier was added at Kenton Bank for the airport extension and for the Sunderland extension new substations were built at Fellgate, Seaburn and Pallion.

The central area substations have a capacity of 4.5 MW whereas the other area substations 2 MW. In order to standardise on two ratings of rectifiers and allow for plant outages, the overload capacity of the units is used. This permits the loss of one rectifier at any substation for a 2-car peak service, or off-peak with a 3-car service. Each central area substation has three 1.5 MW rectifiers and the outer area two 1.0 MW as shown in Figure 4.3. The traction substations and 12-pulse rectifiers are rated in accordance with BS4417 Class F, having an overload capacity of 150% for 2h and 300% from 1 min. The outer area traction substations have duplicate 11 kV feeders for the 2x1 MW rectifiers, from nearest primary substation or substations. In majority of cases, these are fed from separate bulk supply points.

In general, at the Substations, the incoming supply is transformed and rectified using 6 or 12 pulse rectifiers, to provide the DC traction supply through the use of a Transformer Rectifier Unit (TRU). There are a range of TRUs, specified by both their rating (i.e. 1MW, 2MW, 2.5MW or 3MW) and overload capability (i.e. Class F, Class G). The positive pole is connected to the conductor rails through the high speed DC circuit breakers; the negative return is via the running rails.

[24] The Tyne & Wear Metro Strategy 2030.

25 Prickett BR. Electrification of the Tyne and Wear Metro. Electric Power Applications, IEE Proceedings B. 1981; 128: 81-91.

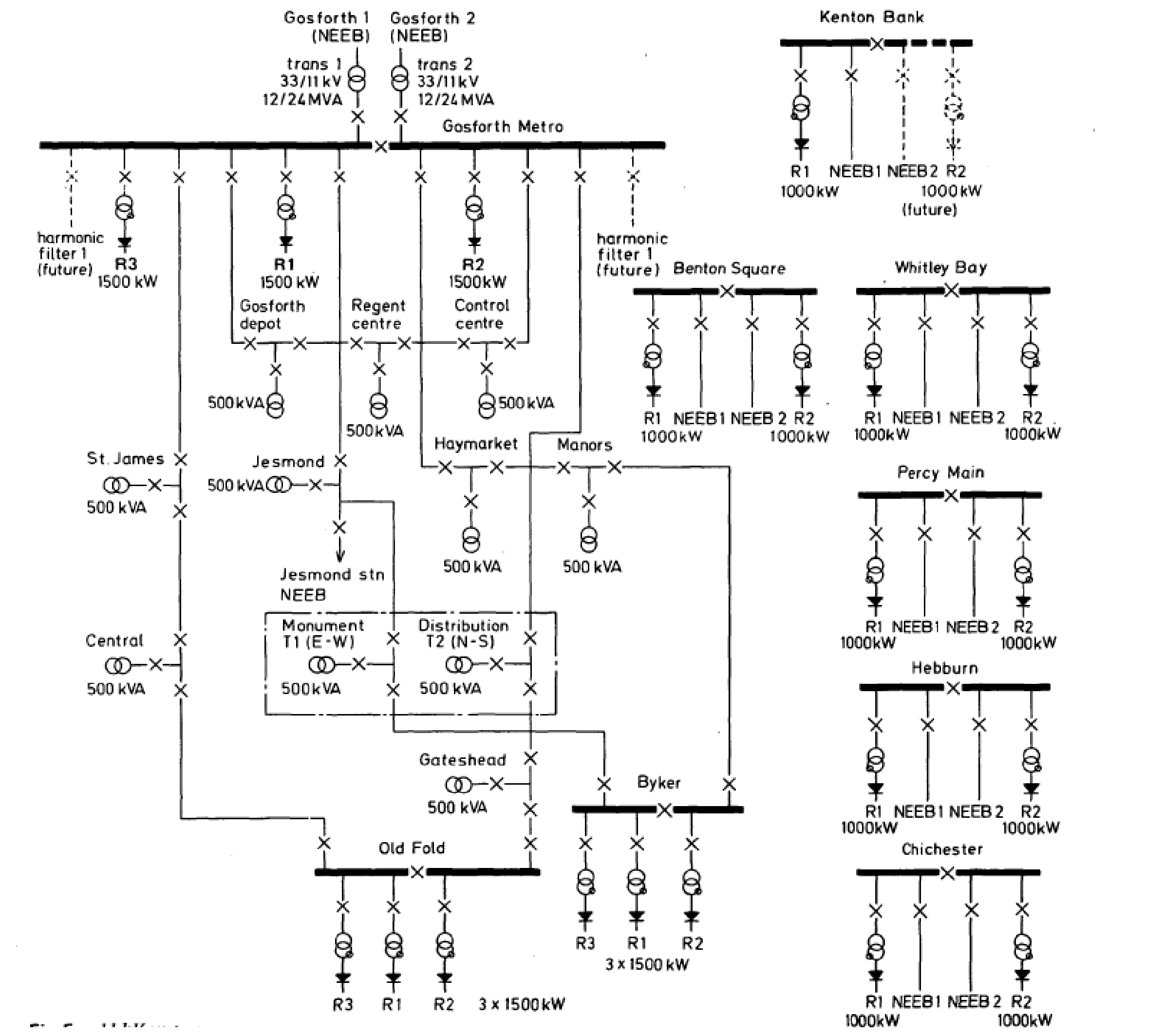

Figure 4.3 - 11kV system feeding traction substations and train stations of Newcastle Metro (original design in 1980)[25]

The equipment of the station distribution substations comprises a 3-panel 11 kV switchboard, a 500kVA Class C auxiliary transformer and a wall-mounted marshalling panel. In the adjacent LV room is the 415 V switchboard controlling station ventilation, lighting, fire alarms, signal supplies, lifts, escalators, tunnel lighting and the interconnecting supply to intermediate tunnel ventilation fans. In the event of the loss of supply from a distribution transformer, nonessential services are disconnected from the LV board, the open point of the 415 V interconnector with the adjacent station is closed automatically and essential service are maintained.

4.1.3.1 Energy consumption in Tyne & Wear Metro

The energy consumption in the Tyne and Wear Metro system in the period April 2012-March 2013 was analysed in detail, with the analysis broken down and classified into traction, depot, station, infrastructure and office use[26]. There were some energy meters in place, but not all of these subsystems are metered individually, and the level of information available varied from one subsystem to another. The total energy consumption predicted from the estimates for each subsystem matched the billed value of 69GWh closely, filling in the margin of uncertainty evaluated for all the subsystems as it can be in Figure 4.4.

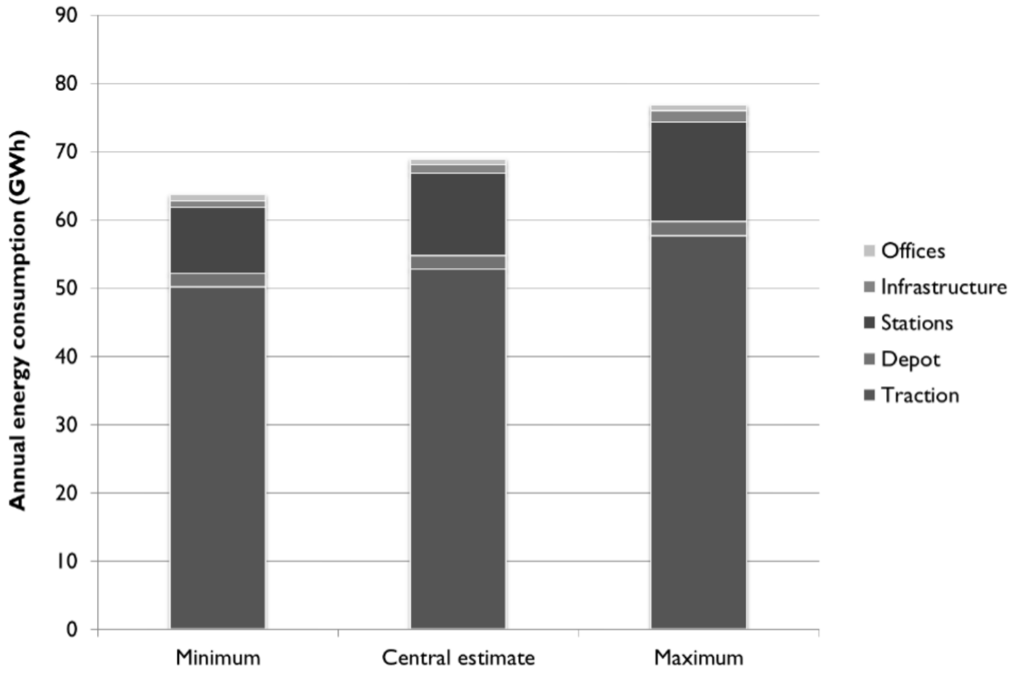

Figure 4.4. Estimates for direct operational energy use of the Tyne & Wear Metro (2013)[26]

Understanding the breakdown of energy consumption within rail systems is key when attempting to focus investment on energy efficiency improvements to a system.

[26] J.P. Powell, P. Batty, A. González-Gil, R. Palacin, ' Determining system-wide energy use in an established metro network', Proceeding of the Institution of Mechanical Engineers Part F: Rail & Rapid Transit, 2016. http://dx.doi.org/10.1177/0954409716674748

5 Energy efficiency solutions for railway networks and Power flow analyses through simulations in a typical Metro Electrical Network

According to literature data[27], 70–90% of the total energy consumption in urban rail is due to rolling stock operation. The remaining part is used in stations and other infrastructure within the system. Furthermore, it is estimated that about 50% of traction energy may be dissipated during braking phases: the energy saving potential offered by the use of regenerative braking has an important relevance in particular with respect to E-LOBSTER. Finally, the auxiliary equipment of the rolling stock may account for about 20% of its total energy consumption.

Railway operators are always looking for a reduction in their operative costs. One of the cost items where it is up to be evaluated how much money may be saved is the energetic bill, which sometimes represents a significant fraction of the total costs (especially in underground and commuter systems).

The expected increase in the use of regenerative braking as well as renewable energy generation in urban rail systems will result in the need for optimised management of energy flows within the network. In this framework, the application of the smart grid concept, originally developed for electric networks with distributed power generation is gaining growing attention[28]. This approach enables efficient management of all the energy sources in the network by taking into account the actual demand. Actually, in this context the power from renewable sources, from regenerative braking or from the public grid can be either used to meet the power demand of the system, or stored for later use shaving peak consumptions, determining in this way relevant cost savings[29].

Modern light rail networks are looking to recover energy from braking which can be quite considerable and can also helpfully smooth out the 'spikes' in power demand on the overhead line equipment (OLE).

In the following paragraphs, first of all, an overview of energy efficiency solutions for railway networks is provided, then a power flow analyses performed in the framework of E-LOBSTER through simulations based on real data from a typical Metro Electrical Network is presented.

5.1 Energy metering & Energy management

Using automated metering systems to collect energy consumption data in vehicles and in general in urban rail subsystems is a valuable approach for optimising energy usage within the system. Actually, a good understanding of energy flows is key to identify areas having energy saving potential and to monitor the effects of the implemented actions [27] [30]. Moreover, data provided by energy meters is essential for energy billing purposes:[31]As a matter of fact, to allow private operators to pay for real energy consumption instead of using average estimations, it could be an incentive for them to apply

[27] González-Gil A, Palacin R, Batty P, Powell JP. "A systems approach to reduce urban rail energy consumption". Energy Conversion and Management 2014, 80, 509-524.

[28] C. Chéron, M. Walter, J. Sandor, E. Wiebe, ERRAC – European railway energy roadmap: towards 2030, In: 9th World Congress on Railway Research – WCRR 2011, Lille, France; 2011.

29 A.E. Díez, I.C. Díez, J.A. Lopera, A. Bohorquez, E. Velandia, A. Albarracin, M. Restrepo, Trolleybuses in smart grids as effective strategy to reduce greenhouse emissions, In: IEEE International Electric Vehicle Conference – IEVC 2012, Greenville, USA; 2012.

30 CENELEC, EN 50463 – Railway applications: Energy measurement on board trains, 2007.

31 T. Stømer, How much longer can we afford to wait? Europ. Rail. Rev. 5 (2012).

energy efficiency measures. Furthermore, smart energy management enables efficient management of all energy sources according to actual demand: the power from renewable resources, for instance, could be either used to instantly meet the power demand of the system, or stored for later use shaving peak consumptions. In this context, as proposed by the E-LOBSTER overall concept, the integration of urban rail networks with other energy independent systems (e.g. other urban mobility systems or renewable power generation plants), could be considered as an extension of the smart grid concept creating synergies among the different systems (e.g. excess regenerative braking energy from metro systems could help to power an urban network of electric vehicles[32], the power generated in nearby RES could be used to feed the urban rail system itself, etc.)

5.2 Renewables resources integration into Railway network

The integration of Renewables resources into Railway network is an interesting option to be considered. As a matter of fact, the availability of renewable energy sources in the area and the local generation of electricity may represent an interesting solution to reduce power consumption from the public network. In this context, photovoltaic solar panels may be installed in stations and depots to meet partially the energy demands[33] as well as solar panels could be installed along the track helping to feed the signalling systems and the substations auxiliaries. Moreover, solar panels on the roof of the rail vehicles could provide power to supply the auxiliary systems[34] [27]. Obviously, the integration of renewable power generation in railway systems requires the use of Energy Storage System, power management controls etc. that could affect the economic viability of these measures. As examples, Transport for Greater Manchester has recently installed an 11kW wind turbine at a train station, and has also installed a similar-sized hydroelectric turbine to power a bus interchange from a river which runs alongside it. Merseytravel has installed a 50kW solar array on their headquarters building. Dijon Metro has installed a 1.5MW solar array[35] on the roofs of their depot buildings as shown in figure 5-1 and its annual energy production exceeds the one used by the depot.

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32 M. Falvo, R. Lamedica, R. Bartoni, G. Maranzano, Energy management in metro-transit systems: An innovative proposal toward an integrated and sustainable urban mobility system including plug-in electric vehicles, Electr. Pow. Syst. Res. 81 (2011) 2127-2138.
33 TramStore21, Building sustainable and efficient tram depots for cities in the 21st century,TramStore21 project, 2013
34 P. Vorobiev, Y. Vorobiev, About the possibilities of using the renewable energy power sources on railway transport, J. Adv. Transport. doi: 10.1002/atr.189 (2011).
35 Metro Strategy 2030 Background Information

Figure 5-1- Dijon's bus/tram depot comprises a 1.5 MW solar panel roof installation (2012)

5.3 Energy storage in railway network

As already seen also in the E-LOBSTER concept, the advances in power electronics and energy storage technologies have enabled ESSs to become an excellent solution for reusing regenerated braking energy in urban rail network. In this context, ESSs can be installed either on board vehicles or at along the track allowing to temporarily store the braking energy of the vehicle and reuse it in the next acceleration phases. If properly dimensioned, ESSs may lead to considerable traction energy savings in urban rail (typically between 15% and 30%). Furthermore, they may contribute to stabilise the network voltage and to shave the power consumption peaks.

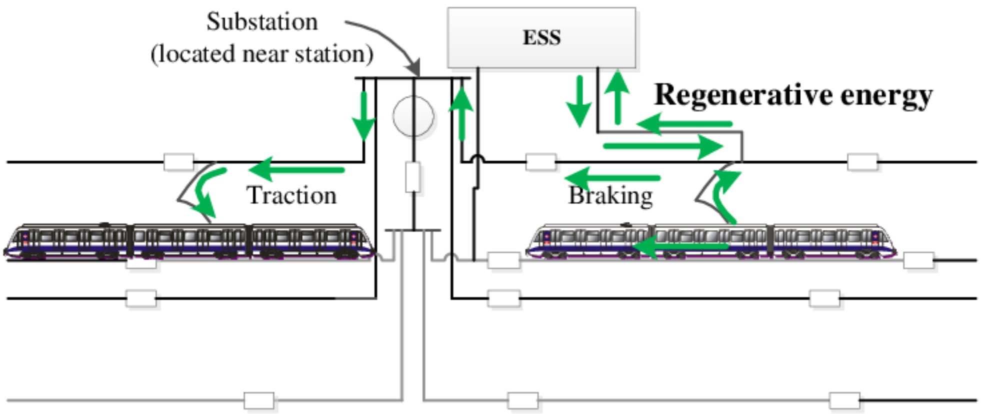

Figure 5-1: Energy Storage System in railway applications

5.3.1 On-Board Energy storage facilities

This option uses large energy-storage systems (traditional batteries, or 'supercapacitors', or a combination of both). Energy recovered during braking is stored into these devices, and then reused directly by the same train, for either accelerating/traction energy, or for auxiliary energy to power lights, heating, control systems. The advantage of this option is that a relevant part of the recovered energy could be re-usable. There is a possibility that traction energy requirements could be reduced by up to 40%-50% using this method. Furthermore, it allows the possibility that trains could actually operate without OLE for a certain distance, and use only the on-board storage to power the train. This would enable operation on short on-track extensions or on-street sectors without the need for OLE, or if OLE is present the train being able to proceed to the next station in an emergency involving loss of overhead power[36]. Just as example, Nice and Paris to name a few are networks currently operating light rail vehicles with on-board energy storage. Furthermore, more advanced 'flash-recharging' technology is currently in use in Seville trams.

5.3.2 Trackside energy storage facilities

This solution requires relatively modest upgrade to the OLE. It would involve the positioning of trackside units on the approach to a station to recover a train's braking energy; when a train on the opposite track was accelerating, it would draw energy from this unit before taking it from the OLE. This solution could potentially give higher energy savings. However, capital and maintenance costs have to be considered. Philadelphia light rail operator SEPTA [37]has installed a trackside energy storage system, with large batteries located at a substation which collect regenerated energy via the OLE.

5.4 Power flow analyses in a typical Metro Electrical Network

A typical Metro was analysed in the framework of E-LOBSTER through the real data measurement of traction substations. This case study is a Line of a typical Metro that is approximately 40km in a ring with 28 train stations. Traction substations are fed through DSO connections in different locations. In this case study, there are 13 traction substations fed by five DSO supply substations spread in network. Traction substations are mainly providing DC supply for trains through rectifiers and some of them also providing supply for train stations loads as Escalators, Lifts, Lightning, Signals, etc. There are some ventilation loads which are also supplied through traction substations. In total, there are six traction substations feeding train station loads and ventilation loads. In all Transformation Stations, two transformers (15kV to 400V) is installed, one is connected, and one is Backup. In traction substations typically there are 3 Transformers of 3.3MVA in which two of them is connected and one is as backup. These transformers are mainly connected to Rectifiers converting 15kVAC to 1500 V DC for traction. As mentioned earlier in some locations, they are also supplying energy to transformer stations. Data are gathered for a week from the traction substations which are connected to DSO point of connections. One of these traction substations is considered for further study. This traction substation is feeding 4 adjacent traction substations and also 8 transformer stations are fed by two of these traction substations.

[36] Metro Strategy 2030 Background Information

[37] J. Poulin, A. Gillespie, K. Morelock, J. McDowall, B. Inniss, SEPTA recycled energy optimization project with regenerative braking energy storage, SEPTA Recycled Energy & Optimization Project, 2012.

Measured Active & reactive power is plotted in Figure 5.4. This figure clearly shows the intermittent consumption has many spikes and this phenomena comes from train load nature. The measured data is gathered every 30 seconds. It should be added there are border lines located in whole distribution network with open circuit breaker switches which guarantees two different HV DSO supplies are not connected in normal operation of network.

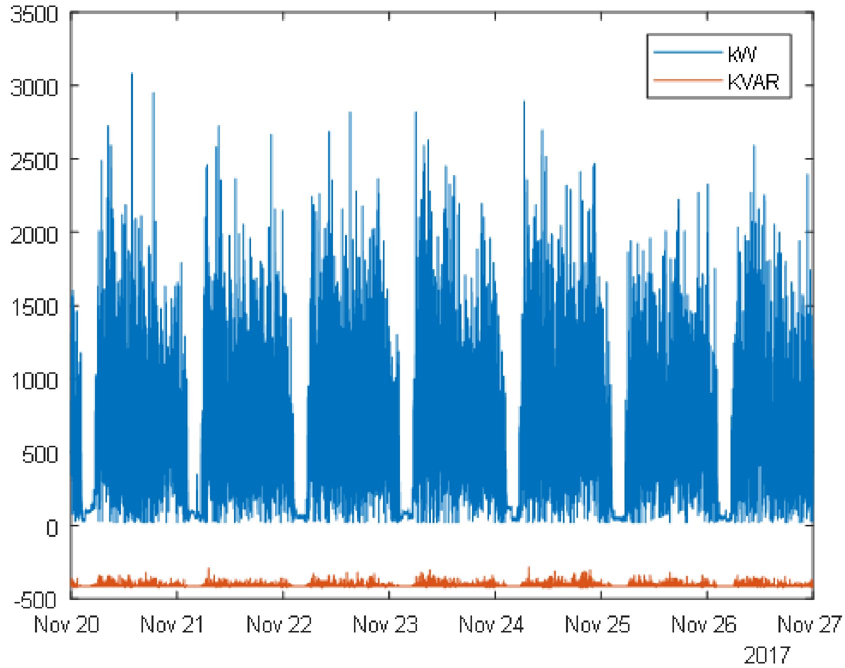

Figure 5.4. Active & Reactive power measured from Traction substation connected to DSO

For more clarification, the active and reactive power of the same traction substation in Figure 5.4 is box plotted for a day in Figure 5.5. A boxplot is a standardized way of displaying the distribution of data based on a five number summary (minimum, first quartile (Q1), median, third quartile (Q3) and maximum). Box plots may also have lines extending vertically from the boxes indicating variability outside the upper and lower quartiles, hence the terms box-and-whisker plot and box-and-whisker diagrams. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol.

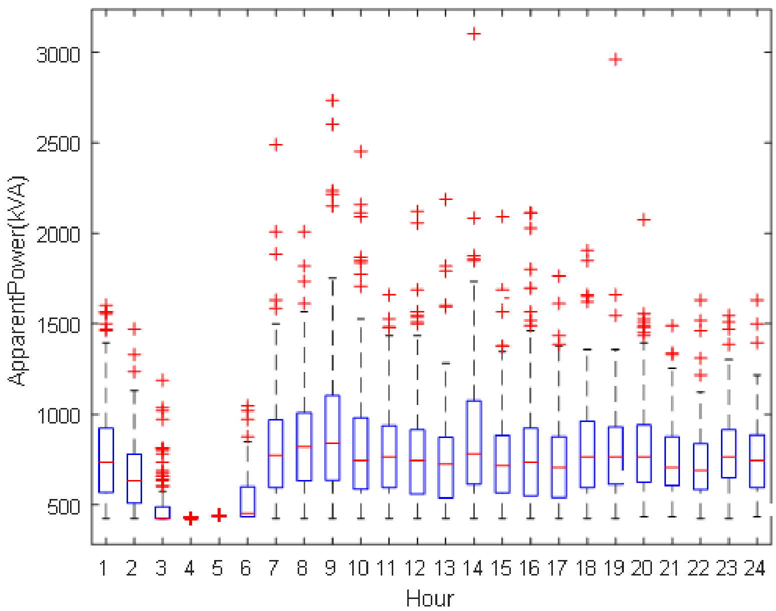

Figure 5.5. Box plot of Apparent power (kVA) of Traction substation connected to DSO

Figure 5.4 & 5.5 clearly shows that based on metro time table, it will be a peak starting from early morning to the evening. There is no train running between 2:30 to 5:30, so the consumption is extremely lower. The line voltage data is also gathered from the same location and are plotted in Figure 5.6 for the same working day.

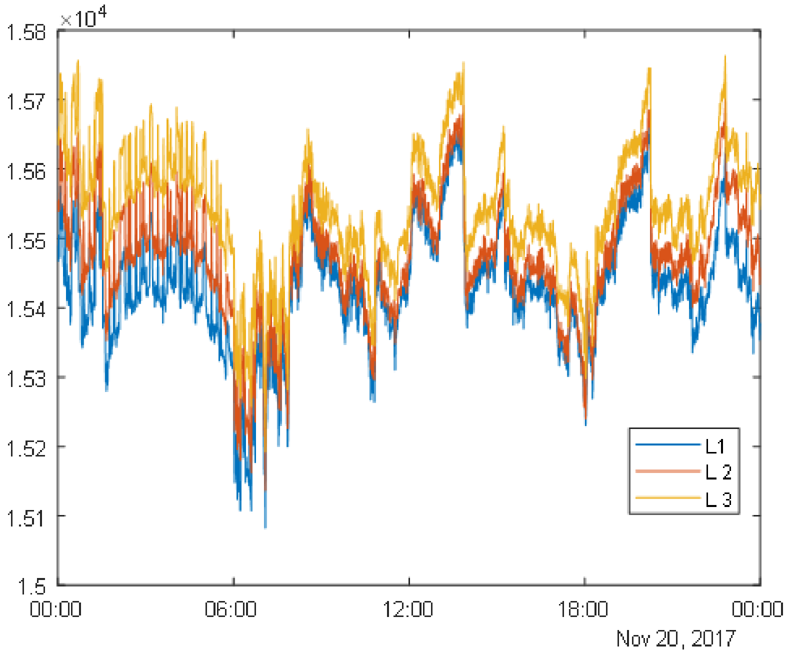

Figure 5.6- The Line Voltages (kV) measured from tractions substation connected to DSO

The voltage mitigates clearly in 10% limits, so there is no problem with violating voltage limits, however it is clearly seen some sort of voltage unbalance is happening. In a three-phase system, voltage unbalance takes place when the magnitudes of phase or line voltages are different and the phase angles differ from the balanced conditions, or both. There are few definitions of voltage unbalance from three different communities. These definitions have important implications when studying for example, the effects of voltage unbalance on the performance of three-phase induction machines. The true definition of voltage unbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component. The percentage voltage unbalance factor (% VUF), or the true definition, is given by:

$\%VUF = \frac{negative\ sequence\ voltgae\ component}{positive\ sequence\ voltage\ component}.100$	(1)

A formula given in (2) avoids the use of complex algebra but gives approximation to the true definition and used for calculating voltage unbalance in this study:

$\%\ Voltage\ Unbalance = \frac{82.\sqrt{V_{abe}^2 + V_{bce}^2 + V_{cae}^2}}{avg\ line\ voltage}$	(2)

Voltage unbalance calculated by Eq.(2) is plotted in Figure 5.7 and it is around 0.6 to 0.7 in minimum load during night and then when train starts working the voltage unbalance decreases around 0.3 in more acceptable range. Since a dedicated feeder cable from DSO substation is connected to traction substation, there will not be any conflict for other customers connected to DSO substation.

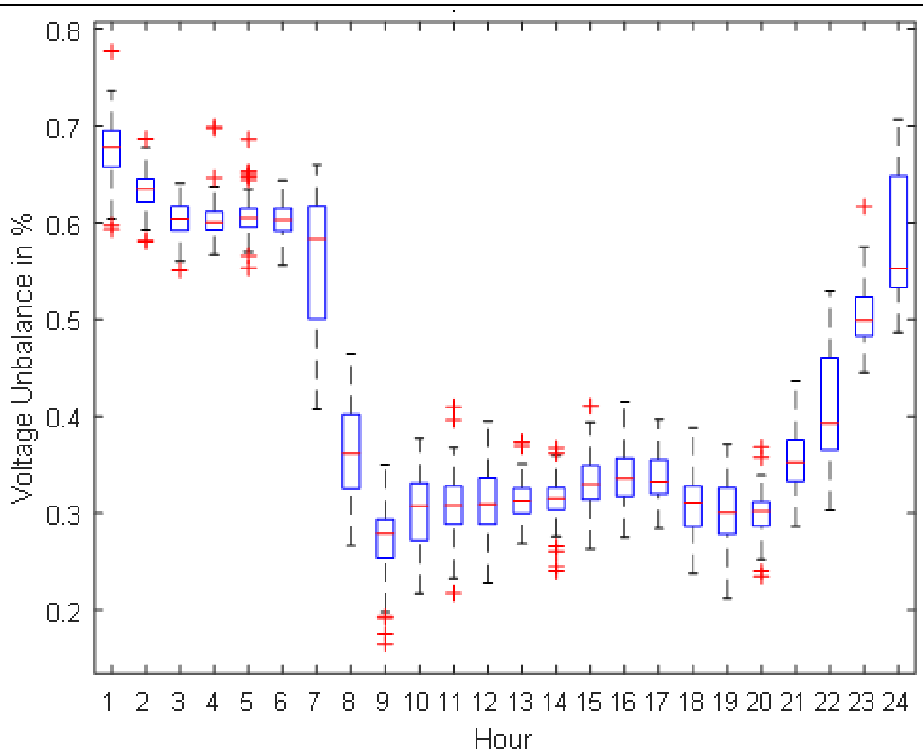

Figure 5.7- Voltage Unbalance

As mentioned earlier, the traction substation (connected to DSO) is feeding 4 adjacent traction substations and two of traction substations are feeding 8 transformer stations. The demand of each transformer station is not measured but the data from these two traction substations which are feeding transformer substation is gathered. There are two cables out from these traction substations to feed transformer stations; one cable labelled as Cable1 is feeding transformer stations loads, the other one labelled Cable2 is feeding ventilation system. There is a changeover between two cables every two months for operation purposes. The load data of cables have been plotted in Figure 5.8 and Figure 5.9. Data is also measured from one of these traction substations feeding four trains stations loads. Figure 5.7 clearly shows that the train station loads are constant during the working hours and will be very low during no train running time. Spikes seen in load data is not consistent for the whole week and as the loads are basically escalators, lights, lifts, signalling and air conditioners, so these few spikes could be ignored.

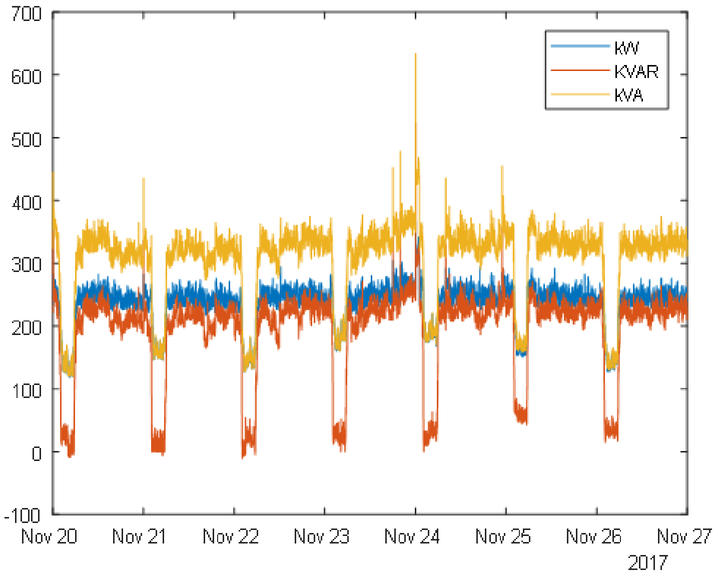

Figure 5.8 - Load data measured of Cable 1 feeding a number of train station loads

Cable 2 is feeding a number of ventilation fans distributed in underground tunnels and the data measured from traction substations feeding a number of them is plotted in Figure 5.9. Some few spikes have been observed which could be ignored as occurring very few times in a week data.

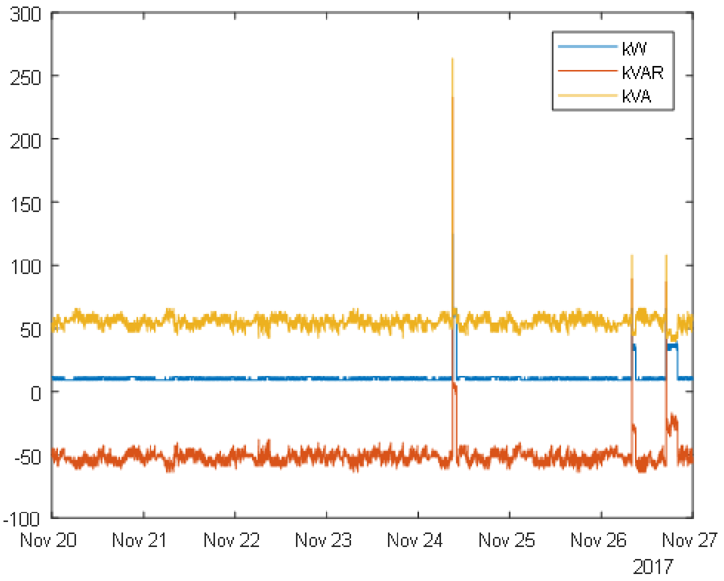

Figure 5.9 - Load data measured of Cable 2 feeding a number of ventilation loads

To calculate the losses in the railway distribution network, the network is modelled in an electrical power systems analysis software called ERACS[38] and the loads of each transformer station is equally divided between transformer stations and losses is calculated in the internal network which shows losses is less than 1% in whole the ring. The internal railway distribution network is well designed and

[38] https://www.eracs.co.uk/

strongly robust so the impact on losses is not considerable in internal railway distribution network however by installing a trackside energy storage, the demand of train will be decreased specially peak shaving of train demand can have a considerable impact on reducing losses.

In summary, the resistive losses in the railway power distribution network are a quadratic function of the current. Therefore, they can be significantly reduced by limiting the power peaks caused by the simultaneous acceleration of different trains in the network. The optimisation of timetables and the use of regenerative braking technologies are key measures for this purpose. Likewise, energy losses may be minimised by selecting higher electrification voltages, although this may imply excessively high investment costs in existing systems. Another option to reduce energy losses in the power supply network is selecting low-resistance materials for the feeder lines. Despite requiring relatively high investment costs, an increasing number of third rail powered systems (e.g. the London Underground) are replacing the standard steel conductor rails by aluminium-based ones, which offer up to 50% less resistance. Superconducting cables may represent an alternative to conventional line conductors but, though promising, this technology is still in the research and development stage[39].

It is worth mentioning that Grid Supply Points (GSP) utilized for providing power to the DC railway network are generally not sole use sites, unlike those which provide power to the AC railway network. Sole use refers to the GSP providing power to the railway network alone, with no other customers fed off the same circuit. As such there are a number of additional feeders that the GSP transformer is connected. This limits the amount of control the railway infrastructure manager has regarding increasing loading on the equipment (this fact comes into consideration when assessing timetable changes and associated enhancement options).

In the second years of the project, additional simulations will be carried out also on the distribution network not connected to the railway preferably in the demo site in order to investigate the local losses. Actually, the DSO owner of this network has been involved in the framework of the project as stakeholders.

39 M. Tomita, Y. Fukumoto, K. Suzuki, M. Miryata, Development of prototype DC superconducting cable for railway system, Physica C Supercond. 470 (2010) S1007–S1008.

6 Conclusion

Smart grid technologies could provide improved real-time information on rail energy consumption and generation, for example from regenerative braking or renewable energy sources, as well as on the performance and spare capacity of electrification assets such as transformers. This information could inform energy management strategies and the replacement or upgrade of electrification assets.

In this report an overview of general architecture of distribution networks have been provided before moving the focus on the strategies to mitigate energy losses in these networks.

Then general architecture of railway power supply systems was illustrated by focusing in particular on energy efficiency solutions for railway networks.

Finally, power flow analyses through simulations by using real data from a typical Metro Electrical Network have been performed for assessing the losses in the railway power distribution network.