FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Simulation of Intelligent Active Distributed Networks
Implementation of Storage Voltage Control

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Abstract

While distributed generation (DG) from renewable energy resources is seen as a key element of future energy supply, current electricity grids are not designed to integrate a steadily increasing share of distributed generators. The hierarchical network topology was designed for unidirectional power flows and passive operation. In order to avoid excessively expensive grid reinforcements, new solutions for active grid operation are necessary. In the context of the Austrian national research project DG DemoNet, different methods for an active distribution network with a high penetration of distributed generation were developed, especially regarding the voltage control in these networks. These methods were simulated for existing Austrian net sections, in the medium voltage systems. This work analysis the possibility to broaden these methods by the application of storage technologies and its integration into the already existing voltage control methods, especially into the coordinated voltage control, which comprises tap changing of the on-load tap changer of the transformer, the production of reactive power and the curtailment of the active power of the power plants. The work explains the changes performed in the algorithm of the coordinated voltage control to admit the integration of storage systems, including the definition of the storage variable and the behavior of the storage system in different voltage scenarios. Simulations were performed to discover the required power and capacity of a theoretical storage device to keep the voltage within the desired limits, with and without other voltage control methods. Several different storage technologies were analyzed, taking into account their characteristics, principal advantages and disadvantages. These technologies were then compared aiming to find those more suitable for the application to the coordinated voltage control method. The simulation results and storage technologies comparison can be used for the modeling of different storage systems, as long as the required variables and parameters are well defined and validated for the application to the voltage control methods.

Resumo

Embora a geração distribuída a partir de recursos energéticos renováveis seja vista como elemento-chave do futuro abastecimento energético, as actuais redes eléctricas não são concebidas para integrar um constante aumento da quota de geração distribuída. A topologia de rede hierarquizada foi concebida para um fluxo de potência unidirecional e operação passiva. A fim de evitar reforços na rede, que são excessivamente caros, novas soluções para uma rede activa são necessários. No contexto do projecto de investigação nacional austríaco DG DemoNet, diferentes métodos para uma rede activa de distribuição com uma elevada taxa de penetração de geração distribuída foram desenvolvidas, especialmente no que diz respeito ao controlo da tensão destas redes. Estes métodos foram simulados para secções da rede austríaca, em sistemas de média tensão. Este trabalho analiza a possibilidade de expandir estes métodos através da aplicação de tecnologias de armazenamento e sua integração aos métodos de controlo de tensão já existentes, especialmente para o método de controlo coordenado de tensão, que inclui transformadores de passo, produção de potência reativa e o corte de potência activa das centrais eléctricas. Este trabalho explica as mudanças realizadas no algoritmo do controlo coordenado de tensão com o fim de permitir a integração dos sistemas de armazenamento, incluindo a definição da variável de armazenamento e o comportamento do sistema de armazenamento para diferentes cenários de tensão. Foram realizadas simulações para descobrir a potência e capacidade necessários de um dispositivo teórico de armazenamento para manter a tensão dentro dos limites desejados, com e sem outros métodos de controle de tensão. Várias tecnologias de armazenamento diferentes foram analisadas, levando em conta as suas principais características, vantagens e desvantagens. Estas tecnologias foram, então, comparadas com o objetivo de encontrar as mais adequadas para a aplicação ao método de controlo coordenado de tensão. Os resultados da simulação e comparação das tecnologias de armazenamento podem ser utilizados para a modelagem de diferentes sistemas de armazenamento, desde que as variáveis e os parâmetros exigidos sejam bem definidos e validados para a aplicação aos métodos de controlo de tensão.

Preface

The voltage control method presented in this work is an extension to the coordinated voltage control in the ambit of the DG DemoNet project. In this project different techniques are applied to solve the voltage problems that can occur on networks with a high share of distributed generation. Since some of these techniques involve the curtailment of active power, some alternative solutions need to be investigated as the power curtailment leads to serious economical issues. One of the alternatives is the application of storage devices that can be used to charge in cases of overvoltage and discharge in cases of undervoltage, keeping the voltage between expected operational limits. However, the modelling of appropriate storage systems for this application requires the knowledge of technical requirements and available technologies that fulfil these requirements.

Simulations were carried out with the objective to dimension the storage systems for voltage control, within the coordinated voltage control algorithm. With this dimensioning it was possible to investigate some technologies and find those more suitable to be applied to these systems.

My main difficulty in this work was to find an accurate correlation between the simulated storage system (concerning mainly their capacity and power) and the available technologies, since many of the time constants of the diverse network components and the precise and complete description of some storage technologies were not available. Another difficult I faced was to understand the behaviour of the algorithm of the coordinated voltage control, which was written in MATLAB® and simulated with DIgSILENT Power Factory®. The interface between the two softwares doesn’t permit debugging, what made the process of changing the algorithm and testing it very complex and time consuming.

This work was accomplished at OFPZ Arsenal Ges.m.b.H (or simply “arsenal research”) in Vienna, Austria and could not be done without the help of Helfried Brunner and Benoît Bletterie, employees of this research institute. They helped me in every way, providing me with useful references and with their experience and time. I learnt a lot during this year at arsenal research and I am glad I had this opportunity to work with them. I would also like to thank to my advisor, Professor Peças Lopes, who deposited his confidence in me and arsenal research and was ready to help when necessary.

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Abbreviations List

CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power
CN	Critical Nodes
CVC	Coordinated Voltage Control
DEA	*Dezentrale Erzeugungsanlage* (Distributed Generator)
DG	Distributed Generation
DNO	Distribution Network Operators
DSM	Demand Side Management
EC	Electrochemical Capacitors
Li-Ion	Lithium-Ion Battery
MV	Medium Voltage
MOC	Multiple Overvoltage Control
NaS	Sodium-Sulfur Battery
P	Active Power
PM	Priority Matrix
PQ	Power Quality
PSB	Polysulfide Bromide Battery
Q	Reactive Power
RE	Renewable Energies
RES	Renewable Energy Systems
RFB	Redox Flow Battery
SMES	Superconducting Magnetic Energy Storage
VRB	Vanadium Redox Flow Battery
VRLA	Valve-regulated lead-acid batteries
ZnBr	Zinc Bromine Flow Battery

1 Introduction

In recent years, distributed generation (DG) and its integration into distribution networks has been the subject of growing interest as it is now projected that the penetration of renewable DG is likely to increase significantly in the upcoming years. The international community, faced with the environmental challenge and the increasing energy demand worldwide, accepted the fact that the future energy strategy should be based on a “clean” energy supply. As the conventional power generation technologies that use fossil fuels represent major sources of CO_2 emissions, distributed and renewable energy technologies have, in the long term, the potential to make a large contribution to the world energy supply, achieving the security of supply and environmental sustainability.

The DG main targets are to decrease the cost of electricity and fuel supplies to competitive levels developing highly efficient concepts and achieving major cost reductions in the entire production chain, as well as to improve reliability, safety, availability, system efficiency and durability with long maintenance intervals of electricity supply.

Therefore all renewable energy technologies and their integration into the network require further research and development to reduce costs, optimize performance and to improve reliability. These aspects will not only contribute to a modern and clean electrical system, but will also make it economically feasible.

1.1 Objectives and Motivation

In the context of the austrian national research project DG DemoNet, different methods for an active distribution network with a high penetration of distributed generation were developed. These methods were implemented in the net simulation environment DIgSILENT PowerFactory® under integration with MATLAB® into existing austrian net sections, in the medium voltage systems. Active networks define networks where the distributed generators and consumers actively contribute to keep the voltage between tolerance limits.

The research performed during the period visiting arsenal research was focusing mainly on the project DG DemoNet Project and the possibility to improve and broaden it, by application of storage technologies for the voltage control and its integration with the already existing voltage control methods.

These existing methods are based on the intelligent usage of the distribution network elements, like transformers and generators, to improve the voltage profiles and keep them between expected limits. The application of the storage systems has the objective to provide an alternative solution for these existing voltage regulation methods and this work has the objective to serve as reference in a future implementation of these solutions to real distribution networks

In a broaden sense, the energy storage technologies can enhance DGs stability and permit DGs to run at a constant and stable output, providing energy to ride-through instantaneous lacks of primary energy and permitting DGs to operate as dispatchable units. This work's application is, however, focused on the voltage control capabilities of the storage systems.

1.2 Chapters Overview

This work is divided in six chapters. The first chapter is this introduction. The second chapter "Distributed Generation" gives an overview about the differences between the traditional centralized generation and the new decentralized generation schemes. It also explains the main goals behind this new electrical generation paradigm and what are the technical challenges due to the integration of this generation to the distribution networks.

The third chapter "DG DemoNet Project" explains briefly the current situation of the distribution networks in Austria and how the DG DemoNet Project deals with the issue of the integration of DG to these networks. It explains the technical aspects of this integration and focuses on the step model, which consists of different approaches for voltage control in distributed networks with high DG penetration. Special attention is given to the coordinated voltage control, which is the most elaborated among the step models. The algorithm of the coordinated voltage control is explained, especially referring to the innovative generation share concept.

The fourth chapter "Energy Storage Systems, Status and Potential" presents a brief history of the storage and presents an overview of many storage technologies used especially for the integration in distributed generation with presence of DG. The application of each of these technologies, their characteristics and their advantages and drawbacks are commented. In the end of the chapter a comparison of these technologies is presented and also how the storage principle was integrated to the coordinated voltage control algorithm, highlighting the changes performed in this algorithm.

The fifth chapter "Study Case: Vorarlberg, Austria" presents a study case used as an example to show the results of the integration of the storage principle to the coordinated voltage control algorithm. This chapter also shows the basic characteristics of the software used for the simulations and a comprehensive list of results of the performed simulations, for the considered storage model systems.

The sixth and last chapter presents a brief discussion about the results obtained and the main difficulties faced during the elaboration of this work. It includes also a discussion about the new improvements to the coordinated voltage control that are currently being implemented. Finally, the possibility to use Demand Side Management together with the analyzed solutions is considered.

2 Distributed Generation

Power systems were designed to generated electricity in large generating stations. These stations produce and transmit electricity through high-voltage transmission systems then, at reduced voltage, transmit it through local distribution systems to consumers.

DG is another power paradigm, where electricity is not generated by some large power stations, but by many small energy sources. This new paradigm introduces many advantages, like reducing the energy losses in transmission, reducing the number of transmission lines and also reducing the need to operate power stations burning fossil fuels such as coal and gas. DG conducts, however, to some technical issues like voltage changes in the networks, the need to special protections and controls.

There is no universally accepted terms for distributed generation, since each author has a definition that can vary somehow in comparison with the others. It can be defined, for example, as (HI-ENERGY, 2008):

"A distributed generation system involves small amounts of generation located on a utility's distribution system for the purpose of meeting local (substation level) peak loads and/or displacing the need to build additional (or upgrade) local distribution lines."

Besides this definition, there are many other which can be considered equivalent or synonyms to distributed generation, like embedded generation or dispersed generation. In fact, many of these definitions try to establish a clear difference to the traditional and centralized generation concept. In this text only the term "distributed generation", and alternatively its abbreviation "DG" will be used, although all of these terms are considered equivalent and interchangeable.

In this chapter, the most important characteristics of the DG are commented, in special regarding its effects on the integration into distribution networks.

2.1 Reasons for Distributed Generation

The conventional arrangement of a modern large power system (Figure 2.1) offers a number of advantages. Large generating units can be made efficient and operated with only a relatively small number of personnel. The interconnected high voltage transmission network allows generator reserve requirements to be minimized and the most efficient generating plant to be dispatched at any time, and bulk power can be transported large distances with limited electrical losses. The distribution networks can be designed for unidirectional flows of power and sized to accommodate customer loads only. However, a number of influences started to play a role over the last few years encouraging DG. Some of these influences are the rational use of energy, the deregulation policy, the diversification of energy sources and specially the need of reduction the gaseous emissions, mainly CO_2.

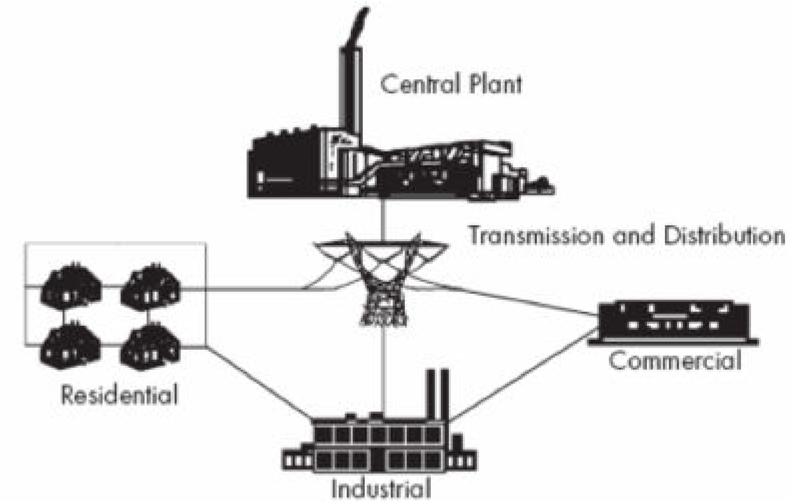


Figure 2.1 – Scheme of a centralized power plant

Environmental impact is a major factor in the consideration of any electrical power scheme, and there is a generally accepted concern over gaseous emissions from fossil-fuelled plants. As part of the Kyoto Protocol, especially the European Union has to reduce substantially the CO_2 emissions, in order to help counter climate changes. Hence most governments have programs to support the exploitation of so-called new renewable energy resources, which include wind power, micro-hydro, solar photovoltaic, landfill gas, energy from waste and biomass generation. Renewable energy sources have much lower energy density than fossil fuels and so the generation plants are smaller and geographically widely spread (Figure 2.2). For example, wind farms must be located in windy areas, while biomass plants, typically of less than 50 MW in capacity, are then connected into the distributed system. In many countries the new renewable generation plants are not planned by the utility but are developed by entrepreneurs and are not centrally dispatched but generate whenever the energy source is available (JENKINS *et al*., 2000).

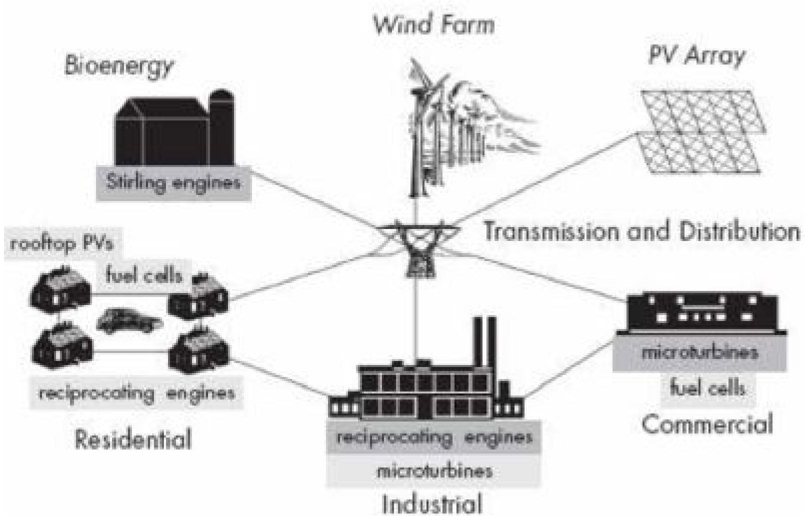


Figure 2.2 – Scheme of distributed generation

Cogeneration or Combined Heat and Power (CHP) schemes, for example, make use of waste heat of thermal generating plants for either industrial processes 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 distances is not economical and so it is necessary to locate the CHP plant close to the heat load. This again leads to relatively small generation units, geographically distributed and with their electrical connection made to the distribution network. Although CHP units can, in principal, be centrally dispatched, they tend to be operated in response to the requirements of the heat load or the electrical load of the host installation rather than the needs of the public electricity supply.

The commercial structure of the electricity supply industry is also playing an important role in the development of DG. In general a deregulated environment and open access to the distribution network is likely to provide greater opportunities for DG.

The benefits of the DG to the power system depend on its location, but normally it reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be built and increases the quality of supply, which leads to a distribution network infrastructure cost deferral. Other benefits include additional energy-related benefits like improved security of supply, avoidance of overcapacity and peak load reduction.

Finally, in some countries the fuel diversity offered by DG is considered to be valuable while in some developing countries the shortage of power is so acute that any generation is to be welcome.

At present, DG is seen almost exclusively as producing energy (kWh) and making no contribution to other functions of the power system (e.g. voltage control, network reliability, generation reserve capacity, etc). Although this is partly due to the technical characteristics of the DG, this restricted the role of the DG is predominantly caused by the administrative and commercial arrangements under which it presently operates.

Looking further into the future, the increased use of fuel cells, micro CHP using novel turbines or Stirling engines and photovoltaic devices integrated into the fabric of buildings may all be anticipated as possible sources of power for DG. If these technologies become cost-effective then their widespread implementation will have very considerable consequences for existing power systems (JENKINS *et al.*, 2000).

2.2 Technical Challenges of Integration of DG into Distribution Networks

Modern distribution systems were designed to accept bulk power at the bulk supply transformers and to distribute it to customers. Thus the flow of both active power (P) and reactive power (Q) was always from the higher to the lower voltage levels (Figure 2.3). Even with interconnected distribution systems, the behavior of the network is well understood and the procedures for both design and operation long established.

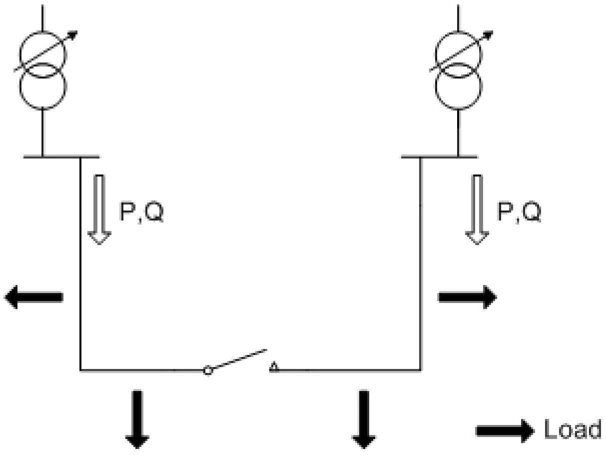


Figure 2.3 – Conventional distribution system

However, with significant penetration of DG 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 by the loads (Figure 2.4). For example, the CHP scheme with the synchronous generator (S) will export active power when the electrical load of the premises falls below the output of the generator, but may absorb or export reactive power depending on the setting of the excitation system of the generator. The wind turbine will export active power but is likely to absorb reactive power as its asynchronous generator (A) requires a source of reactive power to operate. The voltage source converter of the photovoltaic (pv) system will allow export of active power at a set power factor but may introduce harmonic currents, as indicated in Figure 2.5. Thus the power flows through the circuits may be in either direction depending on the relative magnitudes of the active and reactive network loads compared to the generator outputs and any losses in the network.

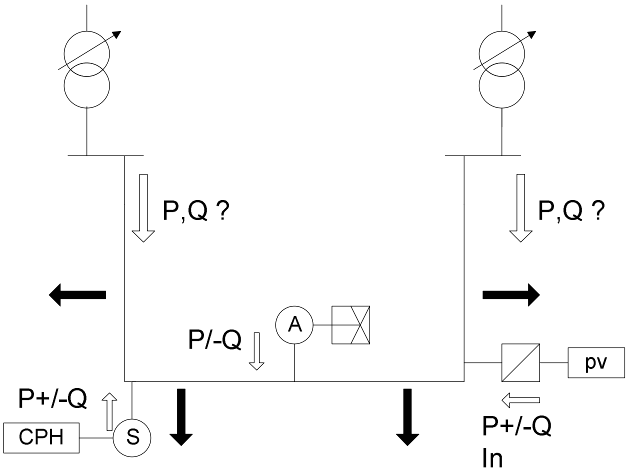


Figure 2.4 – Distribution system with DG

The changes in P and Q flows caused by DG have important technical and economic implications for the power system. The most important technical issues of DG on the distribution system are listed on the next topics.

2.2.1 Network Voltage Changes

Every distribution utility has an obligation to supply its costumers at a voltage within specified limits. This requirement often determines the design and expense of the distribution circuits and so, over the years, techniques have been developed to make the maximum use of distribution circuits to supply costumers within the required voltages.

In a conventional distribution system the voltage drops along network (Figure 2.5); with the connection of DG the voltage may rise (Figure 2.6). If system studies are undertaken to investigate the effect of DG on the network voltage, then these can either consider the impact on the voltage received by customers or may be based on permissible voltage variations of some intermediate section of the distribution network (JENKINS *et al.*, 2000).

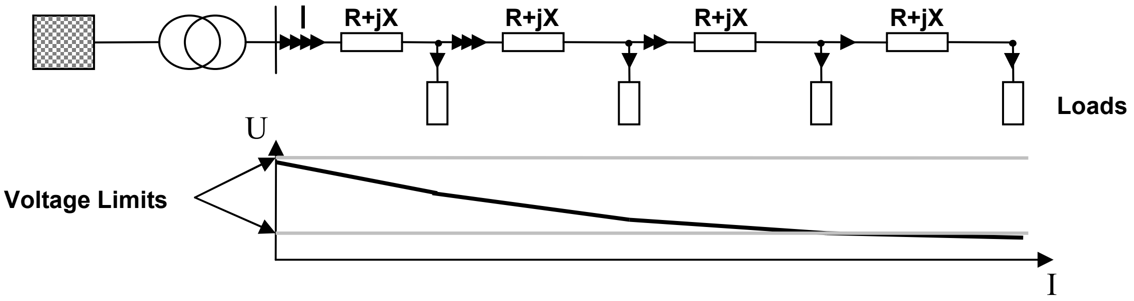


Figure 2.5 – Voltage drop in a conventional distribution network

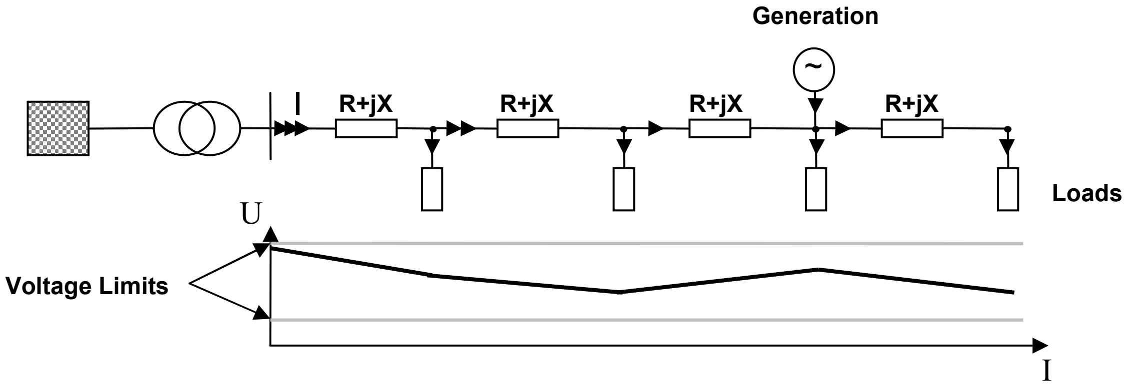


Figure 2.6 – Voltage rise in a distribution network with DG penetration

DG will generally increase voltage at its connection point, which may cause overvoltage during low loading conditions. Different techniques can be used to counteract the voltage rise due to the DG:

- Reinforcement of the network (upgrade the conductor, transformer…);
- Constrain generation;
- Generator reactive power management;

- Controlling the primary substation voltage with the OLTC (on load tap changer) transformer;
- Installing auto transformers or voltage regulators along the critical line;
- Demand side management.

2.2.2 Increase in Network Fault Levels

Most of the DG plants use rotating machines and these will contribute to the network fault levels, by reducing the combined source impedance. Both induction and synchronous generators will increase the fault level of the distribution system although their behavior under sustained fault conditions differs.

In urban areas where the existing fault level approaches the rating of the switchgear, the increase in fault level can be a serious impediment to the development of DG.

The fault level contribution of a DG may be reduced by introducing an impedance between the generator of the network by a transformer or a reactor but at the expense of increasing the losses and wider voltage variations at the generator.

2.2.3 Power Quality

Two aspects of power quality are usually considered to be important: (i) transient voltage variations and (ii) harmonic distortion of the network voltage. Depending on the particular circumstance, DG plant can either decrease or increase the quality of the voltage received by other users of the distribution network.

DG plant can cause transient voltage variations on the network if relatively large current changes during connection and disconnection of the generator are allowed. The magnitude of the current transients can, to a large extent, be eliminated by careful design of the DG plant, although for single generators connected to weak systems, the transient voltage variations caused may be the limitation on their use, rather than steady-state voltage rise. Synchronous generators can be connected to the network with negligible disturbance if synchronized correctly, and anti-parallel soft-start units can be used to limit the magnetizing inrush of induction generators to less than rated current. However, disconnection of the generators when operating at full load may lead to significant, if infrequent, voltage drops. Also, some forms of prime-mover (e.g. fixed speed wind turbines) may cause cyclic variations in the generator output current which can lead to so-called “flicker” nuisance if not adequately controlled. Conversely, however, the addition of DG plant acts to raise the distribution generation fault level. Once the generation is connected any disturbances caused by other customer's loads, or even remote faults, will result in smaller voltage variations and hence improved power quality. It is interesting to note that one conventional approach to improving the power quality of sensitive high value manufacturing plants is to install local generation.

Similarly, incorrectly designed or specified DG plants, with power electronic interfaces to the network, may inject harmonic currents which can lead to unacceptable network voltage distortion. However, directly connected generators can also lower the harmonic impedance of the distribution network and so reduce the network harmonic voltage at the expense of increased harmonic currents in the generation plant and possible problems due to harmonic resonances. This is of particular importance if power factor correction capacitors are used to compensate induction generators (JENKINS *et al.*, 2000).

2.2.4 Protection Schemes

A number of different aspects of DG protection can be identified:

- Protection of the generation equipment from internal faults;
- Protection of the faulted distribution network from fault currents supplied by the generator;
- Anti-Islanding protection;
- Impact of DG on existing distribution system protection.

Protecting the generator from internal faults is usually fairly straightforward. Fault current flowing from the distribution network is used to detect the fault, and techniques used to protect any large motor are generally adequate.

Protection of the faulted distribution network from fault current from the generators is often more difficult. Induction generators cannot supply sustained fault current to a three-phase close-up fault and their sustained contribution to asymmetrical fault is limited. Small synchronous generators require sophisticated exciters and field forcing circuits if they are to provide sustained fault current significantly above their full load current. Thus, for some installations it is necessary to rely on the distribution protection to clear any distribution circuit fault and hence isolate the DG plant which is then tripped on over/undervoltage, over/under frequency protection or anti-islanding protection. This technique of sequential tripping is unusual but necessary, given the inability of some generators to provide adequate fault current for more conventional protection schemes.

"Islanding" protection is a particular issue in a number of countries, particularly where autoreclose is used on the distribution circuits. For a variety of reasons, both technical and administrative, the prolonged operation of a power island fed from the generator, but not connected to the main distribution network is generally considered to be unacceptable. However, intentional islanding can be used, following certain procedures, in order to improve the reliability of distribution networks with high DG penetration. Planned islanding can be applied to avoid loss of load for predictable situations such as maintenance or repair in the upstream grids (PEÇAS LOPES *et al.*, 2005).

The islanding issue is shown in Figure 2.7. If circuit breaker A opens, perhaps on a transient fault, there may be insufficient fault current to operate the circuit breaker B. In this case the generator may be able to continue to supply the load. If the output of the generator is able to match the active and reactive power demand of the load precisely, then there will be no change in either the frequency or voltage of the islanded section of the network. Thus it is very difficult to detect reliably that circuit breaker A has opened using only local measurements at B. In the limit, if there is no current flowing through A (the generator is supplying the entire load) then the network conditions at B are unaffected whether A is open or closed. It may also be seen that since the load is being fed through the delta winding of the transformer then there is no neutral earth on that section of the network.

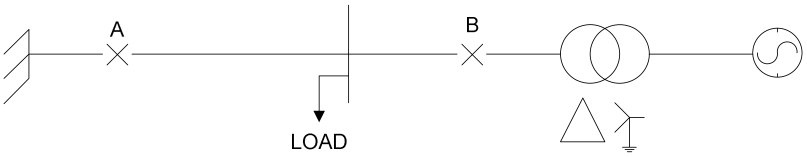


Figure 2.7 – Illustration of the islanding issue

Finally, DG may affect the operation of existing distribution networks by providing flows of fault current which were not expected when the protection was originally designed. The fault contribution from a DG generator can support the network voltage and lead to relays under-reaching.

2.2.5 Stability

For DG schemes, whose object is to generate kWh from new renewable energy sources, considerations of generator transient stability tend not to be of great significance. If a fault occurs somewhere on the distribution network to depress the network voltage and the DG generator trips, then all that is lost is a short period of generation. In contrast, if a DG generator is viewed as providing support for the power system, then its transient stability becomes of considerable importance. Both voltage and/or angle stability may be significant depending on the circumstances.

2.2.6 Grid Losses

Connecting the DG in distribution networks also influences the losses in the network. Small penetrations of distributed generators tend to reduce network power flows and consequently network losses. When the penetrations increases the distributed generators will export power to the grid and may cause increase in network losses, as shown in Figure 2.8.

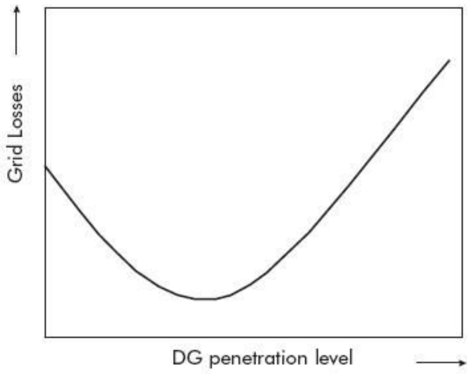


Figure 2.8 – Grid losses related to the penetration of DG (VAN GERWENT, 2006)

2.2.7 Network Operation

DG also has important consequences for operation of the distribution network in that circuits can now be energized from a number of points. This has implications for policies of isolation and earthing for safety before work is undertaken. There may also be more difficulty in obtaining outages for planned maintenance and so reduced flexibility for work on a network with DG connected to it.

To date, most attention has been paid to the immediate technical issues of connecting and operating generation on a distribution system, and most countries have developed standards and practiced to deal with these. In general, the approach adopted has been to ensure that any DG does not reduce the quality of supply offered to other costumers and to consider the generator as “negative load”. Some economic consequences and opportunities of DG are only now being considered, and it is likely that these will become apparent most quickly in electricity supply industries which are deregulated and there is a clear distinction between electricity supply (i.e. provision of kWh) and electricity distribution (i.e. provision of distributed network service).

In order to minimize the negative effects of DG, network operators prefer to connect DG to higher voltages where their impact to voltage profile is minimal (STRBAC *et al.*, 2002). However, the commercial viability of DG projects is sensitive to connection costs. These costs increase considerably with the voltage level at which the DG is connected. Generally the higher the voltage or sparser the network, the higher the connection cost. The developers of DG therefore generally prefer to connect at lower voltages.

Due to the afore-mentioned technical challenges, distribution networks with high DG penetration need an active approach in sense of operation, control, communication and protection. Therefore research and development (R&D) is necessary to overcome barriers and make further use of the benefits of DG. The R&D should be focused on modern information and communication technologies, storage technologies, new protection schemes, new network planning tools, interconnection standards, control and management systems, cost reduction, improvement of efficiency, availability and reliability of DG devices (e.g. with new forecasting methods) and reducing the environmental impact (SCHWAEGERL, 2004).

3 DG DemoNet Project

As was described in the previous chapter, a higher penetration of DG changes the former purely passive distribution system to active, and the unidirectional flow changes to a bidirectional load flow. However, this development is usually not reflected when it comes to network operation, since in most cases DG is simply seen as a negative load. Real active operation means that generation, the network and consumption (loads) within the distribution system actively interact and adapt each other according to the actual load flow situation. The austrian project DG DemoNet-Concept represents new strategies in the field of DG where currently passive distribution networks become active networks, able to accommodate a significant penetration from DG. The conversion from passive to active operation introduces many challenges considering DG network integration, power quality, concepts and strategies for network planning, control and supervision as well as information and communication technologies. As the research work in the field of active networks is mainly focusing on the theoretical part of the problem, the goal of the DG Demo-Net project is the practical realization of the demonstration network where active network approach should be implemented with the least investment costs.

3.1 Current Situation in Austria

Innovative distribution network operators (DNOs) are already taking part in research and demonstration projects. Those operators intend to learn how to deal with the change towards a more and more decentralized electricity system. The DG DemoNet-Concept is being performed by three austrian DNOs and its main objectives are to choose representative parts of networks in Austria for practical realization of demonstration networks with a high penetration of DG, and to analyze within these low and/or medium voltage grid selections, the possibilities for implementing different model systems (Step Model “DG Integration”) and plan the technical, organizational and economical realization.

The share of DG in the networks of the three DNOs is shown in Table 3.1. In two cases the installed capacity of distributed generation is close to the maximum load in the network. The dominating primary energy carriers are hydro power and photovoltaic (with a high number of units but small installed power). In addition, the DG units are not homogeneously distributed in the networks (Figure 3.1).

Table 3.1 – Share of generation in distribution grids (LUGMAIER *et al.*, 2007)

	DNO1 (NL^4 4-7)	DNO1 (NL^4 3–7)	DNO2 (NL^4 3-7)	DNO3 (NL^4 4-7)
$GWh_{gen}/GWh_{dem}{}^{1}$	0,11	0,41	0,54	0,11
$MW_{inst}/MW_{gridmin}{}^{2}$	0,72	2,37	2,76	0,58
$MW_{inst}/MW_{gridmax}{}^{3}$	0,22	0,90	0,94	0,17

1 – Ratio of energy delivered by DG and energy demand in the network (annually)

2 – Ratio of installed DG capacity and minimum load in the network

3 – Ratio of installed DG capacity and maximum load in the network

4 – Network level (level 3 is equivalent to 110 kV, level 7 to 0,4 kV)

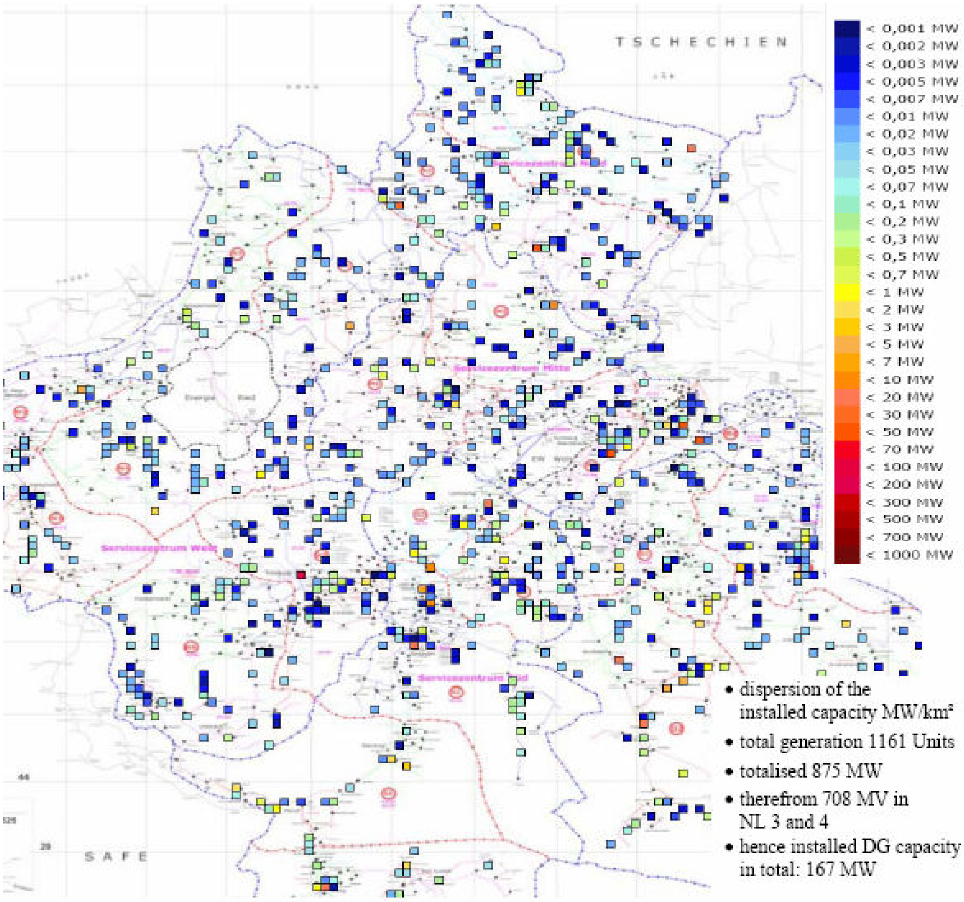


Figure 3.1 – Dispersion of the installed DG power per m², Energie AG OÖ Netz GmbH (LUGMAIER *et al.*, 2007)

The experiences of the DNOs show that, if in the distribution networks the dispersion of DG units is almost like the dispersion of the loads, a DG share (different DG types) of approximate 60% (installed power of DG) of the maximum load in the network seems to be possible without voltage problems, estimated over all. This value will decrease if the units are concentrated at unique nodes, especially in case of peripheral nodes.

The key barrier for generation in distribution networks is the voltage rise effect (overvoltage) due to the power injection, as explained in the section 2.2. If it is not possible to connect the desired power, currently there are two approaches used. The first one is to find a point of common coupling with a higher short circuit power or to reinforce the network. The second possibility is to reduce the feed in power when voltage is exceeding the upper limits.

Demand side management (DSM) and remote control of DG units are, in general, not yet used in respect to voltage level and there are only few measurement data in the peripheral distribution network available. Because of limited share of DG neither the DSM nor measurement data and remote control of DG were required before (LUGMAIER *et al.*, 2007).

3.2 The Voltage Rise Problem

Keeping the voltage between the limits is becoming a primary concern of the DNOs. Increasing levels of DG penetration cause the voltage to rise above the limits, presenting a risk to the customers. As the present DNOs voltage control equipment is only able to handle a limited amount of DG, the modification, replacement and installation of different equipment are necessary to increase the DG penetration in the distribution networks (KUPZOG *et al.*, 2007).

Loads, line impedances, power exported by the DG and the distance of the DG from the primary substation are the most important factors causing the changes in the voltage profile. The voltage profile change in the distribution network with DG can be illustrated on a simple network model, shown in Figure 3.2.

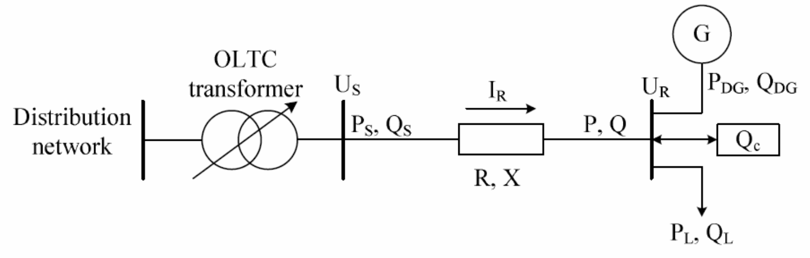


Figure 3.2 – Simple distribution network with DG

P_{DG} and Q_{DG} are the active and reactive power output of the generator respectively, Q_C is the reactive power compensation at the DG site, P_L and Q_L are the load active and reactive power respectively, R and X are the line resistance and reactance respectively, U_S is the voltage at the substation, U_R is voltage at the bus where DG is connected, I_R the current through the line between buses and P and Q the active and reactive power flowing through the line respectively. The following expression can be written for the bus where DG is connected:

$$\underline{U}_R \underline{I}_R^* = P + jQ \Rightarrow \underline{I}_R = \frac{P - jQ}{\underline{U}_R^*} \tag{3.1}$$

Using Kirchoff's voltage law, the voltage at the substation U_S is given by:

$$\underline{U}_S = \underline{U}_R + (R + jX)\underline{I}_R \tag{3.2}$$

Combining and rearranging the Equations 3.1 and 3.2, the voltage at the DG busbar U_R can be expressed as follows:

$$\underline{U}_R = \underline{U}_S - \frac{RP + XQ}{\underline{U}_R^*} - j\frac{XP - RQ}{\underline{U}_R^*} \tag{3.3}$$

If the voltage at the DG busbar is chosen as the reference voltage, $\underline{U}_R = \underline{U}_R^* = \underline{U}_R \angle 0^\circ$, then the Equation 3.3 becomes:

$$U_R = \underline{U}_S - \frac{RP + XQ}{U_R} - j\frac{XP - RQ}{U_R} \tag{3.4}$$

For the distribution lines, the value of R is close or even greater than the value of X. Therefore the imaginary part of the Equation 3.4 is normally small (JENKINS *et al.*, 2000). Since the real part in the Equation 3.4 is much greater than the imaginary part, only the real part can be considered. Thus the Equation 3.4 can be approximated as follows:

$$U_S \approx U_R + \frac{RP + XQ}{U_R} \tag{3.5}$$

In the Equation 3.5 the active and reactive powers are defined, respectively, by:

$$P = P_L - P_{DG} \tag{3.6}$$

$$Q = \pm Q_{DG} \pm Q_C + Q_L \tag{3.7}$$

As the common practice for DNOs is to require distributed generators to operate at unity power factor, no reactive power is injected to or absorbed from the network by the DG.

$$\pm Q_{DG} \pm Q_C \approx 0 \tag{3.8}$$

Regardless to the Equation 3.8 and considering the worst case scenario, which is based on extreme conditions of a minimum load (P_L=0 and Q_L=0) and the maximum generation, voltage at the substation U_S becomes:

$$U_S \approx U_R - \frac{RP_{DG}}{U_R} \tag{3.9}$$

The voltage at the DG busbar U_R can be written as follows:

$$U_R \approx U_S + \frac{RP_{DG}}{U_R} \tag{3.10}$$

It can be seen from Equation 3.10 that the voltage at the DG busbar U_R is higher than the voltage at the substation U_S due to DG active power injected into the line. The voltage at the DG busbar depends mainly on the resistance of the line, the amount of injected active power from the DG and the voltage at the substation. Maximum injected power from the DG can be therefore obtained by reducing the voltage at the substation (with the OLTC). However, the voltage at the substation should be controlled, in a way that voltage at the DG busbar is kept between the DG operation limits. Therefore, in order to effectively control the voltage at substation and to allow or increase the active power injection from the DG, it is necessary to measure the remote voltages on the network.

3.3 Active Voltage Control: The Step Model

According to what was said before, an intelligent approach for integration of a rising share of DG would start, where necessary, with local solutions for each generation unit or sensible network areas. Furthermore, with growing share of DG, an intelligent approach would request a step by step implementation of local measuring and controlling units as well as communication channels and coordinating central systems.

In the framework of the DG DemoNet Project, a set of such innovative approaches for voltage control has been developed. These tools actively use network assets (e.g. On-Load Tap changers, OLTC), distributed generators and even loads to perform voltage control. These tools have been theoretically developed and then implemented into a simulation environment for validation and improvement. For this purpose, the simulation software DIgSILENT PowerFactory® has been used and adapted to allow performing realistic simulations. Validations have been made on exemplary MV networks provided by DNOs. The proposed five steps are shown in Table 3.2 and described in the next topics (LUGMAIER *et al.*, 2007).

Table 3.2 – Step Model "DG Integration" – Voltage control tools used for each step of the model

Step	OLTC	DG	Loads	Decoupling assets
Current practice	Fix set-point	-	-	-
Local voltage control	Fix set-point	✓	✓	✓
"Decoupling solution"	Fix set-point	-	-	✓
Distributed voltage control	Variable set-point	-	-	✓
Coordinated voltage control	Variable set-point	✓	✓	✓

3.3.1 Current Practice

This first step corresponds to the current approach, i.e. passive operation of the distribution network mainly based on the On-Load Tap Changer, OLTC. In case of voltage limit violation due to the connection of distributed generation, the network must be reinforced, also to avoid an automatic disconnection of the DG units because of overvoltage.

3.3.2 Local Voltage Control

In this approach, the OLTC is further controlled traditionally (fix set-point), but some selected generators and/or loads perform local voltage control with reactive and active power management. Due to higher R/X ratios in distribution networks compared to the transmission networks, the use of reactive power management for voltage control may not be always sufficient. If required, active power must be curtailed (regulatory and economical frameworks will be considered in the next steps of the projects). The selection of the generators which perform voltage control must be done on the basis of detailed analysis through offline studies.

3.3.3 "Decoupling Solution"

This approach considers the use of additional assets (e.g. voltage regulators) to "decouple" the voltage in parts of the network for which the voltage situation is different. This solution has been considered at the initial stage of the study, from a theoretical point of view. Like the other solutions, it needs to be economically assessed.

3.3.4 Distributed Voltage Control

In this step, the OLTC is controlled according to real-time voltage measurements at *critical nodes* of the network. In case the voltage exceeds the operational limits at one of the monitored nodes, the OLTC performs a tap changing. The *critical nodes* have to be selected on the basis of offline studies in order to ensure that compliance with the voltage limits at these nodes imply compliance in the whole network. Of course, the effectiveness of this control is limited by the network characteristic (e.g. different load flow characteristic of MV branches). This solution supposes a communication infrastructure with limited requirements between selected nodes and the OLTC controller.

3.3.5 Coordinated Voltage Control

This step represents the most sophisticated and complex control (coordinated use of local voltage control and distributed voltage control). A control unit controls the OLTC and the generators and/or loads participating to local control on the basis of the measurements received for the critical nodes. The use of coordinated local control allows solving the conflict appearing in the previous approach (OLTC not able to maintain the voltage within the limits in the whole network). Like in the previous steps, the critical nodes and the controlled generators have to be suitably selected (selection criteria are currently developed). For this control, the requirements on the communication infrastructure are higher.

Table 3.3 summarizes the most important advantages and drawbacks of the step model from the technical point of view and Figure 3.3 illustrates the sequence of these steps.

Table 3.3 – Step Model "DG Integration" – Important advantages / drawbacks

Operation approach	Advantages	Drawbacks
Current practice	▪ Approved standard solution	▪ limited DG amount
Local control	▪ easy to implement, ▪ P & Q control usually available on most DGs ▪ extendable/scalable	▪ complex selection of controlled DGs ▪ not coordinated
"Decoupling solution"	▪ isolate a problematic area	▪ partly inflexible, difficult to scale
Distributed control	▪ simple ▪ extendable/scalable	▪ communication infrastructure needed ▪ effectiveness depending on the network structure
Coordinated control	▪ coordinated ▪ high effectiveness ▪ effective use of all the resources ▪ extendable/scalable	▪ complexity ▪ high engineering efforts (selection of critical nodes and controlled DGs)

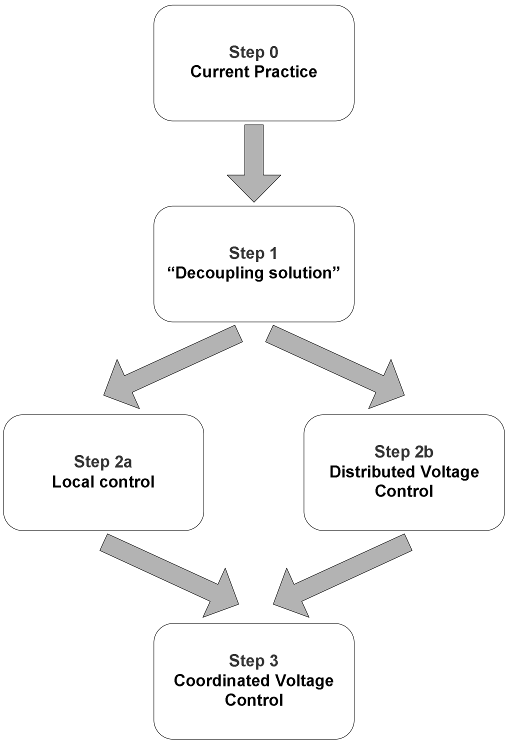


Figure 3.3 – Step Model "DG Integration" – Step model sequence

3.4 Algorithm for Coordinated Voltage Control

In the coordinated voltage control (CVC), the local voltage control with DG units is operating together with centralized OLTC voltage control. This algorithm is designed to keep DG units ‘on line’ as long as possible, so that DG operators can gain maximum revenues for their generation. However, if voltage problems cannot be resolved by this algorithm, the local voltage protection switches will cut off the DG units from the network immediately. The algorithm will only rely on overvoltage protection devices as a fallback solution.

The algorithm is based on the monitoring of grid voltages and regulation of active DG units as well as OLTC transformer (Figure 3.4). The voltage monitoring is performed in a number of nodes, recognized as critical due to explicit voltage deviations in case of changes in load or generation. These so-called critical nodes (CN) are selected in an offline study and indicate the voltage conditions of the network. The number of necessary nodes strongly depends on the network topology.

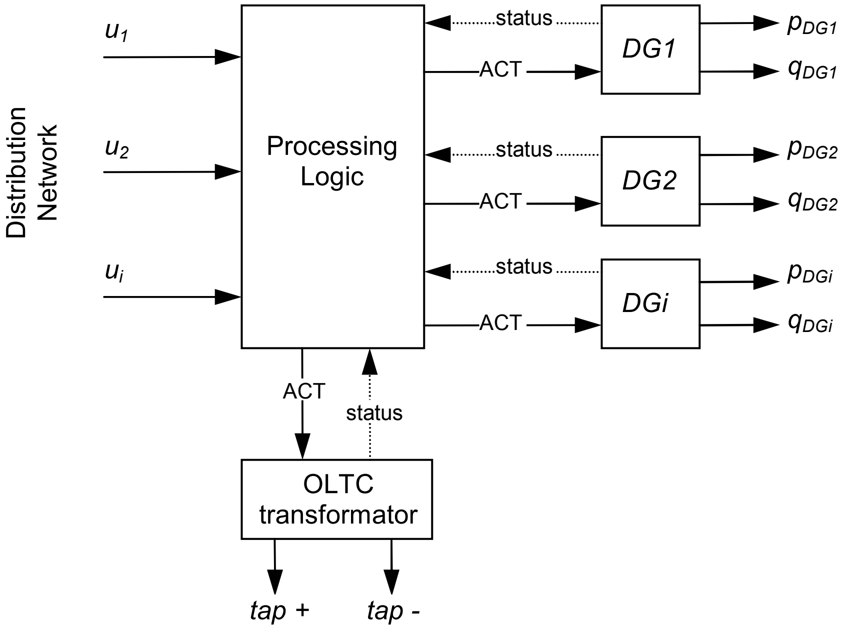


Figure 3.4 – Basic representation of the CVC algorithm (BRUNNER *et al.*, 2007)

Based on the network’s condition the processing logic first activates the OLTC control. By tap changing, it attempts to reach a set point within the voltage limits provided by the grid code. It is possible that a set point is not reached or a control conflict occurs.

A conflict occurs, for example, if two CNs are considered, and the maximum voltage exceeds the upper voltage limit at one of them, while the lowest voltage is near to the lower voltage limit at the other one (Figure 3.5a). In this case, tapping would lead to undervoltage at the second node. Alternatively, if the minimum voltage exceeds the lower voltage limit at one of the nodes and the highest voltage is near to the upper voltage limit at the other one (Figure 3.5b), tapping would lead to overvoltage at the second node.

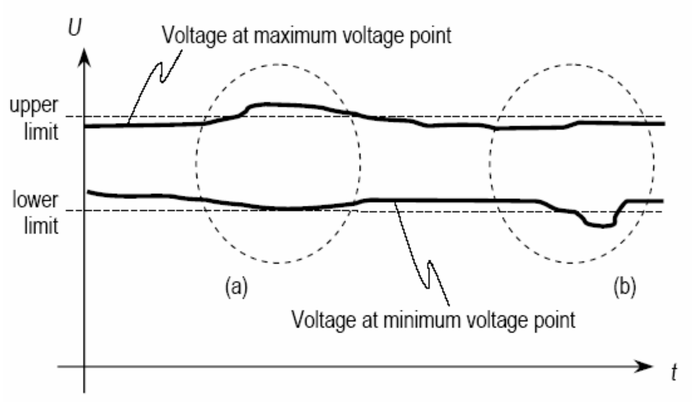
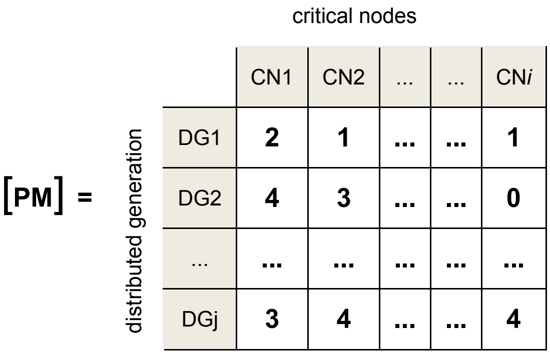


Figure 3.5 – Voltage conflicts – in situations (a) and (b), tap change operation is not possible. In this case, DG units are actively controlled

In case of voltage conflict, local voltage control with DG is activated. Only DG units that allow the voltage controlling are included into the algorithm. A ranking order of DG units is introduced for optimal operation. This ranking is based on the injection share of the DG units and their stochastic nature of energy production. This concept is called the “Power Share Injection Concept”.

This concept makes use of the ranking concept to control voltage at monitored points and introduces the Priority Matrix (PM). This matrix comprises information about active DG units and their role in voltage control. It consists of numbers in a successive order, indicating the intensity of power injection measured at a CN. The structure of the PM is illustrated in the Figure 3.6.

The priority level of each DG unit is determined in a process, in which intentional voltage deviations are generated by rapid changes in the DG unit generation at constant network loading. By measurement of voltage variations caused by the changes, the unit’s influence is recognized and ranked accordingly. The more intense the variations are the more effect has the DG injection on the voltage profile of the monitored node.

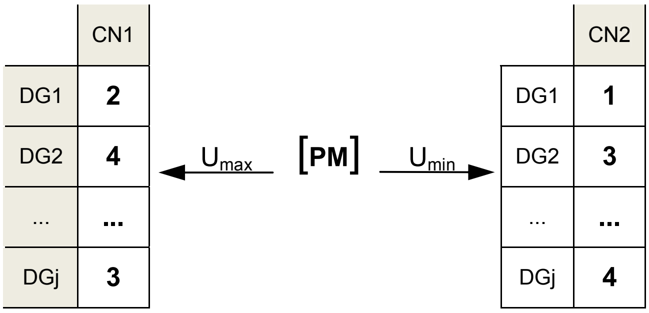


	CN1	CN2	...	...	CN*i*
DG1	**2**	**1**	**...**	**...**	**1**
DG2	**4**	**3**	**...**	**...**	**0**
...	**...**	**...**	**...**	**...**	**...**
DGj	**3**	**4**	**...**	**...**	**4**

Figure 3.6 – Priority Matrix (BRUNNER *et al.*, 2007)

In the matrix, the number of columns equals to number of CN and the number of rows to the number of DG units. The matrix takes into account real-time network conditions and is periodically refreshed. Included are only the units, significantly influencing the node voltages. If an unit is a part of a control scheme but currently not operating its priority is set to zero (Figure 3.6, last column). The highest priority corresponds to the highest number. The number of columns does not necessarily equal to the number of rows.

Since the CVC algorithm considers the minimum and the maximum voltage of the network, the PM provides two priority columns each used in voltage regulation of the corresponding node (Figure 3.7)



	CN1
DG1	**2**
DG2	**4**
...	**...**
DGj	**3**

	CN2
DG1	**1**
DG2	**3**
...	**...**
DGj	**4**

Figure 3.7 – Priority Matrix Decoupling (BRUNNER *et al.*, 2007)

First, the unit with the highest priority is activated. With reference to Figure 3.7, these are the units DG2 for maximum voltage and DG_j for minimum voltage regulation. The units are provided with the regulated signal (min or max voltage), set point and the activation signal. The schema is illustrated in Figure 3.8. The activation signal governs the regulation. When the signal is “on” the unit activates its reactive power control. If this action does not improve the voltage and the regulation range of the first unit is used, a second unit is activated. The sequence continues until the reactive power reserve of all units is exploited. If the sequence of these actions still does not improve the voltage, the active power control activation follows in the same manner. The sequence continues until the voltage of regulated nodes meets the criteria, which means bringing the voltage back within the specified regulation band, or all units are put in operation. The deactivation process is performed in the inverse order.

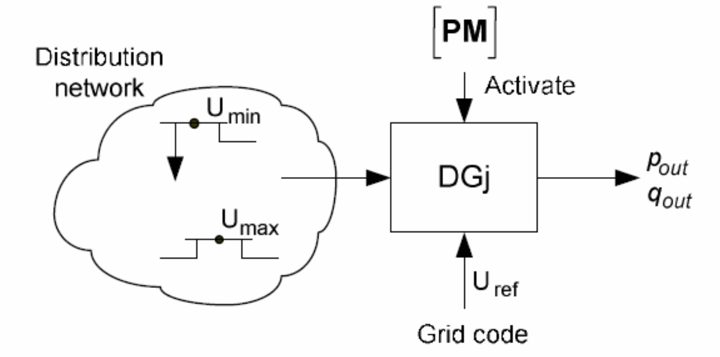


Figure 3.8 – DG Unit Control Scheme (BRUNNER *et al.*, 2007)

Both P and Q management are calculated according to the control mechanism present in the CVC algorithm. Q and P controls are based in the usage of a PI control, which receives the voltage values and voltage limits as inputs and calculates ΔQ and ΔPQ, as shown in Figure 3.9.

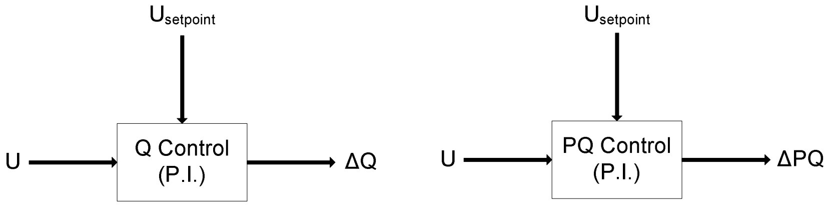


Figure 3.9 – Calculation of the active and reactive power management in the CVC algorithm

It is important to note that, while ΔQ is calculated independently of P, ΔP influences the reactive power, and therefore, is called ΔPQ.

The complete flow chart algorithm of CVC algorithm is presented in Figure 3.10. This flow chart includes the OLTC tapping and the local voltage control.

Simulations accomplished at arsenal research show that while the passively operated grid suffers from overvoltage conditions already at 50 % DG of maximum load, the CVC approach is still able to keep voltages in the limits at 150 % installed DG of maximum load. To be able to integrate more than 150 % of the maximum demand DG power into the example network, the network should be reinforced (KUPZOG *et al*., 2007).

In order to evaluate the performance of the power injection share concept, a test was conducted, whose aim was to demonstrate network conditions in case of installation of additional DG units to it. The results show that without the scheme, the integration of these additional units was not possible due to numerous tap changer conflict situations; however, by using the power injection share concept, the integration of the additional DG units is possible without any voltage limit violation (BRUNNER *et al*., 2007).

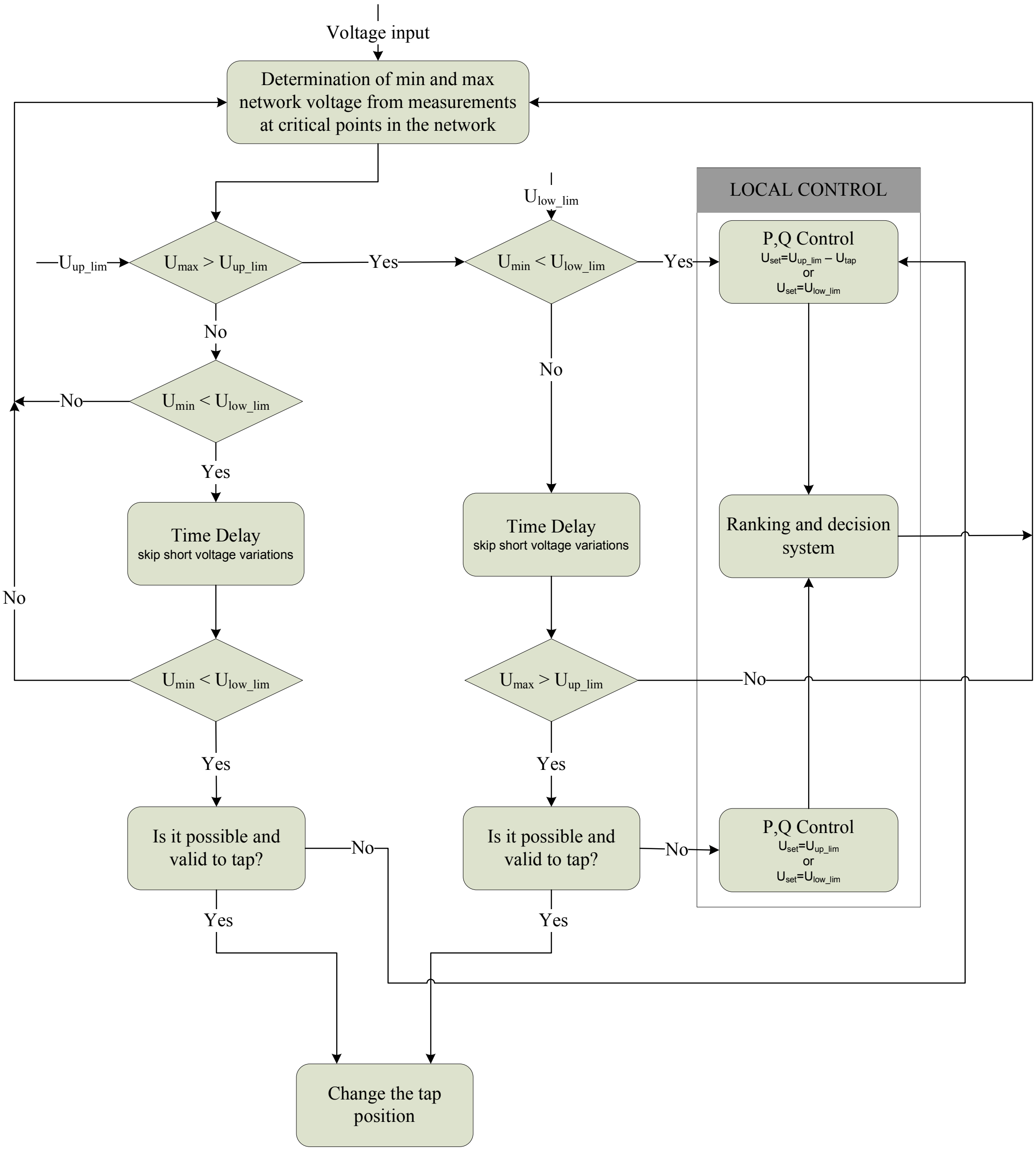


Figure 3.10 – Flow chart algorithm of the CVC

4 Energy Storage Systems, Status and Potential

One of the major issues surrounding the various replacements for carbon-based fuels is the ability to store the energy until the demand is present, as most renewable sources are intermittent in nature. While oil can be stored in large tanks and coal can be stored in a pile, a shift to intermittent sources of energy requires some sort of electricity storage system analogous to a storage tank so that power can be dispatched when needed. Therefore, to keep from losing this energy, the electricity must be converted into a different kind of energy until consumer demands rise. Although many different ideas for this storage exist, an efficient universal way to solve this problem has yet to materialize (WALKER, 2007). In this chapter, a brief history of the storage systems is presented and the different technologies are analyzed, regarding their status and potential, specially referring to storage systems that could be used for integration to the voltage control methods in the framework of the DG DemoNet-Concept.

4.1 Storage Systems: History

Energy storage as a natural process is as old as the universe itself - the energy present at the initial creation of the universe has been stored in stars such as the Sun, and is now being used by humans directly (e.g. through solar heating), or indirectly (e.g. by growing crops or conversion into electricity in solar cells).

As a purposeful activity, energy storage has existed since pre-history, though it was often not explicitly recognized as such. An example of deliberate mechanical energy storage is the use of logs or boulders as defensive measures in ancient strongholds - the logs or boulders were collected at the top of a hill or wall, and the energy thus stored used to attack invaders who came within range.

One of the oldest forms of energy storage involves harvesting ice from lakes and rivers, which was stored in well insulated warehouses and sold or used throughout the year for almost everything for what mechanical refrigeration is used today, including preserving food, cooling drinks, and air conditioning. The Hungarian Parliament Building in Budapest is still air conditioned with ice harvested from Lake Balaton in the winter.

A more recent application is the control of waterways to drive water mills for processing grain or powering machinery. Complex systems of reservoirs and dams were constructed to store and release water (and the potential energy it contained) when required.

Energy storage became a dominant factor in economic development with the widespread introduction of electricity and refined chemical fuels, such as gasoline, kerosene and natural gas in the late 1800s. Unlike other common energy storage used in prior use, such as wood or coal, electricity must be used as it is generated and cannot be stored on anything other than a minor scale. Electricity is transmitted in a closed circuit, and for essentially any practical purpose cannot be stored as electrical energy. This meant that changes in demand could not be accommodated without either cutting supplies (e.g. via brownouts or blackouts) or arranging for a storage technique.

An early solution to the problem of storing energy for electrical purposes was the development of the battery, an electrochemical storage device. It has been of limited use in electric power systems due to small capacity and high cost. A similar possible solution with the same type of problems is the capacitor.

Chemical fuels have become the dominant form of energy storage, both in electrical generation and energy transportation. Chemical fuels commonly uses processed coal, gasoline, diesel fuel, natural gas, liquefied petroleum gas (LPG), propane, butane, ethanol, biodiesel and hydrogen. All of these chemicals are readily converted to mechanical energy and then to electrical energy using heat engines (turbines or other internal combustion engines, or boilers or other external combustion engines) used for electrical power generation. Heat engine powered generators are nearly universal, ranging from small engines producing only a few kW to utility-scale generators with ratings up to 800 MW.

Electrochemical devices called fuel cells were invented about the same time as the battery. However, for many reasons, fuel cells were not well developed until the advent of manned spaceflight (the Gemini Program) when lightweight, non-thermal, sources of electricity were required in spacecraft. Fuel cell development has increased in recent years to an attempt to increase conversion efficiency of chemical energy stored in hydrocarbon or hydrogen fuels into electricity.

At this time, liquid hydrocarbon fuels are the dominant forms of energy storage for use in transportation. Unfortunately, these produce greenhouse gases when used to power cars, trucks, trains, ships and aircraft. Carbon-free energy carriers, such as hydrogen, or carbon-neutral energy carriers, such as some forms of ethanol or biodiesel, are being sought in response to concerns about the consequences of greenhouse gas emissions.

In some areas of the world (Washington and Oregon in the USA, Wales in the United Kingdom and western Austria are examples) enjoying particular geographical conditions, large quantities of water can be stored in elevated reservoirs, using excess electricity at times of low demand to pump water up to the reservoirs, then letting the water fall through turbine generators to retrieve the energy when demand peaks.

Energy storage has been closely associated with solar installations, including both solar heating and photovoltaic (PV) applications. Today it can be found several different storage technologies, depending on the application. Some more recent technologies have also been investigated, such as flywheels or compressed air storage in underground caverns, but to date no widely available solution to the challenge of mass energy storage has been deployed commercially. However, many utilities provide incentives for energy storage applications, while time-of-day rates and stiff demand charges also entice customers to consider these opportunities (DISTRICT ENERGY, 2008).

4.2 Storage Systems: Applications and Technologies

Energy storage systems play the important role of unifying, distributing and enhancing the capabilities of alternative and renewable energy-distributed generating systems, namely by:

Enhancing the Power Quality

Energy storage can provide "ride-through" for momentary outages, and extended protection from longer outages. Coupled with advanced power electronics, storage systems can reduce harmonic distortions, and eliminate voltage sags and surges.

Providing Renewables Support

In combination with renewable resources, energy storage can increase the value of photovoltaic (PV) and wind-generated electricity, making supply coincident with periods of peak consumer demand, permitting DG to operate as a dispatchable unit.

Providing Utility Support

Energy storage systems can be used to follow load, stabilize voltage & frequency, manage peak loads, improve power quality, defer upgrade investments, and support renewables.

Large-scale electricity storage technologies cover a wide spectrum of applications, ranging from fast power quality applications to improve reliability all the way to slow energy management applications to improve profitability. These applications require energy discharges from a fraction of a second in high power applications to hours in high energy applications (Figure 4.1).

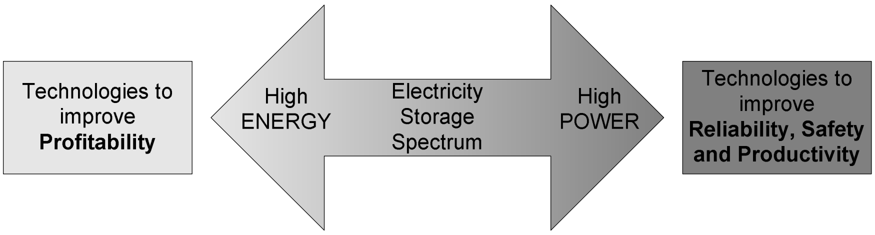


Figure 4.1 – Electricity storage spectrum

The high power side of this spectrum includes power quality and uninterrupted power supply (UPS) applications, where electricity storage technologies are used within fractions of a second to improve reliability. The high energy side of this spectrum includes energy management applications such as load leveling, peak shaving and arbitrage where electricity storage technologies are used in daily cycles for economic gain. In between the above two extremes of the electricity storage spectrum are a range of applications where stored energy is used in minutes rather than seconds or hours. This range includes spinning reserve applications for electric power grid stability and switching between energy sources (ESA, 2007/2008).

Based on the electricity storage spectrum and most common applications of the storage system technologies, SCHOENUNG *et al.*, 2003 classifies these applications as bulk energy storage, for the purpose of load-leveling or load management, distributed generation (DG) for peak shaving, and power quality (PQ) or end-use reliability. These specifications together determine the stored energy requirement. The power levels and storage times for the various application categories are listed in Table 4.1.

Table 4.1 – Application category specifications for storage systems (SCHOENUNG *et al.*, 2003)

Application Category	Discharge Power Range	Discharge Time Range	Stored Energy Range	Representative Applications
Bulk Energy Storage	10-1000 MW	1-8 hours	10-8000 MWh	Load leveling, spinning Reserve
Distributed Generation	100-2000 kW	0,5-4 hours	50-8000 kWh	Peak shaving, transmission deferral
Power Quality	0,1-2 MW	1-30 hours	0,1-60 MJ (0,028-16,67 kWh)	End-use power quality and reliability

Depending on the application, diverse storage system technologies can be used. Some of them are best suited for bulk energy application, but not to DG or PQ. There are others, however, that are suitable for DG and bulk storage or DG and PQ. In general, the information for DG storage is similar to that in the section for bulk energy storage. However, these systems are much smaller in size and are expected to be placed in an existing facility, which reduces the balance of plant cost.

The following topics present a variety of storage technologies, with their technical characteristics, vantages, drawbacks and the most common applications. In the next topic these technologies are compared, in order to figure out what are the best suited for the implementation to the voltage control scheme in the ambit of this work. Table 4.2 presents a summary of the analyzed technologies.

Table 4.2 – Summary of the investigated storage technologies

Direct Storage	**Indirect Storage**	
Electrical	Mechanical	Chemical
• Supercapacitor • SMES	• Pumped Hydro Storage • CAES • Flywheel	• Batteries • Redox-Flow Batteries • Hydrogen Storage

On the table 4.2, “Direct Storage” consists of those technologies that store electricity without converting it into any other form or energy, while “Indirect Storage” consists of technologies that store electricity converting it into one (or more) different forms of energy.

4.2.1 Supercapacitors

Electrochemical capacitors (EC) have components related to both a battery and a capacitor. They store electrical energy in the two series capacitors of the electric double layer, which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms. The capacitance and energy density of these devices are thousands of times larger than electrolytic capacitors. The electrodes are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage but are less expensive and work in a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage current. Figure 4.2 shows the basic setup of a Supercapacitor system.

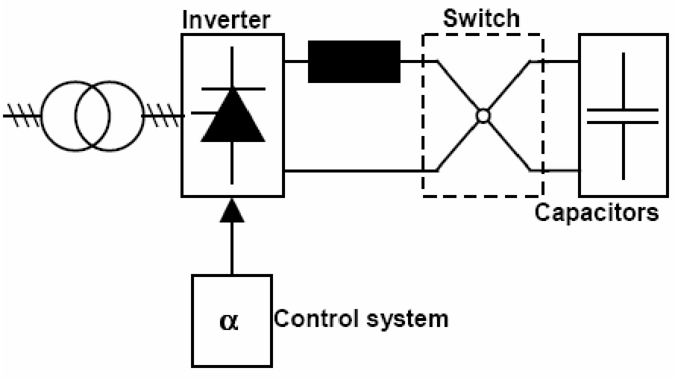


Figure 4.2 – Setup of a Supercapacitor (SELS *et al.*, Sep. 2001)

Compared to batteries, ECs have lower energy density but they can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capability).

Some characteristics of the supercapacitors are summarized in Table 4.3, based on (BLAABJERG *et al.*, 2007) and (SCHOENUNG *et al.*, 2003). Table 4.4 summarizes their principal advantages and drawbacks.

Table 4.3 – Overall characteristics of supercapacitors

Energy-related cost (delivered)	[€/kWh]	20.100
Power-related cost	[€/kW]	201
Replacement cost	[€/kWh]	0
Replacement Frequency (Life time)	[yr]	~10
Operation and maintenance costs	[€/kW-yr]	3,36
Efficiency (AC to AC)	[%]	~95
Storage losses	[%]	0,01
Range of capacity	[F]	0,05 – 5000
Cell voltage range	[V]	0 – 1 (Aqueous electrolyte) 0 – 2,3 (Organic electrolyte)
Energy density	[Wh/kg]	up to 5
Power density	[kW/kg]	up to 20
Temperature range	[ºC]	-40 – 70
Discharge time	[sec]	up to 5 sec at $U_{max}/2$
Charging time	[sec]	up to 5 sec

Table 4.4 – Advantages and drawbacks of Supercapacitors (ERBEN, 2008)

Advantages	Drawbacks
• Very high capacity (many kF) • High power density • Very high cycling lifetime • Minor inner resistance • Fast loading capacity • Deep discharging stability	• High costs • Low energy density • High self-discharging rate (insignificant if used as short time storage system) • Additional electronic is necessary due to the variable voltage

Supercapacitors are ideal devices for PQ and short-term energy storage. For some capacitor systems, this is less than one second, whereas for others it can be as long as a few minutes. Individual units store a limited amount of energy, however depending on design; a great deal of it can be removed in a second or so.

There is an increasing interest in developing high cycle life, high-energy supercapacitors, that could be used on high energy applications (NAMISNYK, 2003). Presently, very small super capacitors in the range of seven to ten watts are widely available commercially for consumer power quality applications and are commonly found in household electrical devices. Development of large scale capacitors has been focused on electric vehicles. Currently, small scale power quality (< 250 kW) is considered to be the most promising utility use for advanced capacitors.

4.2.2 Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator. Figure 4.3 shows the basic setup of a SMES unit.

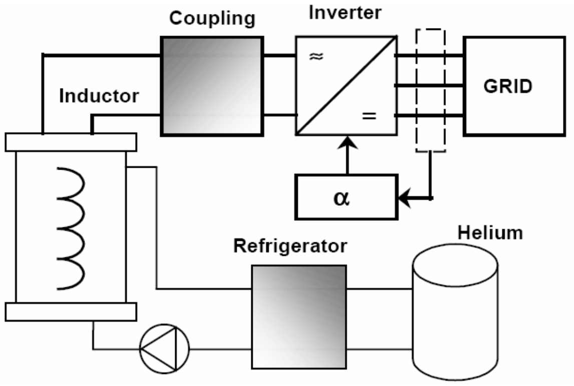


Figure 4.3 – Basic setup of a SMES unit (SELS *et al.*, Oct. 2001)

Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2-3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95%. (CHEUNG, 2002/2003).

Table 4.5 summarizes the principal advantages and drawbacks of the SMES systems.

Table 4.5 – Advantages and drawbacks of SMES systems (ERBEN, 2008)

Advantages	Drawbacks
• Very high efficiency (> 95%) • Very short loading time (minutes) • Very fast accessibility to the stored energy (ms) • High power possible also for small stored energy • Reactive and active power don't depend on each other • High cycling lifetime • Doesn't contain any dangerous material • Doesn't produce any hazardous emissions during operation	• Continuous refrigeration and thermal isolation are necessary • High purchase costs (in comparison to batteries) • High operational costs due to refrigeration • Low energy capacity • Energy supply is only possible during short time periods

Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving PQ. If SMES were to be used for utilities it would be a diurnal storage device, charged from base load power at night and meeting peak loads during the day. Table 4.6 shows some parameters and costs of a SMES system.

Table 4.6 – Parameters and costs for SMES systems (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	33.500
Power-related cost	[€/kW]	134
Replacement cost	[€/kWh]	0
Replacement frequency (life time)	[yr]	N/A
Operation and maintenance costs	[€/kW-yr]	6,7
Efficiency (AC to AC)	[%]	~95
Storage losses	[%]	1

There are several small SMES units available for commercial use and several larger test projects. Several 1 MW units are used for power quality control in installations around the world, especially to provide power quality at manufacturing plants requiring ultra-clean power, such as microchip fabrication facilities.

4.2.3 Pumped Hydro Storage

Conventional pumped hydro uses two water reservoirs, separated vertically. During off peak hours water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Pumped hydro was first used in Italy and Switzerland in the 1890's. By 1933 reversible pump-turbines with motor-generators were available. Adjustable speed machines are now being used to improve efficiency. Pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days. Figure 4.4 shows a basic scheme of a pumped hydro storage system.

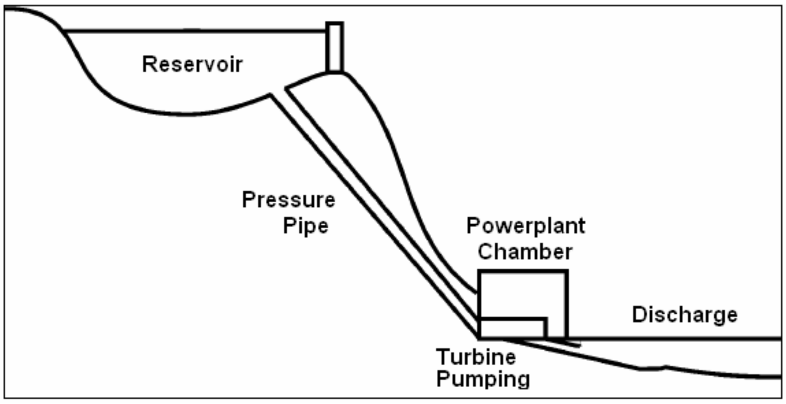


Figure 4.4 – Pumped Hydro storage scheme (ERBEN, 2008)

Their efficiency is in the 70% to 85% range. There is over 90 GW of pumped storage in operation world wide, which is about 3% of the global generation capacity. Pumped storage plants are characterized by long construction times and high capital expenditure. Pumped storage is the most widespread energy storage system in use on power networks. Its main applications are for energy management, frequency control and provision of reserve.

Table 4.7 shows some parameters and costs of a Pumped Hydro Storage system for bulky energy application, and Table 4.8 shows their main advantages and drawbacks.

Table 4.7 – Parameters and costs for Pumped Hydro storage systems (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	6,7
Power-related cost	[€/kW]	~670
Replacement cost	[€/kWh]	0
Replacement frequency (life time)	[yr]	N/A
Operation and maintenance costs	[€/kW-yr]	1,68
Efficiency (AC to AC)	[%]	70 – 85

Table 4.8 – Advantages and drawbacks of Pumped Hydro storage systems (ERBEN, 2008)

Advantages	Drawbacks
• Capability to achieve high powers in short time (1 – 3 min) • Modern systems can be run from 0 to full load in 1 to 2 min. • Very high storage capacity • Relative high cycling efficiency	• High installation costs • Negative impact to the territory (reservoir)

4.2.4 Compressed Air Energy Storage (CAES)

CAES plants use off-peak energy to compress and store air in an air-tight underground storage cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. Figure 4.5 shows the scheme of a CAES system.

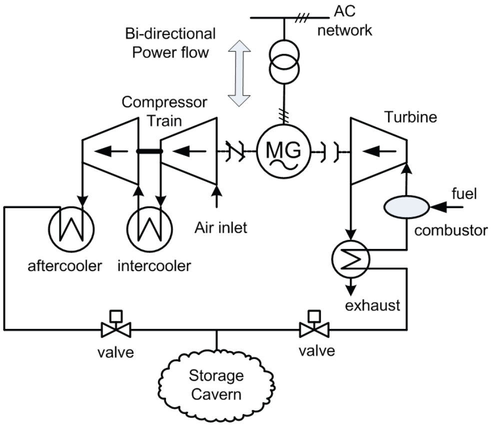


Figure 4.5 – Scheme of a CAES system (BLAABJERG *et al.*, 2007)

The sitting of CAES plant requires favorable geology for the storage reservoir as well as a suitable location near transmission lines and fuel supplies. Potential sites for underground storage are grouped into three categories:

- Rock caverns created by excavating comparatively hard and impervious rock formations;
- Salt caverns created by solution or dry mining of salt formations;
- Porous media reservoirs made by water bearing aquifers or depleted gas or oil fields e.g., sandstone, fissured limestone.

Table 4.9 summarizes the principal advantages and drawbacks of the CAES systems and Table 4.10 shows some parameters and costs of these systems applied to bulky energy storage.

Table 4.9 – Advantages and drawbacks of CAES systems

Advantages	Drawbacks
• Air is unlimited and freely available • Production and usage of compressed air involves well known technologies • Can achieve very high efficiency • No emissions • The storage period is longer than other storage methods (very small losses)	• Necessity of favorable geology for the underground installation • It takes about 1,5 to 2 years to create caverns by dissolving salt

Table 4.10 – Parameters and costs for a CAES system (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	2,02
Power-related cost	[€/kW]	284
Replacement cost	[€/kWh]	0
Replacement frequency (life time)	[yr]	N/A
Operation and maintenance costs	[€/kW-yr]	1,68
Efficiency (AC to AC)	[%]	73

The largest commercial CAES is a 2700 MW plant that is planned for construction in Norton, Ohio. This 9-units plant will compress air to 1500 psi (pounds per square inch) in an existing limestone mine some 670 meters under ground. This project has been started in 2001, but in early 2007 construction had not actually begun.

Besides the CAES systems for bulky storage systems, small compressed air energy storage systems (CAES-surface) have been proposed for DG applications. In this technology, the compressed air is stored at high pressure in steel pipes that are typically used for natural gas transmission. These pipes are relatively inexpensive and are generally available. They can be placed on the surface or buried at a modest depth for safety. Units between 50 kW and 50 MW are possible. Because there are no installed examples, the projected cost estimates are quite uncertain (SCHOENUNG *et al.*, 2003).

4.2.5 Flywheels

Flywheels are electromechanical storage systems in which energy is stored as kinetic energy of a rotating mass. The progresses in the power electronics, composite materials, manufacturing quality control as well as a system approach in development of these devices has made possible the realization of “mechanical batteries” able to cover a wide range of applications. Nowadays, the flywheel energy storage systems are considered the enabling technology for applications such as space satellites, power quality and integration of renewable energies.

A flywheel storage device consists of a massive rotating cylinder (comprised of a rim attached to a shaft) that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. The use of magnetic bearings and a vacuum chamber helps to reduce energy losses. Figure 4.6 shows the block diagram of a Flywheel for grid connected applications.

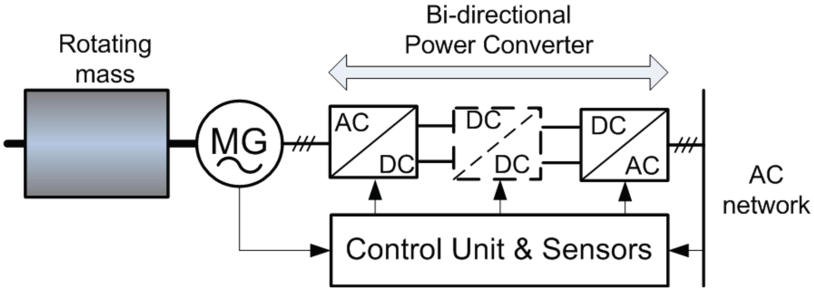


Figure 4.6 – Block diagram of a Flywheel for grid connected applications. (BLAABJERG *et al.*, 2007)

The motor/generator can be an induction machine or a permanent magnet synchronous machine. The electrical machine can also be integrated with the flywheel. In order to increase the effective capacity a mechanical gearbox is used to connect the electrical machine to the flywheel.

Usually, the power electronic interface consists of a back-to-back power converter. However, in some configuration an additional DC/DC conversion stage can be inserted in the DC-link circuit.

In motoring mode the flywheel stores mechanical energy speeding up as it accumulates energy and slowing down as the flywheel delivers energy to the AC network.

Flywheels systems are divided into two main categories: low speed systems which are commercially available and the high speed ones which are in development and are just becoming available.

The low speed flywheels have steel rotors, conventional bearings and operating speeds up to 6.000 rpm, while the high speed ones can operate up to 50.000 rpm due to the advanced composite materials for the rotor combined with magnetic bearings. Prototypes addressed to automotive and spacecraft applications which can run up to 110.000 rpm are reported in some publications.

Some parameters of the flywheels are summarized in Table 4.11, based on (BODACH, 2006). These parameters take into account the current technology status and the development target of the technology.

Table 4.11 – Characteristics of Flywheels (current and expected)

		Technology Status	**Development Target**
Revolutions	[min]	2.000 – 3.000	To 100.000
Energy density	[kWs/kg]	15 – 200	150-500
Power	[MW]	< 15	< 50
Cycling lifetime	--	1.000.000	1.000.000
Efficiency	[%]	85 – 90	90 – 95
Self discharging	[%/h]	3 – 20	1 – 10

Table 4.12 shows some parameters and costs of a Flywheel system, for both DG (high speed flywheels) and PQ (high/low speed flywheels) and Table 4.13 presents a resume of the principal advantages and drawbacks of this technology.

Table 4.12 – Parameters and costs for Flywheel systems (SCHOENUNG *et al.*, 2003)

		DG	**PQ**
Energy-related cost (delivered)	[€/kWh]	670	670 – 33.500
Power-related cost	[€/kW]	201	201 – 223
Replacement cost	[€/kWh]	0	0
Replacement frequency (life time)	[yr]	N/A	N/A
Operation and maintenance costs	[€/kW-yr]	670/yr	3,35
Efficiency (AC to AC)	[%]	95	90-95
Storage losses	[%]	0,05	0,05 – 0,2

Table 4.13 – Advantages and drawbacks of Flywheels (SCHOENUNG *et al.*, 2003)

Advantages	Drawbacks
• Long life time • Compact • High power density (quickly chargeable and dischargeable) • High energy density (4 to 5 times greater than conventional batteries) • High Efficiency (to 80%) • Minor maintenance needs • Immune to temperature fluctuations • Environment friendly (exhaust-free and no chemical agents) • Relatively immune to bad operation conditions (e.g. deep discharge has no effect on the life time)	• High costs (due to the life time, but small when compared to batteries) • Security aspects concerning the rotor • If a part of the system doesn't work, the complete system must be turned off • cannot deliver its rated power at very low speeds

While high-power flywheels are developed and deployed for aerospace and UPS applications, there is an effort, pioneered by Beacon Power, to optimize high-energy, low cost commercial flywheel designs for long duration operation (up to several hours).

4.2.6 Batteries

The most established way of storing electricity is in the form of chemical energy in batteries. A battery comprises of one or more electrochemical cells and each cell consists of a liquid, paste, or solid electrolyte together with a positive electrode and a negative electrode.

During discharge, electrochemical reactions occur at the two electrodes generating a flow of electrons through an external circuit. The reactions are reversible, allowing the battery to be recharged by applying an external voltage across the electrodes.

Battery systems range from mature and reliable technologies, such as lead acid, which have been proven and developed over many years, to various newer designs which are at different stages of development. Sections 4.2.6.1 to 4.2.6.4 provide some information and characteristics of some battery technologies.

4.2.6.1 Lead-Acid Battery

Lead-acid is one of the oldest and most developed battery technologies. The batteries used in renewable energy systems are classified in two major technologies based on the electrolyte:

- Flooded lead acid batteries – represent the “classical” technology with the electrodes and the separators immersed in the liquid electrolyte. Water electrolysis and gas release lead to water loss during overcharging. Therefore, regular maintenance is needed.
- Valve-regulated lead-acid batteries (VRLA) are characterized by the immobilized electrolyte and, therefore, considerably less maintenance is necessary.

Basically, flooded lead-acid battery technology for renewable energy storage systems is the large-scale application of a technology similar to that found in automobile batteries. Flooded lead-acid batteries are manufactured in large numbers for many uses and their operating characteristics and technology are well understood by manufacturers.

VRLAs use the same basic electrochemical technology as flooded lead-acid batteries, but these batteries are closed with a pressure regulating valve, so that they are essentially sealed. In addition, the acid electrolyte is immobilized. This eliminates the need to add water to the cells to keep the electrolyte functioning properly, or to mix the electrolyte to prevent stratification. The oxygen recombination and the valves of VRLAs prevent the venting of hydrogen and oxygen gases and the ingress of air into the cells. The battery subsystem may need to be replaced more frequently than with the flooded lead-acid battery, increasing the cost of the system.

These batteries are used in renewable energy applications providing stand-by energy or working on regular basis in hybrid systems. Some advantages and drawbacks of these batteries are given in Table 4.14.

Table 4.14 – Advantages and drawbacks of Lead-acid batteries

Advantages	Drawbacks
• Good efficiency • Low maintenance level • Easy to install • Effective recycling • Low investment price • Low system cost over battery life	• Reduced life-cycle compared with renewable energy conversion systems especially wind and PV • Sensible to extreme operating conditions such as extreme temperature and extreme depth-of-discharge • Sensible to overcharge and extreme range of charging currents

These batteries are commonly installed in uninterruptible power supply (UPS) systems as well as in renewable and distributed power systems. The largest one installed is a 40 MWh system in Chino, California (Figure 4.7).

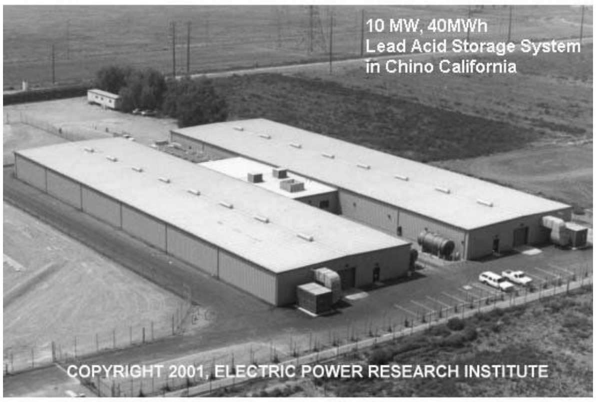


Figure 4.7 – Lead-Acid storage system in Chino, California (ESA, 2007/2008)

Table 4.15 presents some parameters and costs of this time of battery for bulky storage, DG and PQ applications.

Table 4.15 – Parameters and costs for Lead-acid battery systems (SCHOENUNG *et al.*, 2003)

		Bulky	**DG**	**PQ**
Energy-related cost (delivered)	[€/kWh]	100,5 – 134	100,5 – 134	201
Power-related cost	[€/kW]	83,7	117,3	167,5
Replacement cost	[€/kWh]	100,5 – 134	100,5 – 134	201
Replacement frequency (life time)	[yr]	5 – 6	5 – 6	10
Operation and maintenance costs	[€/kW-yr]	3,35 – 10	3,35 – 10	6,7
Efficiency (AC to AC)	[%]	75	75	75
Storage losses	[%]	N/A	0,1	0,2

4.2.6.2 Sodium Sulfur Battery (NaS)

The NaS battery consists of liquid (molten) sulfur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, positive Na+ ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 volts. This process is reversible as charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. The battery is kept at about 300 ºC to allow this process. Figure 4.8 shows a scheme of the NaS cell.

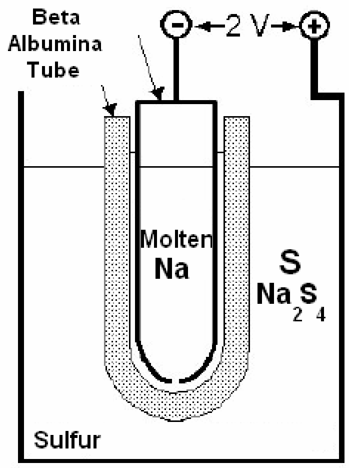


Figure 4.8 – NaS cell scheme (ESA, 2007/2008)

NaS battery cells have a pulse power capability over six times their continuous rating (for 30 seconds). This attribute enables the NaS battery to be economically used in combined power quality and peak shaving applications. Table 4.16 shows the parameters and costs of NaS battery systems for bulky storage and DG.

Table 4.16 – Parameters and costs for NaS systems (SCHOENUNG *et al.*, 2003)

		Bulky	DG
Energy-related cost (delivered)	[€/kWh]	167,5	167,5
Power-related cost	[€/kW]	100,5	100,5
Replacement cost	[€/kWh]	154	154
Replacement frequency (life time)	[yr]	10	15
Operation and maintenance costs	[€/kW-yr]	13,4	13,4
Efficiency (AC to AC)	[%]	70	70
Storage losses	[%]	N/A	0,05

NaS battery technology has been demonstrated at over 30 sites in Japan totaling more than 20 MW with stored energy suitable for 8 hours daily peak shaving. The largest NaS installation is a 6MW, 8h unit for Tokyo Electric Power Company.

4.2.6.3 Lithium Ion Battery (Li-Ion)

Li-ion batteries have a high power densities (kW/m^3), energy densities (J/m^3), specific powers (kW/kg) and specific energies (kW/kg) when compared to the batteries discussed above. They have also a long life cycle (3.000 cycles at 80% depth of discharge). The cathode in these batteries is a lithiated metal oxide (LiCoO2, LiMO2, etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts (such as LiPF6) dissolved in organic carbonates. When the battery is being charged, the Lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. Figure 4.9 shows the working principle of a Li-Ion battery.

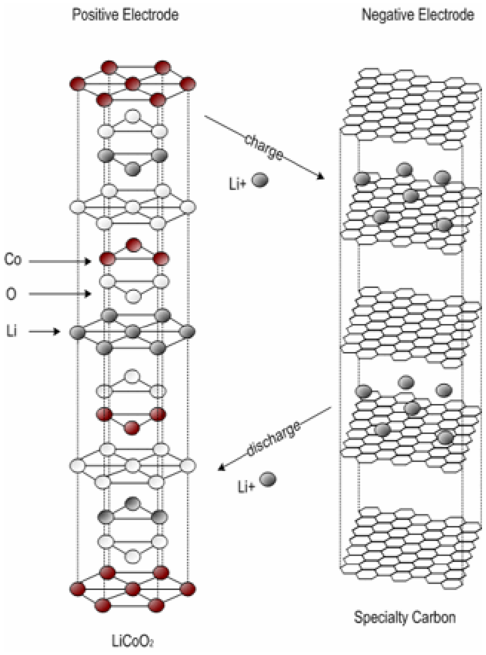


Figure 4.9 –Working principle of a Li-Ion battery

While Li-ion batteries took over 50% of small portable market in a few years (like mobile phones and laptop batteries), there are some challenges for making large-scale Li-ion batteries. The main hurdle is the high cost (above €400/kWh) due to special packaging and internal overcharge protection circuits. Several companies are working to reduce the manufacturing cost of Li-ion batteries to capture large energy markets.

Another drawback of this battery is that its life span is dependent upon aging from time of manufacturing (shelf life) regardless of whether it was charged, and not just on the number of charge/discharge cycles. So an older battery will not last as long as a new battery due solely to its age, unlike other batteries.

Table 4.17 shows some parameters and costs of a Li-Ion battery for both DG and PQ applications.

Table 4.17 – Parameters and costs for Li-Ion systems (SCHOENUNG *et al.*, 2003)

		PQ	**DG**
Energy-related cost (delivered)	[€/kWh]	335	335
Power-related cost	[€/kW]	134	117,3
Replacement cost	[€/kWh]	335	335
Replacement frequency (life time)	[yr]	10	10
Operation and maintenance costs	[€/kW-yr]	6,7	16,8
Efficiency (AC to AC)	[%]	85	85
Storage losses	[%]	0,01	0,01

4.2.6.4 Metal-Air Battery

Metal-air batteries are the most compact and, potentially, the least expensive batteries available. They are also environmentally benign.

The principle of operation of these batteries is based on the electrochemical coupling of a reactive metal anode to an air electrode. Thus, a battery with an inexhaustible cathode reactant from the oxygen air is obtained.

The anodes in these batteries are commonly available metals with high energy density like aluminum or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH- ion conductor such as KOH. Figure 4.10 shows the scheme of the metal-air battery.

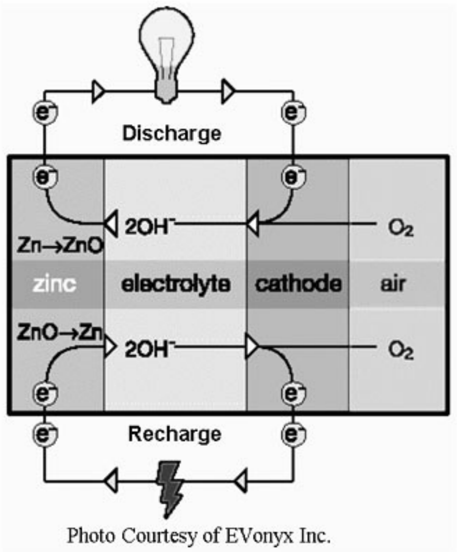


Photo Courtesy of EVonyx Inc.

Figure 4.10 – Metal-Air Battery scheme (ESA, 2007/2008)

Research efforts have focused in development of rechargeable systems and currently there are mechanically and electrically rechargeable metal-air batteries. However, in renewable energy system applications only the second type is of interest.

Some advantages and drawbacks associated with the metal-air batteries are given in Table 4.18.

Table 4.18 – Advantages and drawbacks of Metal-Air batteries

Advantages	Drawbacks
• High-energy density • Flat discharged voltage • Long shelf life • Relatively low cost • Capacity independent of load and temperature when working within normal operation range	• Limited output power • Low current density obtainable • Limited operating temperature range • Hydrogen evolution from anode corrosion • Carbonation of alkali electrolyte

The main disadvantage, however, is that electrical recharging of these batteries is very difficult and inefficient. Rechargeable metal air batteries that are under development have a life of only a few hundred cycles and efficiency about 50%.

While the high energy density and low cost of metal-air batteries may make them ideal for many primary battery applications, the electrical rechargeability feature of these batteries needs to be developed further before they can compete with other rechargeable battery technologies.

4.2.7 Redox-Flow Batteries

A flow battery is a form of rechargeable battery in which electrolyte containing one or more dissolved electroactive species flows through a power cell/reactor that converts chemical energy to electricity. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor, although gravity feed systems are also known. Flow batteries can be rapidly "recharged" by replacing the electrolyte liquid (in a similar way to refilling fuel tanks for internal combustion engines) while simultaneously recovering the spent material for re-energization.

Various classes of flow batteries exist including the redox (reduction-oxidation) flow battery, in which all electroactive components are dissolved in the electrolyte. If one or more electroactive component is deposited as a solid layer, the system is known as a hybrid flow battery. The main difference between these two types of flow battery is that the energy of the redox flow battery can be determined fully independently of the battery power, because the energy is related to the electrolyte volume (tank size) and the power to the reactor size.

The hybrid flow battery, similarly to a conventional battery, is limited in energy to the amount of solid material that can be accommodated within the reactor. In practical terms this means that the discharge time of a redox flow battery (RFB) at full power can be varied, as required, from several minutes to many days, whereas a hybrid flow battery may be typically varied from several minutes to a few hours. Figure 4.11 shows the schematic diagram of a RFB.

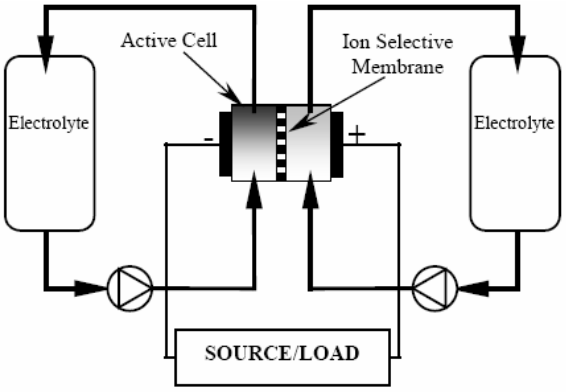


Figure 4.11 – Schematic diagram of a Redox flow battery (SELS *et al.*, Oct. 2001)

Besides the fact that the storage capacity of a RFB is independent of the battery power, while only depending on the concentration of the electrolyte, the RFB have other advantages when compared to ordinary batteries. They are very cheap and can withstand overloading and totally discharging without any risk of damage. One of the major disadvantages is the use of aggressive chemical solutions, which can have a major impact on the environment. Since the 1990s, the “Regenesys Energy Storage System” project is doing intensive research to the usability of RFB for large power ratings in the United Kingdom.

Sections 4.2.7.1 to 4.2.7.3 provide some information and characteristics of some flow battery technologies.

4.2.7.1 Vanadium Redox Flow Battery (VRB)

VRB stores energy by employing vanadium redox couples (V2+/V3+ in the negative and V4+/V5+ in the positive half-cells). These are stored in mild sulfuric acid solutions (electrolytes). During the charge/discharge cycles, H+ ions are exchanged between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane. The cell voltage is 1,4 - 1,6 volts.

The main advantages of the vanadium redox battery is that it can offer almost unlimited capacity simply by using larger and larger storage tanks, it can be left completely discharged for long periods with no ill effects, it can be recharged simply by replacing the electrolyte if no power source is available to charge it, and if the electrolytes are accidentally mixed the battery suffers no permanent damage.

The main disadvantages with vanadium redox technology are a relatively poor energy-to-volume ratio, and the system complexity in comparison with standard storage batteries. Table 4.19 shows some parameters and costs of a VRB for DG applications.

Table 4.19 – Parameters and costs for a VRB system (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	402
Power-related cost	[€/kW]	117,3
Replacement cost	[€/kWh]	402
Replacement frequency (life time)	[yr]	10
Operation and maintenance costs	[€/kW-yr]	13,4
Efficiency (AC to AC)	[%]	70
Storage losses	[%]	0,2

Currently installed vanadium batteries include a 1,5 MW UPS system in a semiconductor fabrication plant in Japan and a 250 kW, 2MWh load leveler in use at Castle Valley, Utah.

4.2.7.2 Zinc Bromine Flow Battery (ZnBr)

The zinc-bromine flow battery is a type of hybrid flow battery. In each cell of a ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. During discharge, Zn and Br combine into zinc bromide, generating 1,8 volts across each cell. This will increase the $Zn2^+$ and Br^- ion density in both electrolyte tanks. During charge, metallic zinc will be deposited as a thin film on one side of the carbon-plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge. Table 4.20 shows some parameters and costs of VRB systems applied to DG.

Table 4.20 – Parameters and costs for a ZnBr system (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	268
Power-related cost	[€/kW]	117,3
Replacement cost	[€/kWh]	67
Replacement frequency (life time)	[yr]	8
Operation and maintenance costs	[€/kW-yr]	13,4
Efficiency (AC to AC)	[%]	60
Storage losses	[%]	0,01

This type of battery is optimal for long-term energy storage as it can be designed to achieve very low self-discharge when the system is in standby. For this application, the fluid electrolyte is drained from the cells and added to the fluid already in the storage tanks. Restart under these conditions requires activation of the circulation system, allowing the battery to deliver maximum power within 30 seconds. The system can also be operated as an uninterruptible power supply (UPS), delivering maximum power within a few 60 Hz cycles. This capability requires operation of the circulation system approximately once per hour to maintain some active fluids in the cell stack which does increase the self-discharge rate.

The ZnBr battery was developed by Exxon in the early 1970's and some multi-kWh units are now available pre-assembled, complete with plumbing and power electronics. Today there are about 2,5 MWh of ZnBr batteries installed in utility and manufacturing facilities.

4.2.7.3 Polysulfide Bromide Battery (PSB)

This battery has been developed by Regenesys Technologies Ltd. It is a regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulfide). PSB electrolytes are brought close together in the battery cells where they are separated by a polymer membrane that only allows positive sodium ions to go through, producing about 1,5 volts across the membrane.

PSB focuses on large-scale applications (bulky storage). Cells are electrically connected in series and parallel to obtain the desired voltage and current levels. This battery works at room temperature. The battery has been verified in the laboratory and demonstrated at multi-kW scale in the UK. Table 4.21 shows parameters and overall costs of a PSB system.

Table 4.21 – Parameters and costs for a PSB (Regenesys®) system (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	67
Power-related cost	[€/kW]	184,2
Replacement cost	[€/kWh]	100,5/kW
Replacement frequency (life time)	[yr]	10
Operation and maintenance costs	[€/kW-yr]	10
Efficiency (AC to AC)	[%]	65

Regenesys Technologies had a project to build a 120 MWh, 15 MW energy storage plant using this technology at Innogy's Little Barford Power Station in the UK, however, financial problems have terminated the project.

BLAABJERG *et al.*, 2007, presents a comparison between the different flow battery technologies considering their main characteristics and application ranges. This comparison is given in the Table 4.22.

Table 4.22 – Comparison between different technologies of flow batteries (BLAABJERG *et al.*, 2007)

		VRB	ZnBr	PSB
Power range	[MW]	0,25 – 3 10 possible	5 – 500	0,05 – 4
Energy density	[Wh/kg]	25 – 35	-	75 – 85
Specific power	[W/kg]	60 – 100	-	-
Nominal Cell Voltage (open circuit)	[V]	1,6	1,5	1,8
Complete System Voltage	[kV]	up to 6,6	?	0,108 (60 cell stack)
Energy efficiency for system	[%]	80	60 – 70	70 – 75
Life time		10 – 15 years	15 years	1.500 cycles
Applications		UPS peak shift/cut load leveling	peak demands DG	DG
Price	[€/kW]	1.100 – 6.000	N/A	N/A
Technology status	-	available	available	available

4.2.8 Hydrogen Storage

The hydrogen storage is an interesting storage system for the future. The application of electricity causes electrolysis, decomposing water into hydrogen and oxygen. The hydrogen is then stored, consisting of a chemical energy storage system. When necessary, the chemical energy is converted into electrical energy and heat, through the oxidation of hydrogen with oxygen in fuel cells. The chemical product of this transformation is pure water. The achievable efficiencies are 45% (electrical) and 35% (thermical). Figure 4.12 shows the principle of a hydrogen storage system.

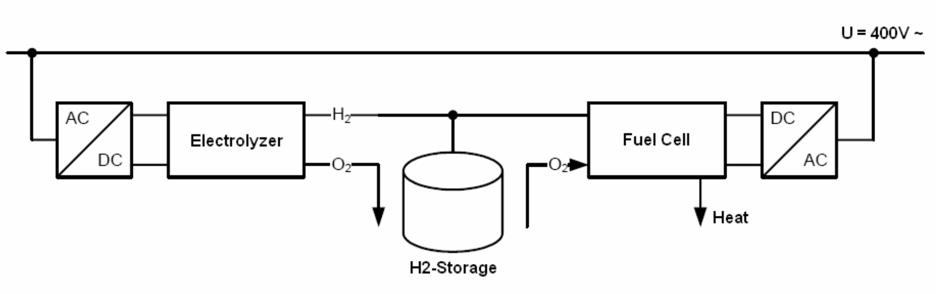


Figure 4.12 – Principle of the hydrogen storage system (BODACH, 2006)

Table 4.23 summarizes the principal advantages and drawbacks of the hydrogen storage systems.

Table 4.23 – Advantages and drawbacks of hydrogen storage

Advantages	Drawbacks
• Harmless to the environment • Modern systems can be run from 0 to full load in 1 to 2 min. • Power and Capacity of the storage system are independent from each other • Relative high cycling efficiency	• Achievable overall efficiency is around 25% • The technology is not yet commercially available, especially regarding the fuel cells that do not yet achieve life cycles of at least 8600 h (one year).

Hydrogen-based systems can only be considered as energy storage technologies if the production and storage of hydrogen is part of the overall system. If hydrogen is simply supplied as a consumable or produced from the conversion of natural gas, then such a system is a generator and is not really a storage system. Table 4.24 shows parameters and costs of a hydrogen fuel cell applied to DG.

Table 4.24 – Parameters and costs for a hydrogen fuel cell system (SCHOENUNG *et al.*, 2003)

Energy-related cost (delivered)	[€/kWh]	10
Power-related cost	[€/kW]	201
Replacement cost	[€/kWh]	67/kW
Replacement frequency (life time)	[yr]	10
Operation and maintenance costs	[€/kW-yr]	1,67
Efficiency (AC to AC)	[%]	~45
Storage losses	[%]	0

A field test attempt to implement a hydrogen storage system was carried out by the Scandinavian energy company Norsk Hydro on the norwegian island of Utsira. The system consists of an electrolyser (48 kW), a fuel cell (10 kW) and a hydrogen engine (55 kW). The project's goal was to use the hydrogen storage system in combination with a wind energy plant in order to perform load leveling.

4.2.9 Other Systems Storing Primary Energy

Another category of storage system can be considered: systems storing primary energy. As an example, biogas systems are usually fitted with as gas storage which, if properly designed, could be used for voltage control purpose. This storage system would behave similarly to the Pumped Hydro Storage. Figure 4.13 shows a biogas storage system located in Burgenland, Austria.

Figure 4.13 – Biogas storage system in Burgenland, Austria

4.3 Storage Systems: Technologies Comparison

As said before, the different technologies presented above have different applications. The technologies are classified according to the energy, bridging time and transient response required for their operation. Moreover they can be categorized in terms of energy density requirements or in terms of power density requirements.

Figure 4.14 shows a comparison between different storage technologies regarding their volume energy density (E/V [MWh/m³] – storage energy capacity divided by its volume) and their weight energy density (E/m [kWh/ton] – storage energy capacity divided by its mass). Metal-air batteries have the highest energy density in this chart. However, the electrically rechargeable types, such as zinc-air batteries, have a relatively small cycle life and are still in the development stage. The energy density ranges reflect the differences among manufacturers, product models and the impact of packaging.

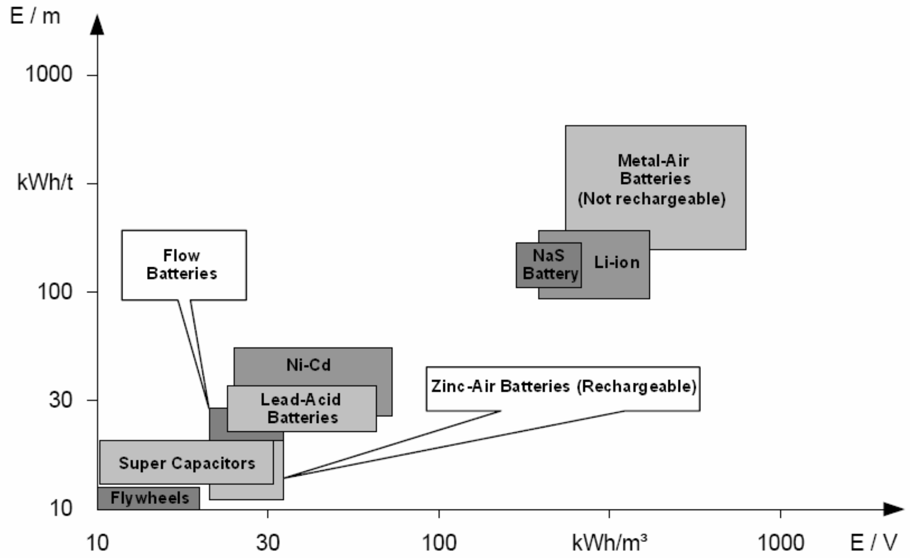


Figure 4.14 – Volume and weight energy densities for different storage technologies (ESA, 2007/2008)

Efficiency and cycle life are two important parameters to consider along with other parameters before selecting a storage technology. Both of these parameters affect the overall storage cost. Low efficiency increases the effective energy cost as only a fraction of the stored energy could be utilized. Low cycle life also increases the total cost as the storage device needs to be replaced more often. The present values of these expenses need to be considered along with the capital cost and operating expenses to obtain a better picture of the total ownership cost for a storage technology. Figure 4.15 shows the comparison between the efficiency and life cycles for the considered storage technologies.

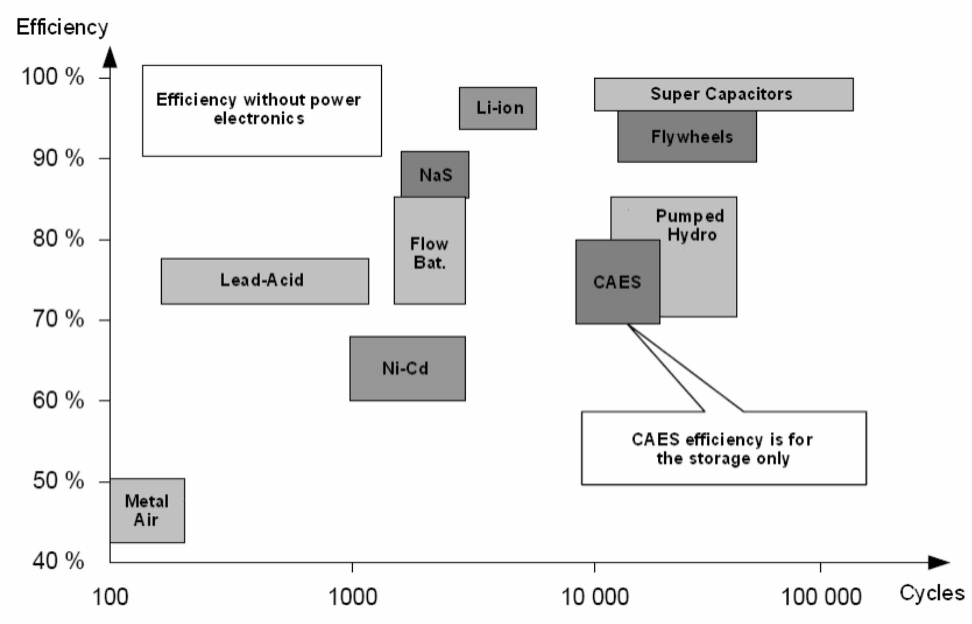


Figure 4.15 – Efficiency and life cycles for different storage technologies (ESA, 2007/2008)

In the previous figure it is clear that the supercapacitors have high cycle stability, what is very important for the fluctuating energy fraction of a network with a high DG penetration. By the observation of both diagrams (Figures 4.14 and 4.15), it is clear that, for a global DG storage solution, the combination of different technologies is the best option, as the necessary energy fraction can be stored in the batteries and the fluctuating energy fraction in supercapacitors.

The final and most comprehensive comparison takes into account the electricity storage spectrum explained in the last topic. The electric energy storage systems are divided in three major functional categories, shown in Figure 4.16.

These categories can be considered equivalent to the PQ, DG and bulky storage applications. The Power Quality & UPS refers to applications where the stored energy is only applied for seconds or less, as needed, to assure continuity of quality power. In the Bridging Power applications, the stored energy is used for seconds to minutes to assure continuity of service when switching from one source of energy generation to another. Finally, in the Energy Management applications, the stored energy is used to decouple the timing of generation and consumption of electric energy, like load leveling (the charging of storage when energy cost is low and utilization as needed).

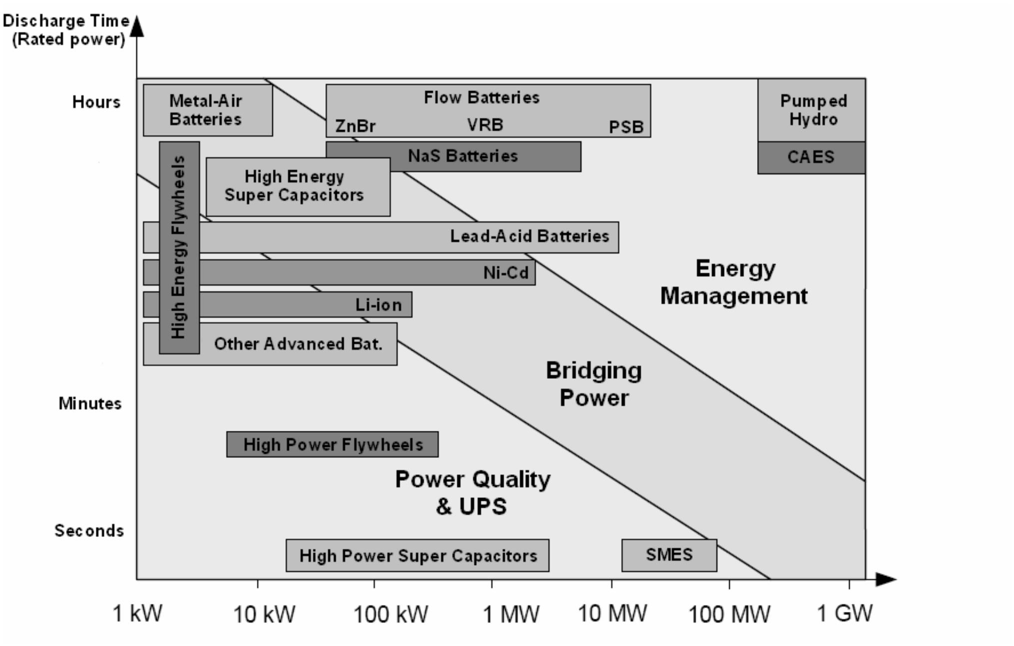


Figure 4.16 – Discharge time at rated power (ESA, 2007/2008)

It can be seen from the figure above that Pumped Hydro Storage and Compressed Air Energy Storage can not be integrated to low voltage networks due to their nominal power (P_{nom} >> 10MW). The other technologies cover a broader power range and can be, therefore, used in such networks (BODACH, 2006).

Alternatively, some of the storage technologies can also be allocated according to their energy supply time, which is shown in Table 4.25. According to (BODACH, 2006), the storage systems supply times up to 20 min are classified as short-period, those over one week as long-period, and the rest of them as average-period.

Table 4.25 – Storage applications in the energy supply field (BODACH, 2006)

Energy Transfer (full load)	Class	Hydrogen	CAES	Pumped Hydro Storage	Redox Flow Batteries	Other Batteries	Flywheels	SMES	Super Capacitor
4 months	Long period	X							
3 weeks		X							
3 days	Average period	X	X	X	X				
8 hours		X	X	X	X	X			
2 hours		X	X	X	X	X			
20 min	Short Period	X	X	X	X	X	X		X
3 min		X		X	X	X	X		X
20 sec					X	X	X	X	X

ESA® presents another comparison table, based on the aforementioned spectrum of applications presented in Figure 4.1. This classification is shown on Table 4.26.

Table 4.26 – Application of different storage system technologies (ESA, 2007/2008)

Storage Technologies	**Power** Application	**Energy** Application
Pumped Storage		●
CAES		●
Flow Batteries (VRB, ZnBr, PSB)	◑	●
Metal-Air		●
NaS	●	●
Li-ion	●	○
Other Advanced Batteries	●	○
Lead-Acid	●	○
Flywheels	●	○
SMES	●	
Super Capacitors	●	◑

●	Fully capable and reasonable
◑	Reasonable for this application
○	Feasible but not quite practical or economical
NONE	Not feasible or economical

The analysis of all the comparisons among technologies helps to identify those more suitable to be applied to the CVC in the framework of the DG DemoNet-Concept. But first it is necessary to consider how the storage systems were integrated to the CVC. The next topic explains this integration and presents a discussion about what technologies, among those analyzed, are best suitable to be used.

4.4 Integration of Storage Systems to the Coordinated Voltage Control

For the integration of the Storage Devices (SD) into the CVC, some changes in its algorithm were proposed. These changes take into account the characteristics defining the storage systems applied to the voltage control in DG networks.

The new CVC algorithm is also based on the power injection share concept and considers the installation of SD at some of the critical nodes of the network, which are detected in an offline study, as explained in the chapter 3.

Many changes were conducted in order to incorporate the SD to the CVC algorithm. First of all, the SD itself was defined as a generator/load device. It means that, differently from the DGs, the SD can not only inject active power to the network, but also absorb active power from it. Practically, the SD works as a dual generator/load.

For the correct definition of the SD, a number of parameters needed to be considered, these parameters, their units and their definition are presented on the Table 4.27. Figure 4.17 shows how a SD was represented in the CVC algorithm code.

Table 4.27 – Storage parameters

Parameter [UNIT]	**Definition**
F_{nom} [Hz]	**Nominal frequency**
U_{nom} [V]	**Nominal Voltage**
E_{full} [MWh]	**StorageUpperLimit(*)**
E_{empty} [MWh]	**StorageLowerLimit(*)**
E_{inst} [MWh]	**CurrentValue(*)**
E_{sp} [MWh]	**StorageSetPoint(*)**
P_{max} [W]	**Maximal power that can be charged/discharged in one time unit**
dP_{max} [W]	**Maximal power gradient of the storage system.**
t_a [s]	**Access time: time necessary to start/stop the charge/discharge of the SD**
η_{cha} [%]	**Charge efficiency**
η_{dis} [%]	**Discharge efficiency**
E_{aut} [%/h]	**Auto-discharge**
K_p, K_i	**Parameters of the P.I. Control**

(*) See Figure 4.17 below:

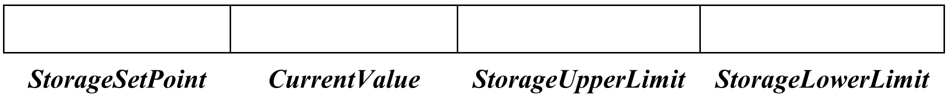


Figure 4.17 – Storage device definition added to the CVC algorithm

The *CurrentValue* represents the current amount of energy (MWh) stored in the SD at a certain point in time (sum of all three phases). The *StorageUpperLimit* denotes the size, or maximal capacity, of the SD. When the *CurrentValue* is equal to *StorageUpperLimit*, it means that the SD can not absorb any power from the network; or, from the voltage control perspective, it is at its limit. The same occurs if the *CurrentValue* is equal to *StorageLowerLimit*, which represents the minimal amount of energy that can be stored in the SD; in this work, this value is considered to be zero.

The *StorageSetPoint* represents the set point to be achieved when the SD does not need to contribute to the voltage control. In the case the SD is connected to an overvoltage node, for example, this value is set to the *StorageLowerLimit*, so the SD can discharge (generator) when no voltage control is needed, optimizing its contribution in case of a future overvoltage. On the other hand, when connected to an undervoltage node, the *StorageSetPoint* is set to *StorageUpperLimit*, so the SD can charge (load) when no voltage control is needed, also optimizing it’s voltage control capacity in case of future undervoltage. Of course this *StorageSetPoint* adjust can lead to overvoltage and undervoltage, respectively, however, the whole CVC is prepared to deal with these situations. Figure 4.18 shows the action performed by the SD control in the cases where the voltage is outside the upper and lower limits and when the voltage is ok, but the *CurrentValue* and *StorageSetPoint* have different values.

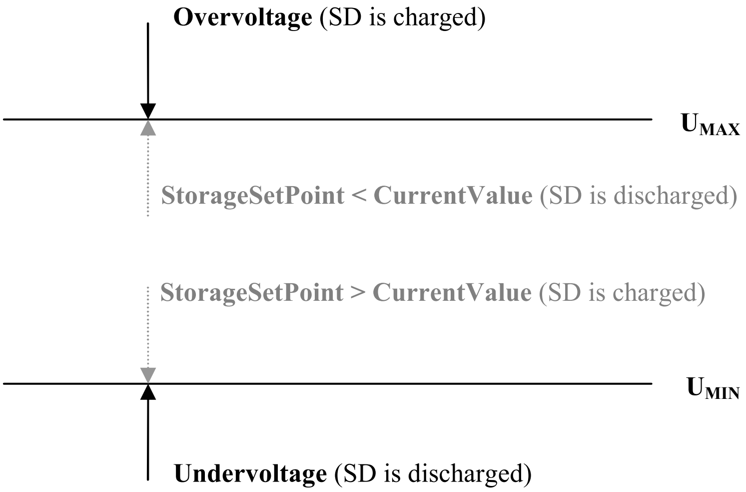


Figure 4.18 – Storage device model added to the CVC, showing the control action in different cases

In the CVC algorithm, both E_{aut} and t_a were considered to be zero. The first one, the battery auto-discharge value, was not considered because it is much smaller when compared with the charge/discharge rates for this application, making it have a minor relevance in the simulations. t_a, however, though important, was not considered since many time constants of the network still need to be investigated and validated. Of course this affects the simulations, as explained later and it is expected to be improved in the near future, since a time constants investigation is being currently carried out (See chapter 6).

For a better modeling of the SD in the CVC algorithm to broaden its applicability to different storage technologies, they were divided in two different models, depending on their physical and operation characteristics. The Storage Model 1 (Figure 4.19) considers a SD connected to the same bus the generator is connected. In this model, Pout is the sum of the SD output and the generator output, which are independent from each other. If the generator is at its maximal output value, the storage system can still discharge. It is important to note, that the value P_{SD} shown in the figure can not be greater than the P_{MAX} (Table 4.27).

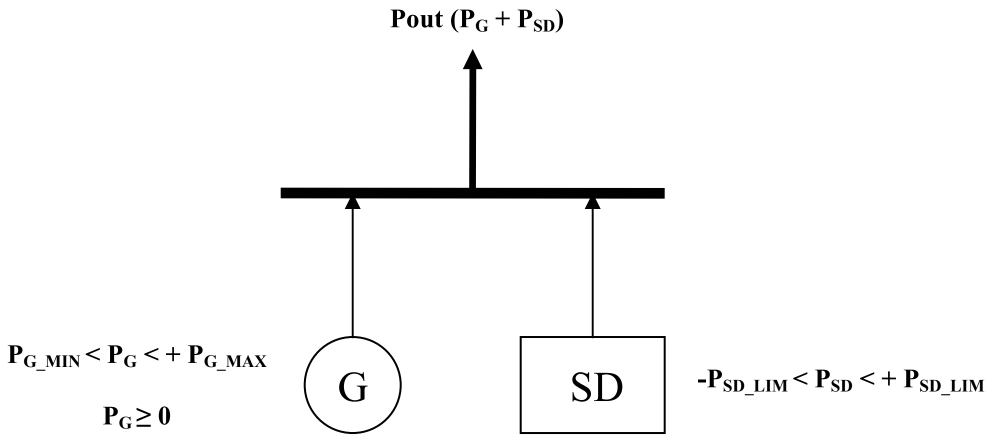


Figure 4.19 – Storage Model 1 – Standalone Storage System

The Storage Model 2 (Figure 4.20) considers that Pout is equal to the generator output, which is a sum of the required generation and the storage output. In this model, if the generator is at its maximal output value, the storage system can not discharge, as they are dependent from each other. In this case, P_{OUT} can not be greater than P_{MAX} (Table 4.27).

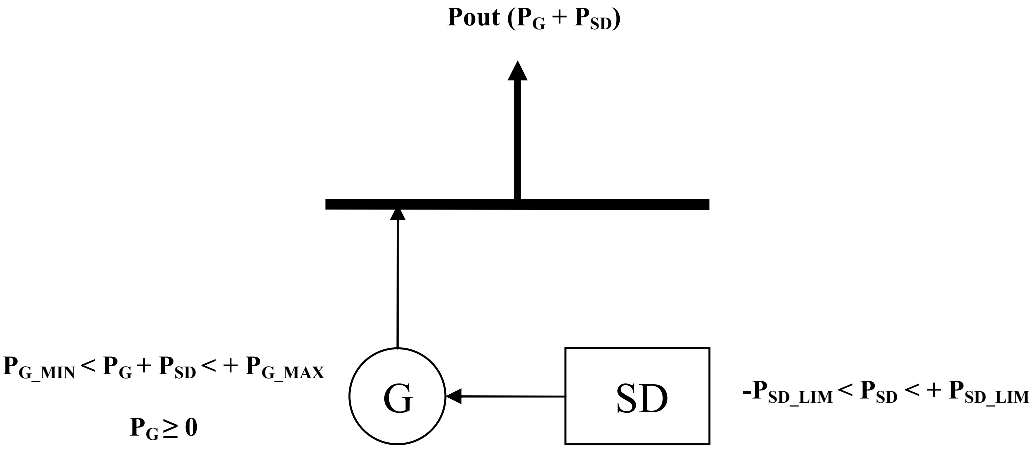


Figure 4.20 – Storage Model 2 – Integrated Storage System

The original local voltage control part of the CVC algorithm considers that active power voltage control is introduced in the case of reactive power management reaches its limit. With the introduction of the Storage Model 1, the active power voltage is introduced only after the SD reaches its limit. Therefore, this new voltage control acts between the reactive and active power voltage control. Figure 4.21 shows the change in the flow chart algorithm of the CVC.

For the Storage Model 2, the storage control is also performed after the Q control and before the PQ control, but in this case the storage control is nothing more a PQ control performed by a generator that is not part of the original PQ control scheme. It means that, after the Q control is exploited, the generator that incorporates the storage control is activated and when its control's capacity is also exploited, the PQ control, through the priority matrix is activated.

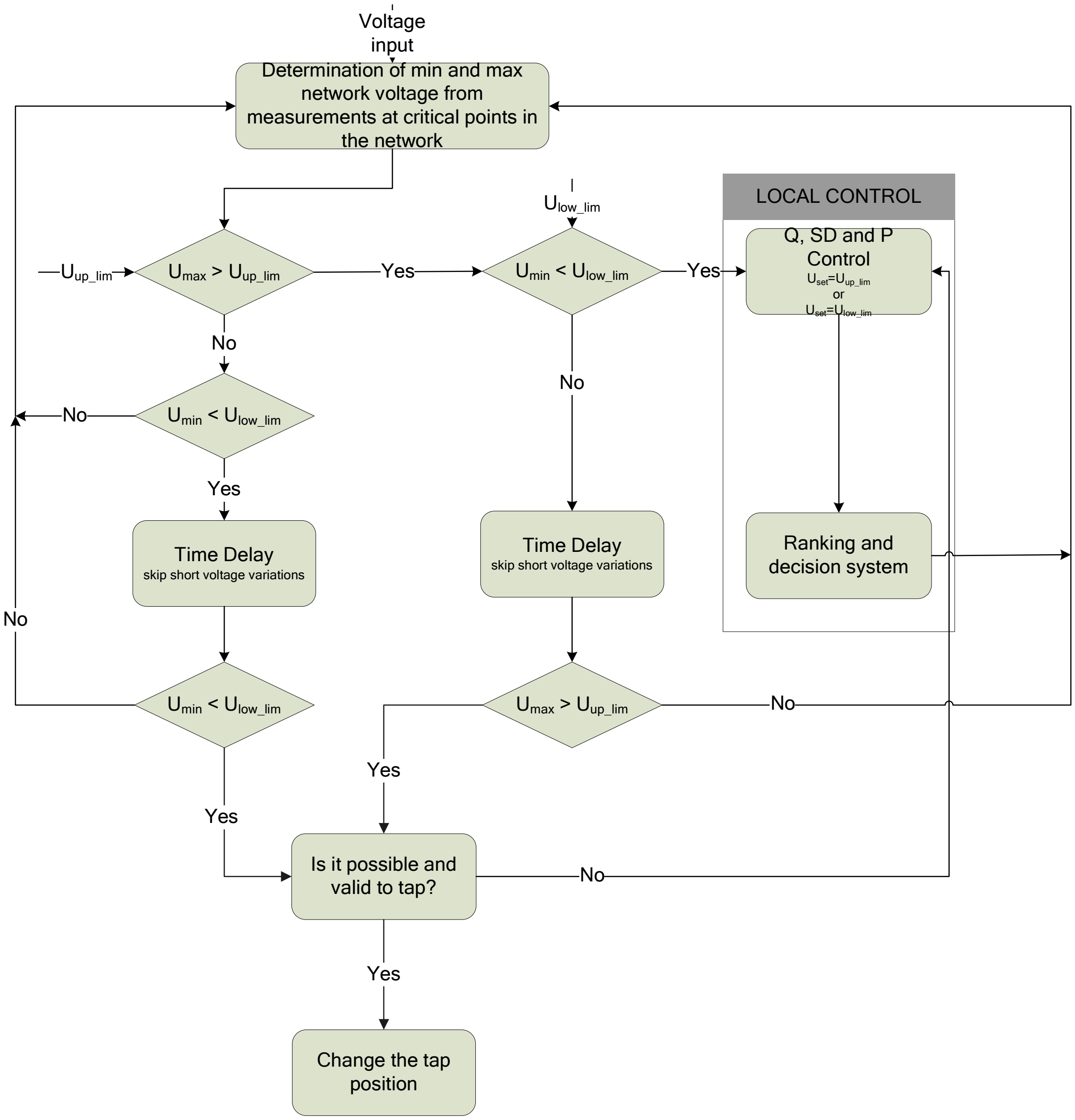


Figure 4.21 – Flow chart algorithm of the CVC with the addition of the SD Control

The SD also participates in the power injection share concept, as it works as a generator when discharging. When charging, however, the Storage Model 1 works as a load; this improves the capacity of the device in controlling also undervoltage. As an example, in a situation where there is overvoltage, but it is not possible to activate the centralized OLTC voltage control due to the possibility of undervoltage in another node, the SD could discharge, rising the overall voltage and, making it possible to tap the transformer. It is not necessary to have different voltage setpoints for conflict conditions anymore, in comparison with the flow chart shown in chapter 3. Figure 4.22 shows a basic representation of the CVC algorithm with the addition of the SD control.

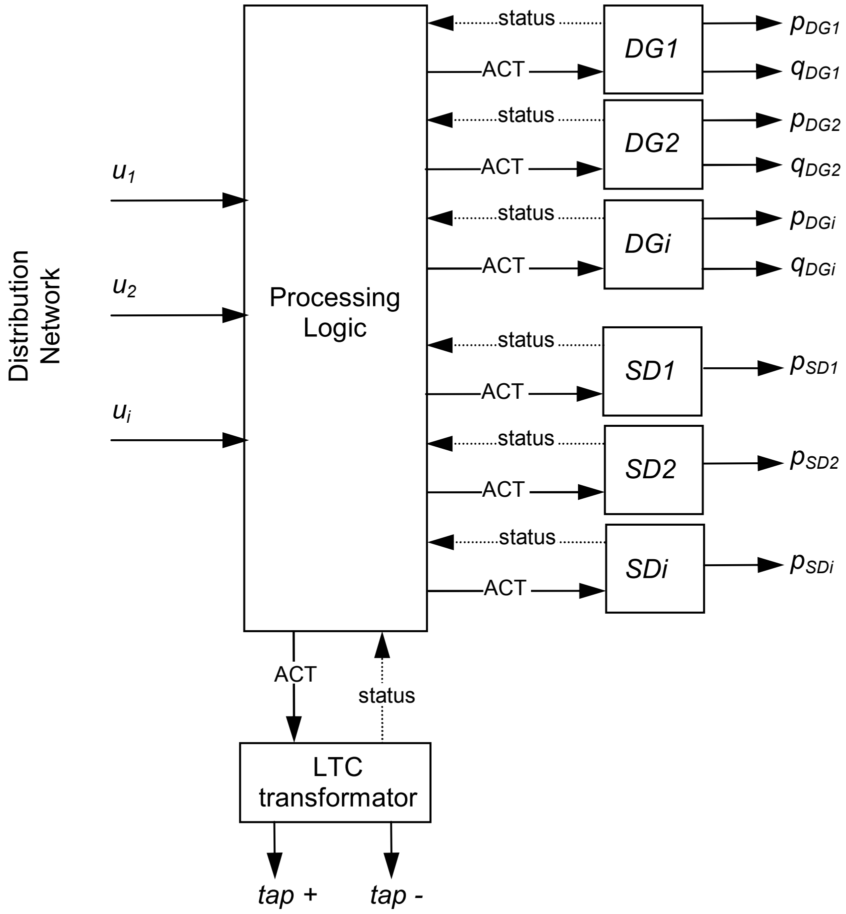
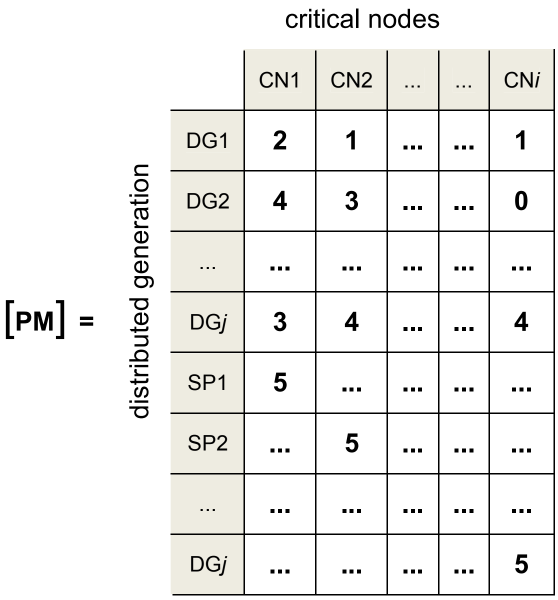


Figure 4.22 – Basic representation of the CVC algorithm with SD control

The Priority Matrix presented in the chapter 3 was also modified in order to accommodate the addition of the SD control. The new priority matrix is shown on Figure 4.23. Since the SDs of the Storage Model 1 control the active and not the reactive power, the SDs are added to the active power priority matrix. New lines are added to this matrix corresponding to the number of SDs considered. Differently from the DG units, SDs are considered to contribute to the voltage regulation only at the nodes where they are connected to. As the SD control is performed before the PQ control, the contribution of a SD to the node it is connected is always greater (**5** on the figure 4.23) than the contribution of other DGs to this same node.



[PM] =

critical nodes

distributed generation

	CN1	CN2	...	...	CN*i*
DG1	**2**	**1**	**...**	**...**	**1**
DG2	**4**	**3**	**...**	**...**	**0**
...	**...**	**...**	**...**	**...**	**...**
DG*j*	**3**	**4**	**...**	**...**	**4**
SP1	**5**	**...**	**...**	**...**	**...**
SP2	**...**	**5**	**...**	**...**	**...**
...	**...**	**...**	**...**	**...**	**...**
DG*j*	**...**	**...**	**...**	**...**	**5**

Figure 4.23 – Active Power Priority Matrix with Storage Control

It is important to ratify that, as explained in the chapter 3, if voltage problems cannot be resolved by this algorithm, even with the addition of SDs, the local voltage protection switches will cut off the DG units from the network immediately. The algorithm will only rely on overvoltage protection devices as a fallback solution. Of course this will depend on the SD dimensioning and its economical aspects.

With the storage comparisons presented in the last topic and the method to apply the SD control to the CVC algorithm present here, it is possible to identify the most suitable technologies for this application.

As explained in chapter 3, the main goal of the DG DemoNet-Concept is to change the currently passive distribution networks to active networks able to accommodate a significant penetration of DG. This high penetration of DG normally leads to voltage rises along the distribution networks where they are present, while it is still possible to have low voltages in some other areas of the network, due to a high presence of loads.

The voltage regulation techniques introduced by the DG DemoNet-Concept are used to keep the voltage within the limits in hourly/daily cycles. The load and generation profiles of the network are read in a time interval of 15 min, all over the year. Therefore, the technologies oriented only to the PQ applications like SMES, High Power (high and low speeds) Flywheels and Supercapacitors are not suitable to be used in the CVC.

The Li-Ion batteries are still only used for a variety of small applications, but its application to DG or bulky storage is far from being practical and economical.

Some other technologies could be suitable for the integration to the CVC, like the Hydrogen Storage, High Energy Flywheels and High Energy Supercapacitors, but they are at an early development status and it is not clear if they will be available in the next years and if it will be possible to use them in high energy applications.

The Metal-Air Battery is also not a good option, due to its recharging issue, since the expected storage system needs to charge, discharge in daily cycles and this cannot be constrained by a poor recharging performance. The rechargeable types are still being researched and can be a good option in the future.

The Lead-Acid Batteries have a reduced lifecycle and are sensible to extreme depth of discharge, what is a critical constraint for the storage systems needed for the integration to the CVC, since the systems need to have the capacity be fully charged or discharged in daily cycles without major changes in their efficiencies and operation.

The other evaluated technologies, namely Flow Batteries (VRB, ZnBr and PSB), Sodium Sulfur Battery (NaS), Compressed Air Energy Storage (CAES) and Pumped Hydro Storage can be considered as possible solutions for the integration of storage devices into the CVC. The flow batteries and the NaS battery can be modelled by the Storage Model 1 and the Pumped Hydro Storage, as well as the Biogas Storage, by the Storage Model 2, due to their physical characteristics and operation parameters.

5 Study Case: Vorarlberg, Austria

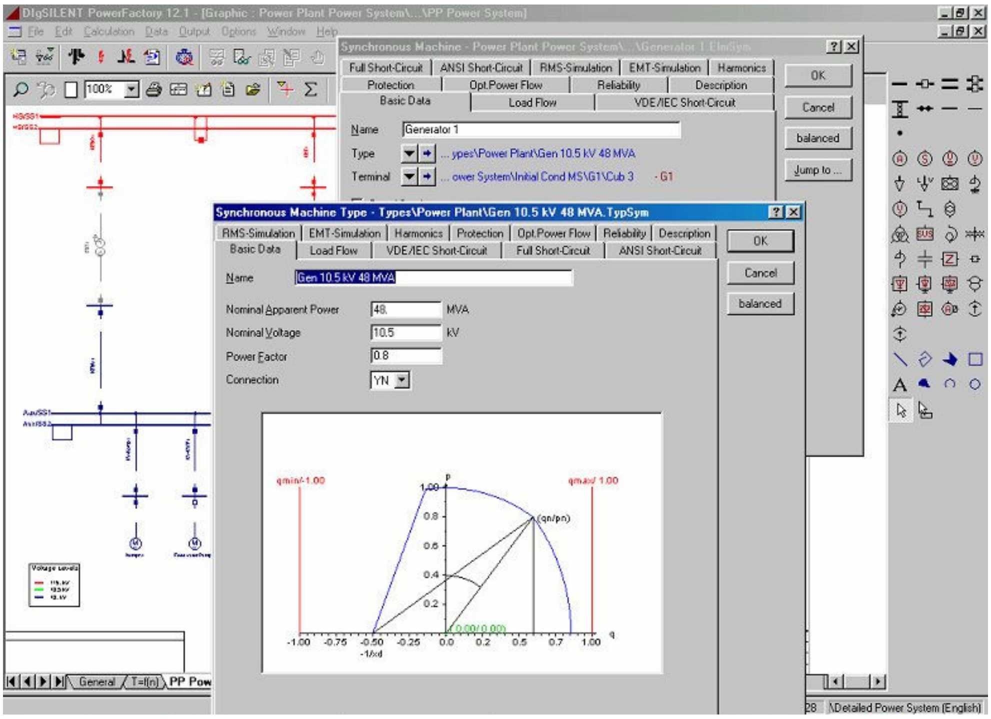
In this chapter a study case is considered in order to evaluate the results obtained by adding SDs to the CVC. Simulations were carried out using the software DIgSILENT PowerFactory® and MATLAB®, as explained in the next topic, and had the main objectives to integrate storage systems into the coordinated voltage control and provide rules for the dimensioning of the SD and for the comparison with the original CVC system. Due to the length of the simulations, year simulations, which would be useful for economical considerations, could not be performed.

5.1 DIgSILENT PowerFactory® Software Overview

The calculation software PowerFactory®, as written by DIgSILENT, is a computer aided engineering tool for the analysis of industrial, utility and commercial electrical power systems. It is designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. The name DIgSILENT stands for Digital SimuLation and Electrical NeTwork calculation program.

DIgSILENT PowerFactory® software incorporates a list of simulation functionalities including load flow and fault analysis of complete AC/DC network representation, low voltage network analysis, distribution network optimization, harmonic analysis, interface SCADA, power electronic device modeling, among others.

The software performs within a fully graphical windowing environment as shown in Figure 5.1. Separate windows are available for output display, single line graphics and substation drawings, data base editing and calculation functions. Additionally, multiple windows in each window class may be open simultaneously to show for example different aspects of the same substation graphic, or to highlight different hierarchies in a network single line graphic.



Name: Generator 1
Type: ... ypes\Power Plant\Gen 10.5 kV 48 MVA
Terminal: ... ower System\Initial Cond MS\G1\Cub 3 - G1

Name: Gen 10.5 kV 48 MVA
Nominal Apparent Power: 48. MVA
Nominal Voltage: 10.5 kV
Power Factor: 0.8
Connection: YN

Figure 5.1 – Graphical windowing environment in DIgSILENT PowerFactory® simulation software.

DIgSILENT PowerFactory® also provides a fully integrated graphical editing environment, which enables the user to draw and modify electrical grids, operate several windows with different layers and grid sections simultaneously, display calculation results immediately in result boxes within the single line diagram, among other functionalities.

The software also features definition of user written models within a fully graphical environment (block diagrams – Figure 5.2). The integrated graphical editor provides the needed flexibility to implement the most complex models also supporting unlimited model nested. Connectivity checks are permanently active ensuring proper “wiring” of all frame signals and model connections.

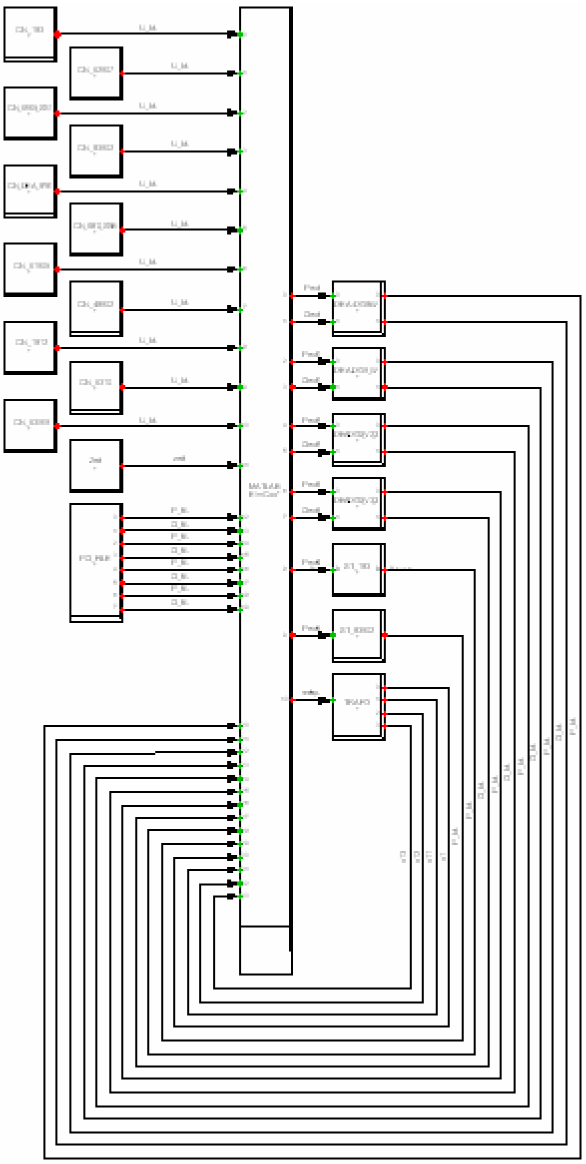


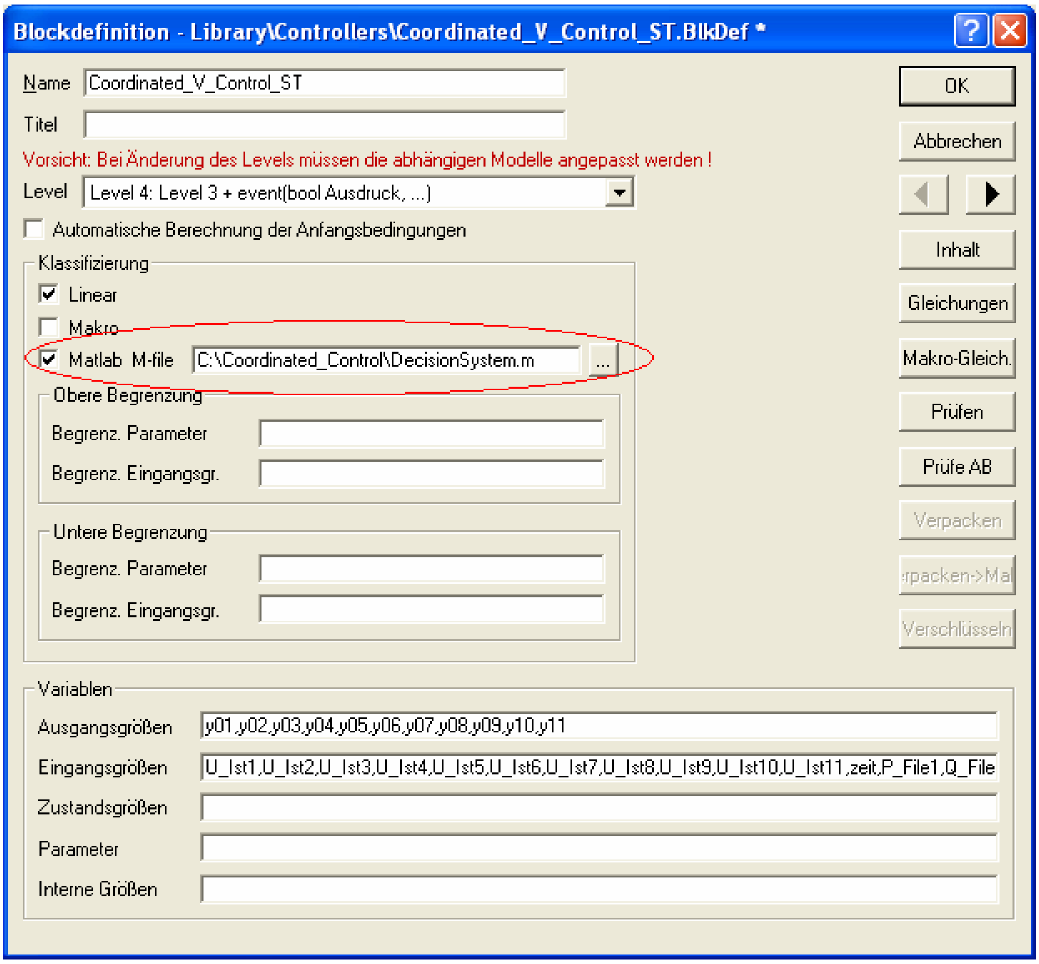
Figure 5.2 – User written models within a graphical environment.

Although DIgSILENT PowerFactory® contains a comprehensive model library and built-in functions, there are many cases in which the user may want to implement additional control options and calculation functionality. In such cases the DIgSILENT Simulation Language (DSL) can be used, which allows the creation of any kind of static or dynamic multi-input/multi-output model.

Additionally to designing controllers or various electrical and mechanical models using the DIgSILENT Simulation Language, there is also the possibility to use an interface to MATLAB®. This interface gives the opportunity to model controller or very complex transfer functions using the MATLAB® environment and insert them as a block definition into a frame in a PowerFactory® transient simulation. PowerFactory® can correspond to the

MATLAB® program during the simulation. It transfers the input values of a block to MATLAB® for every time step, which will then simulate a specified *.m file in its own environment and gives back the results as the outputs of the block.

In this work the interface between DIgSILENT PowerFactory® and MATLAB® was used, since the local, centralized and coordinated voltage control were implemented as *.m files in MATLAB®. The main reason for this was the possibility to use the flexibility of the matrix-oriented MATLAB® language. Figure 5.3 shows how the MATLAB® integration is done in the DIgSILENT environment.



Blockdefinition - Library\Controllers\Coordinated_V_Control_ST.BlkDef *

Name: Coordinated_V_Control_ST

Titel:

Vorsicht: Bei Änderung des Levels müssen die abhängigen Modelle angepasst werden !

Level: Level 4: Level 3 + event(bool Ausdruck, ...)

☐ Automatische Berechnung der Anfangsbedingungen

Klassifizierung
☑ Linear
☐ Makro
☑ Matlab M-file: C:\Coordinated_Control\DecisionSystem.m

Obere Begrenzung
Begrenz. Parameter:
Begrenz. Eingangsgr.:

Untere Begrenzung
Begrenz. Parameter:
Begrenz. Eingangsgr.:

Variablen
Ausgangsgrößen: y01,y02,y03,y04,y05,y06,y07,y08,y09,y10,y11
Eingangsgrößen: U_Ist1,U_Ist2,U_Ist3,U_Ist4,U_Ist5,U_Ist6,U_Ist7,U_Ist8,U_Ist9,U_Ist10,U_Ist11,zeit,P_File1,Q_File
Zustandsgrößen:
Parameter:
Interne Größen:

Figure 5.3 – MATLAB® integration through *.m file

In the figure above, the variables y01, y02, y03… are the MATLAB® outputs to the PowerFactory® environment, while the variables U_Ist1, U_Ist2… are the inputs to MATLAB®. On Figure 5.2, MATLAB® is represented by the central and elongated block, while the arrows represent its inputs and outputs.

5.2 Study Case Network Analysis

In order to evaluate the performance of the presented control scheme, a test case was conducted. The test network is a part of the distribution network operated by VKW Vorarlberg, Austria (Figure 5.4). The network is represented by 81 km of cable and overhead lines, one transmission network interconnection, 116 nodes, 75 loads and 31 distributed generators. In the network model wind (pink), photovoltaic (yellow), hydro (blue) and biomass (brown) generators are represented by simplified models (negative loads) and equipped with adequate control systems. An exponential dependence on the bus voltages was assumed to represent the nonlinear loads.

In simulation, real load and generation profiles were considered. The profiles included 15 minutes measurements of energy consumption (production) on feeders of active elements and are available for one year. For the test, a time step of 0,1 second and a simulation interval of one day (1440 minutes) were adopted. One second of the simulation time is equivalent to one minute in real time; therefore, one day has 1440 seconds in the simulation time.

Planning and operation rules were provided by the distribution network operator. Although strict restrictions on grid voltages are included, due to high DG penetration, in current praxis small-scale voltage deviations are tolerated. In the tests, the targeted voltage was considered to be between 0,98 p.u. and 1,03 p.u. or -2 % and +3 % of the nominal voltage. The undervoltage limit was chosen to be 0,94 instead of 0,98 since no monitored node had voltages under 0,94 and, therefore, the undervoltage analysis could not be performed if the original undervoltage limit was used.

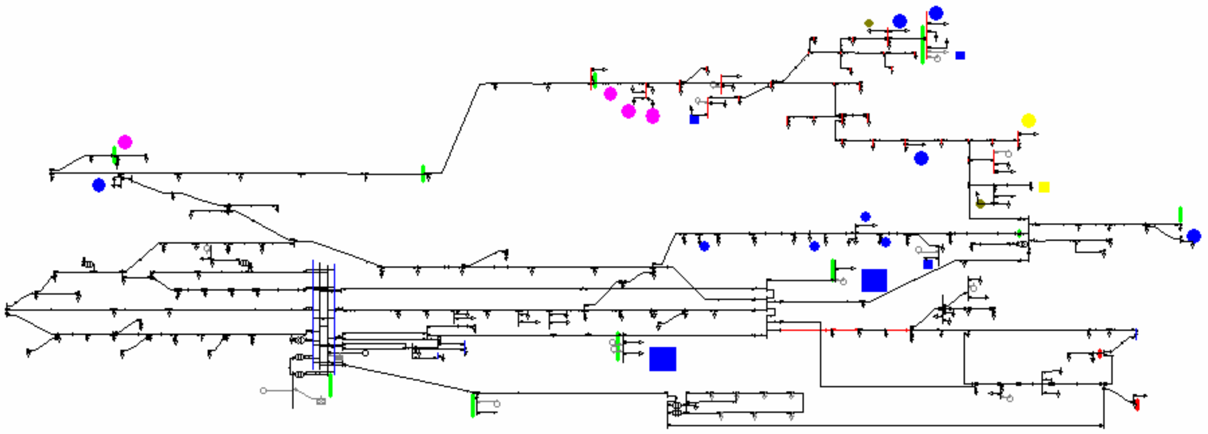


Figure 5.4 – Study case network – Vorarlberg, Austria

In the network the green and red nodes represent overvoltage and undervoltage nodes, respectively. In the simulation, eleven critical nodes were taken into account: 183, 62907, 62905_SS1, 83902, DEA_8781, 61810_SSB, 61905, 48902, 1812, 6310, 63/9/9. Figure 5.5 shows the voltage profile for these nodes during the whole year. These critical nodes were identified based on the offline studies explained in chapter 3. The results show that the nodes DEA_8781, 61810_SSB, 61905, 48902, 1812, 63/9/9 remain between the tolerated voltage limits during all the year, ranging from 0,985 to 1,015 p.u.. These nodes were therefore not considered on the tests (light grey color on the figure). The nodes 62907 and 62905_SS1 present undervoltage (dark grey color on the figure); their voltages range from 0,959 to 0,983 p.u.. Both nodes have almost the same voltage profile during all year, due to their physical proximity, therefore, only the node 62905_SS1 was considered out of these two. The nodes 183, 83902 and 6310 present overvoltage (black color on the figure); their voltages range from 0,992 to 1,066 and they were all considered for the simulations.

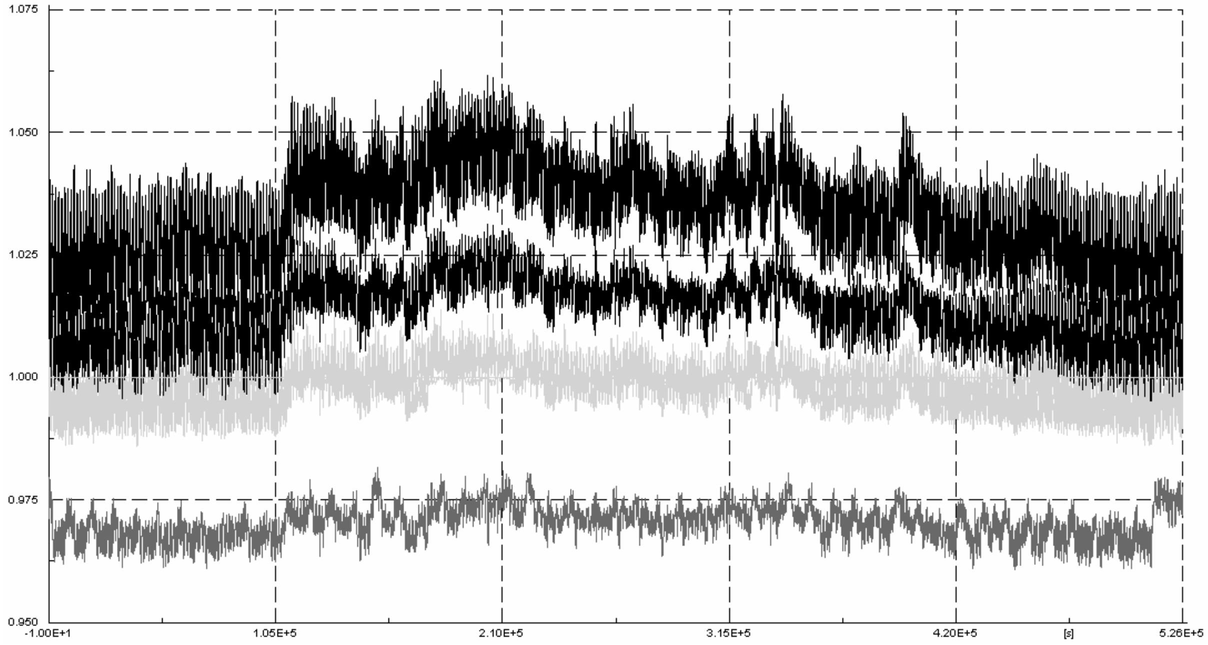


Figure 5.5 – Yearly voltage profile (p.u.) for the eleven nodes

The test was performed for both storage models presented in chapter 4. Four DG units and an existing transformer (61.810_UM2) with the OLTC option were included. The tap changer reaction time was 20s.

For the Storage Model 1 (standalone storage system), the voltage regulation scheme was composed also of storage devices connected to the node 83902, which is the more critical node among the overvoltage nodes, and to the node 62905_SS1, which is an undervoltage node. These elements were named in DIgSILENT as SD_83902 and SD_62905_SS1 respectively. Figure 5.6 shows the connection of both SDs to their respective nodes.

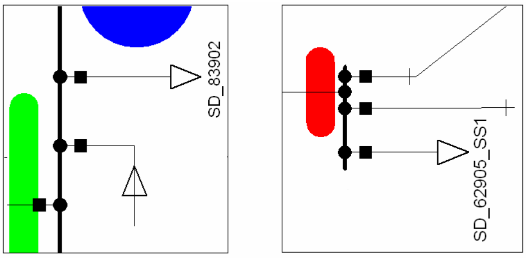


Figure 5.6 – SDs connected to the selected critical nodes – Storage Model 1

To illustrate the integration of the SDs into the CVC using the voltage share concept, the priority matrixes for Q and PQ control are presented. Four DGs were considered on the tests due to their contributions to the voltage regulation at the selected critical nodes; these DGs are DEA_DG8_W, DEA_DG9_W, DEA_DG13_V2_2MW and DEA_DG13_V3_2MW. Two new rows were added to both priority matrixes, each line referring to one of the two SDs. Since the SDs in the Storage Model 1 don't manage reactive power, they don't contribute to the Q control, as shown in Table 5.1. No DG contributed to the voltage at node 62905_SS1.

Table 5.1 – Priority Matrix for Q Control – Storage Model 1

Critical Nodes					
62905-SS1	183	83902	6310		
X	X	X	**1**	DEA_DG8_W	**DG**
X	X	**4**	**4**	DEA_DG9_W	
X	**4**	**3**	**3**	DEA_DG13_V2_2MW	
X	**3**	X	**2**	DEA_DG13_V3_2MW	
X	X	X	X	SD_83902	**SD**
X	X	X	X	SD_62905_SS1	

Even though the SD control is performed before the PQ control, the SDs were added to the PQ priority matrix (Table 5.2), as they also contribute to the active power regulation. They have of course higher priority when compared to DGs, but their contribution to the voltage control is locally limited, as explained in chapter 4. Even though no DG contributes to the voltage at node 62905_SS1, the SD can contribute to this node, because of its capacity to absorb power from system by charging.

Table 5.2 – Priority Matrix for PQ Control – Storage Model 1

Critical Nodes					
62905-SS1	183	83902	6310		
X	X	X	**1**	DEA_DG8_W	**DG**
X	X	**4**	**4**	DEA_DG9_W	
X	**4**	**3**	**3**	DEA_DG13_V2_2MW	
X	**3**	X	**2**	DEA_DG13_V3_2MW	
X	X	**5**	X	SD_83902	**SD**
5	X	X	X	SD_62905_SS1	

For the Storage Model 2 (integrated storage system), the voltage regulation scheme was applied only to the overvoltage node 83902, since no generator is connected to the undervoltage nodes. It was not necessary to create a new element in DIgSILENT, since the storage system is the generator DEA_DG10_W (Figure 5.7).

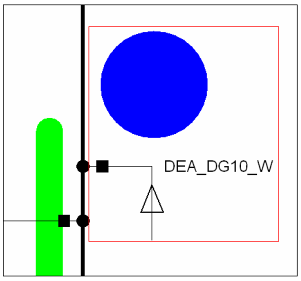


Figure 5.7 – Generator DEA_DG10_W – Storage Model 2

Table 5.3 shows the Q priority matrix for the Storage Model 2. Since this storage system is in fact a generator, the contribution to the reactive power is also considered.

Table 5.3 – Priority Matrix for Q Control – Model 2

Critical Nodes					
62905-SS1	183	83902	6310		
X	X	X	**1**	DEA_DG8_W	**DG**
X	X	**4**	**4**	DEA_DG9_W	
X	**4**	**3**	**3**	DEA_DG13_V2_2MW	
X	**3**	X	**2**	DEA_DG13_V3_2MW	
5	X	X	X	DEA_DG10_W	**SD**

Finally, Table 5.4 shows the PQ priority matrix for the Storage Model 2. It can be noted that it is exactly the same as the Q priority matrix.

Table 5.4 – Priority Matrix for PQ Control – Model 2

Critical Nodes					
62905-SS1	183	83902	6310		
X	X	X	**1**	DEA_DG8_W	**DG**
X	X	**4**	**4**	DEA_DG9_W	
X	**4**	**3**	**3**	DEA_DG13_V2_2MW	
X	**3**	X	**2**	DEA_DG13_V3_2MW	
5	X	X	X	DEA_DG10_W	**SD**

5.3 Simulations and Results

The objectives of the simulations are to verify what are the required capacity and power of the SD to keep the voltage always within the considered limits and, therefore, serve as a tool for a future dimensioning using one or more of the evaluated storage technologies and then, make it possible to implement the CVC with SDs in real distribution networks

All the figures presented in this section were obtained with DIgSILENT PowerFactory® software and the x-axis represents the simulation time, where one second is equivalent to one minute in the real time.

Since the SD control is activated before the PQ control, it is also interesting to verify the amount of energy curtailed in order to keep the voltage within the limits, in the scenario where no storage control is available (original CVC).

For the simulations a tolerance margin of 0,05 % has been used besides the voltage limits of -2 % and +3 % of the nominal voltage. The power factory was considered to be 0,95 p.u..

Considering the yearly voltage profile presented in Figure 5.5, the highest voltage occurs on the 127th day of the year, May 7, at the node 83902 and has the value of 1,06 p.u.. For this same day, the lowest voltage occurs at the node 62905_SS1 and has the value of 0,97 p.u..

Figure 5.8 shows the voltage profile for May 7 at the overvoltage critical nodes, considering the application of the original CVC algorithm and ignoring the undervoltage at the node 62905_SS1. Figure 5.9 and 5.10 show the behavior of the DEA_DG9_W and DEA_DG13_V2_2MW respectively, as they try to control the voltage at the node 83902.

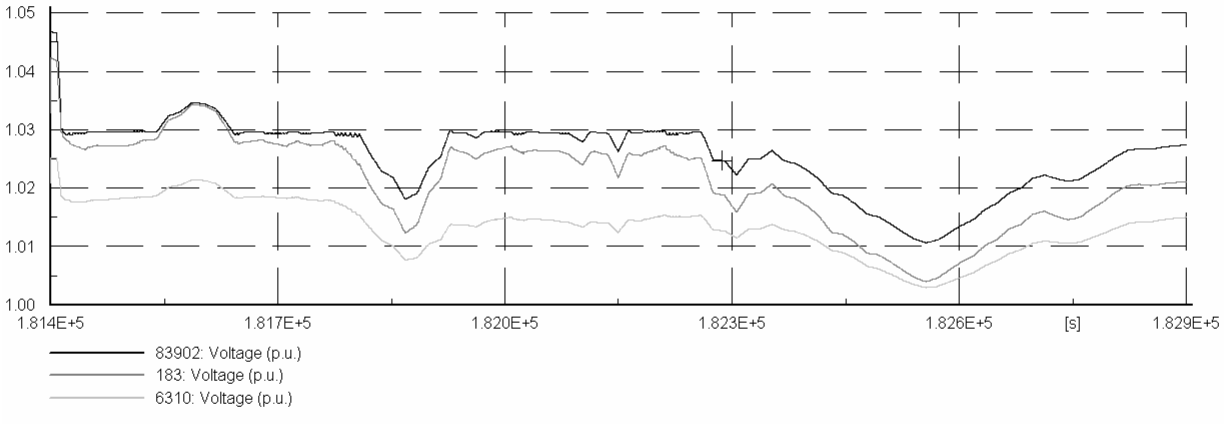


Figure 5.8 – Coordinated voltage control at overvoltage nodes

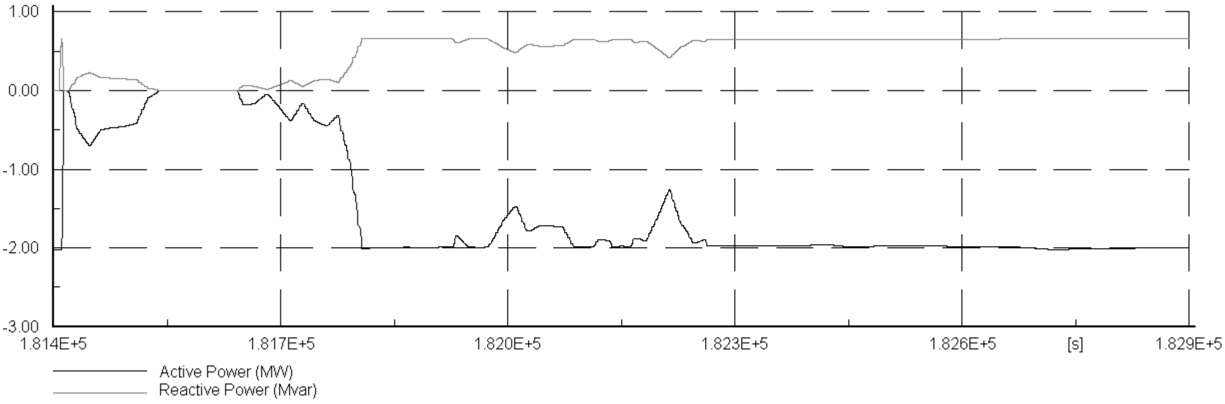


Figure 5.9 – Active and reactive power at DEA_DG9_W

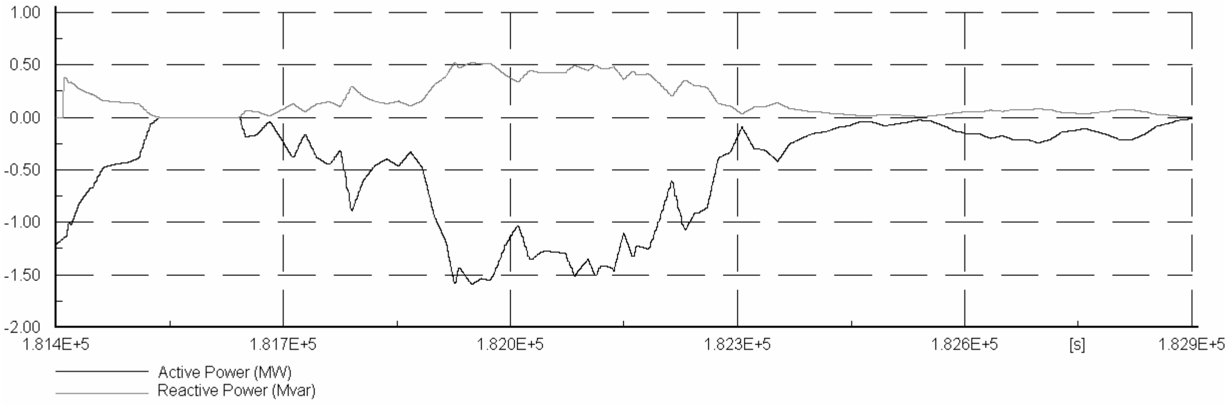


Figure 5.10 – Active and reactive power at DEA_DG13_V2_2MW

Even though only one node (83902) is being controlled, it can be seen the influence of the voltage of this node on the voltage of the other nodes.

After the transformer is at its limit (cannot tap anymore) and after the reactive powers reach their limits, the PQ contributions of DEA_DG9_W and DEA_DG13_V2_2MW to the voltage at the node 83902 are necessary, curtailing the power. They also reach their limit (Power ≈ 0) for some time during the simulation, however, that is not enough to keep the voltage within the limits during all the considered period.

The same test was carried out, but this time taking the undervoltage into account. Figures 5.11 and 5.12 show the voltage profiles for over- and undervoltage. Figures 5.13 and 5.14 show the power at DEA_DG9_W and DEA_DG13_V2_2MW and Figure 5.15 shows the transformer tap positions during the voltage control.

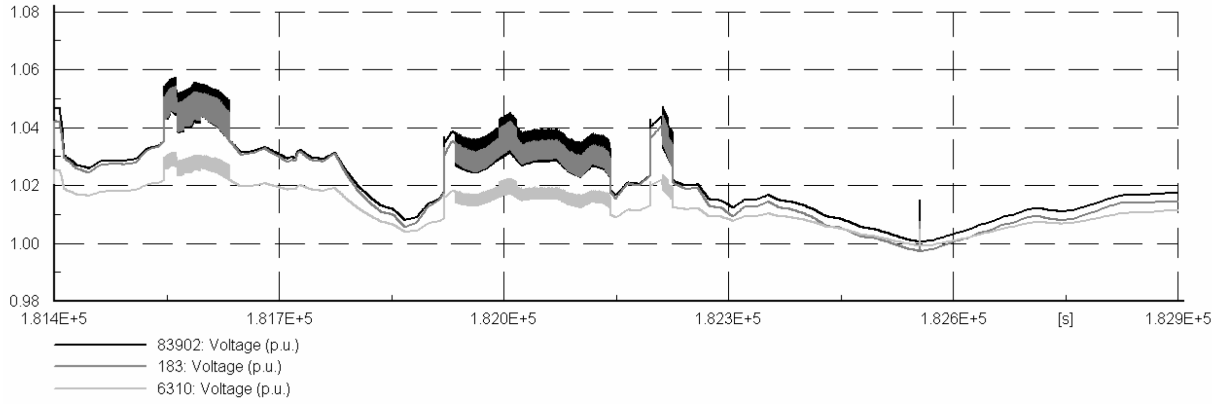


Figure 5.11 – CVC: Overvoltage

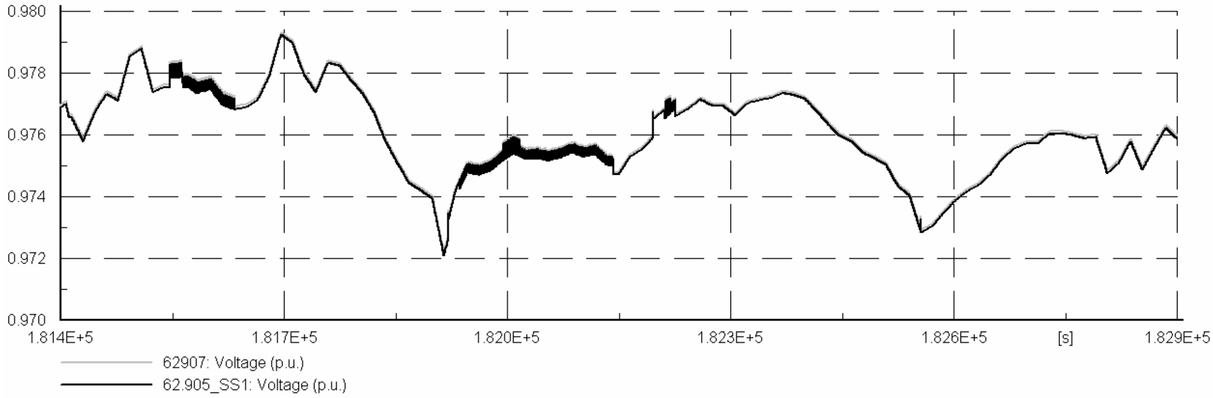


Figure 5.12 – CVC: Undervoltage

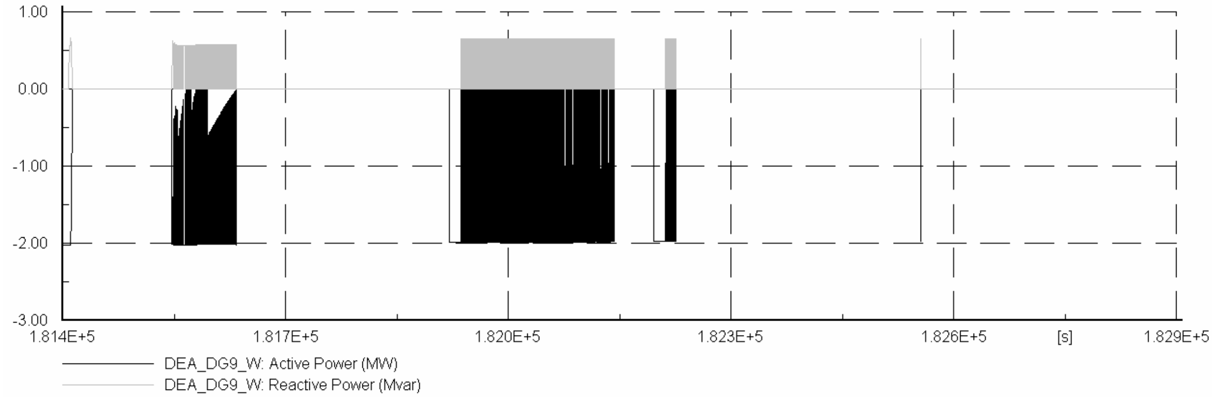


Figure 5.13 – Active and reactive power at DEA_DG9_W

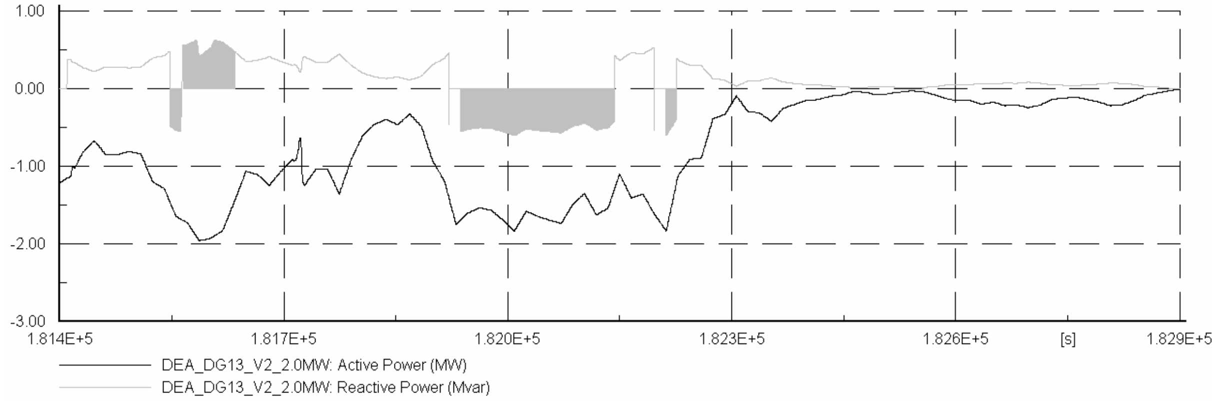


Figure 5.14 – Active and reactive power at DEA_DG13_V2_2MW

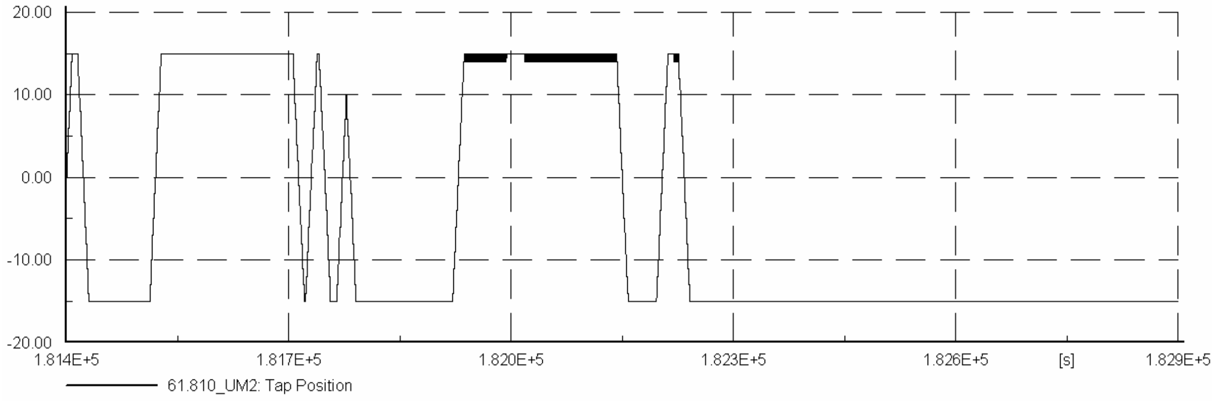


Figure 5.15 – Tap positions of the transformer 61.810_UM2

When the control “jumps” from the node 83902 to the node 62.905_SS1, and vice versa, the control is turned off and starts again at the new node. This causes instability in this control scheme, as shown on the figures above.

In this situation, the coordinated voltage control cannot control both overvoltage and undervoltage. After the transformer reaches its limit, it cannot be tapped anymore and nothing can be done to keep the voltage at the node 62905_SS1 between the limits.

The application of the SDs to the CVC was accomplished separately for each of the two storage system models presented in the chapter 4. Furthermore, many cases were considered, especially to evaluate the requirements for the storage control in the presence or not of the other voltage control methods.

5.3.1 Storage Model 1 – Standalone Storage System

The tests were accomplished to figure out what were the minimum storage parameters to keep the voltage within the limits, taking into account also the other control methods of the coordinated voltage control. The storage device definitions for both SDs on this model are represented in Figures 5.16 and 5.17, respectively.

0	**0**	**SD_Size (83902)**	**0**
StorageSetPoint	***CurrentValue***	***StorageUpperLimit***	***StorageLowerLimit***

Figure 5.16 – SD definition for SD_83902

SD_Size (62905-SS1)	**SD_Size (62905-SS1)**	**SD_Size (62905-SS1)**	**0**
StorageSetPoint	***CurrentValue***	***StorageUpperLimit***	***StorageLowerLimit***

Figure 5.17 – SD definition for SD_62905-SS1

As explained in chapter 4, the SD definition depends on its usage for either overvoltage or undervoltage control. SD_83902 is connected to an overvoltage node, thus both the initial value (*CurrentValue*) and the *StorageSetPoint* for this SD are set to zero in order to optimize its capacity to absorb energy from the network and, therefore, control the overvoltage. On the other hand, SD_62905_SS1 is connected to an undervoltage node and, therefore, is defined as having both *CurrentValue* and *StorageSetPoint* equal to *StorageUpperLimit*, in order to inject as much energy as possible into the network to raise the voltage, when necessary. The value of SD_Size was calculated using the Equation 5.1.

$$SD\_Size[MW/0.1\min] = \frac{SD\_Capacity}{Time\_Step} \times 60 \tag{5.1}$$

where SD_Capacity is the real capacity of the SD (MWh) and Time_Step is 0,1 second. The value is multiplied by 60 because one second in the simulation time corresponds to one minute in the real time, as explained before. Therefore, SD_Size is nothing more than the real capacity of the storage device (SD_Capacity), but represented in other units.

5.3.1.1 Unlimited Output Power – w/ Q Control, w/o PQ Control

Initially, a test was made considering both SD_Size and P_{max} (Table 4.27) unlimited, in order to check which would be the minimal parameters of a SD to keep the voltage within the limits during all day, without the need to use PQ control. Only the nodes with SDs connected to them were controlled. Figures 5.18 and 5.19 show the power outputs of the SDs.

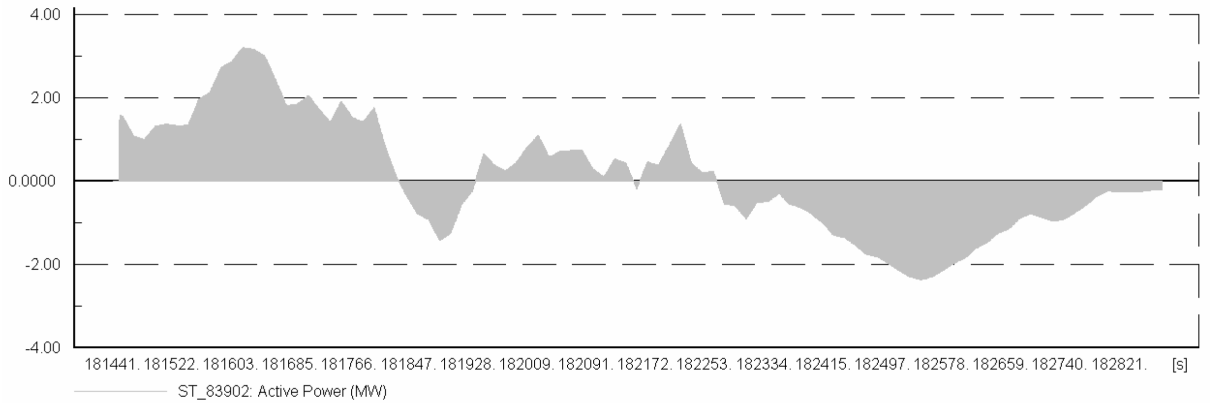


Figure 5.18 – Storage power – SD_83902

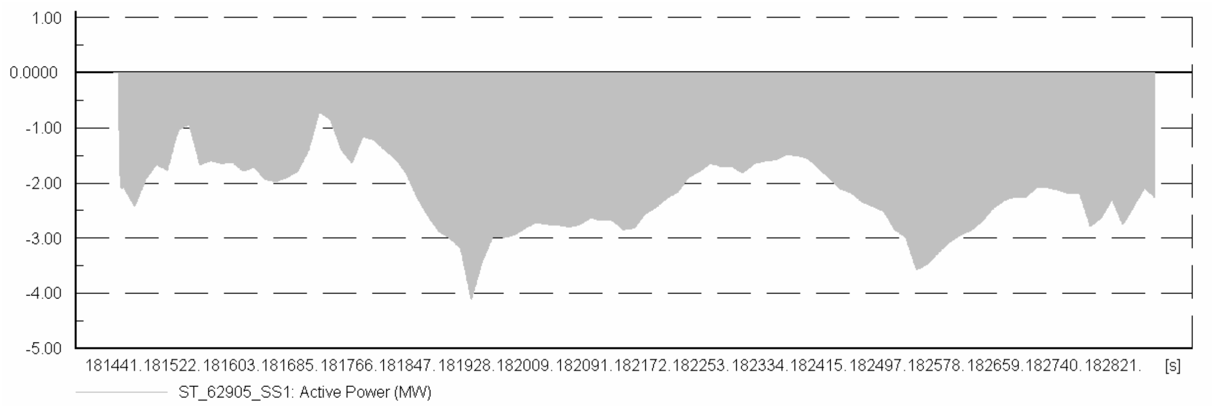


Figure 5.19 – Storage power – SD_62905_SS1

Figure 5.18 shows that SD_83902 was both charged and discharged during the considered period. P_{max} was 3,20 MW (charge) and P_{min} -2,37 MW (discharge), so the P_{max} for this SD is the absolute maximum, which means 3,20 MW. Even though the node 83902 is an overvoltage node, SD_83902 was not necessary to control the voltage in some periods, where the tap changer and the Q control were enough. In these periods, the SD was discharged, to be "as empty as possible" and be prepared to control future high voltages on that node. The SD_Size was simply calculated considering the point in time when the SD had its maximum ever stored energy amount; this value was 26,11 MWh (converted from MW/0,1min using the Equation 5.1) for this particular day.

The SD_62905_SS1 was discharged during all the time. This is due to the fact that the tap changer was tapped down to control the overvoltage, but not tapped up, to avoid control conflicts. Besides that, Q did not contribute this node; therefore, the SD was the only way to control it, discharging a great amount of energy during all the day. As the input voltages for this node are always under the undervoltage limit, the SD had no chance to charge, but only discharge. The P_{min} was -4,09MW (or 4,09 MW absolute) and the calculated SD_Size, 52,75 MWh.

Figures 5.20 and 5.21 show the voltage profiles due to the application of these SDs in the coordinated voltage control. The voltage at the node 83902 is kept within the limits during all the time, however, the node 183, which was not controlled in this example, presented overvoltage. The voltage at the node 62.905_SS1 is also kept within the limits and, even though the node 62907 was not controlled, it had also its voltage kept between the limits, due to the physical proximity between these two undervoltage nodes.

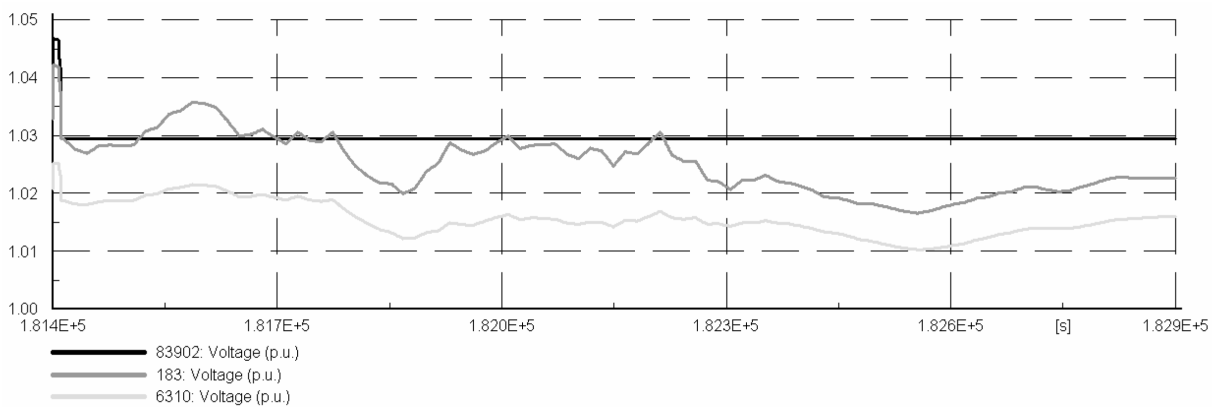


Figure 5.20 – Application of the CVC with SD (Storage Model 1) to overvoltage nodes

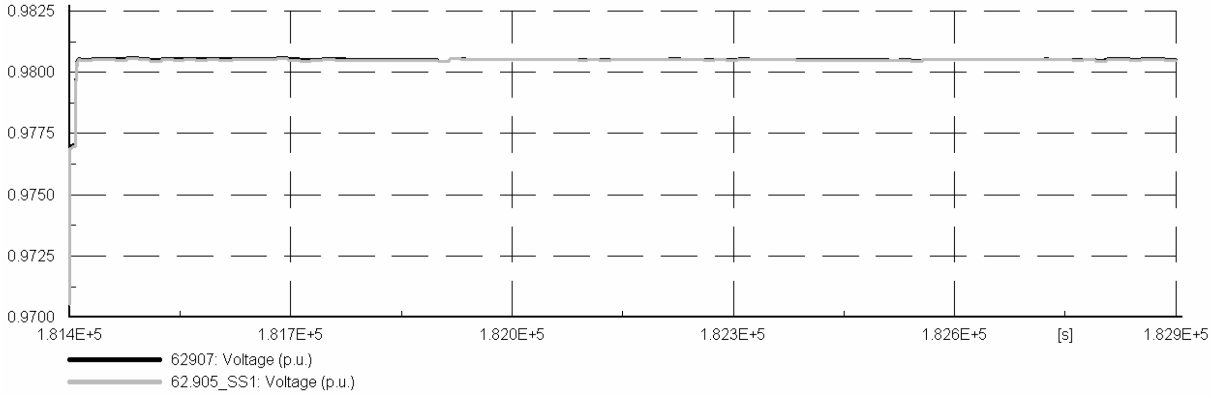


Figure 5.21 – Application of the CVC with SD (Storage Model 1) to undervoltage nodes

5.3.1.2 Unlimited Output Power – w/ Q Control, w/o PQ Control (MOC)

Another test was carried out, but this time with the possibility to control all the overvoltage nodes simultaneously ("MOC" – Multiple Overvoltage Control). SD_83902 was permitted to control also the voltage at the node 183. With this modification, the new PQ priority matrix would be as shown on table 5.5.

Table 5.5 – Priority matrix for PQ control (SD_83902 contributes also to the voltage at the node 183)

Critical Nodes					
62905-SS1	183	83902	6310		
X	X	X	**1**	DEA_DG8_W	**DG**
X	X	**4**	**4**	DEA_DG9_W	
X	**4**	**3**	**3**	DEA_DG13_V2_2MW	
X	**3**	X	**2**	DEA_DG13_V3_2MW	
X	**5**	**5**	X	SD_83902	**SD**
5	X	X	X	SD_62905_SS1	

Figures 5.22 and 5.23 show the voltage profiles for the overvoltage nodes and the SD_83902 power output, respectively.

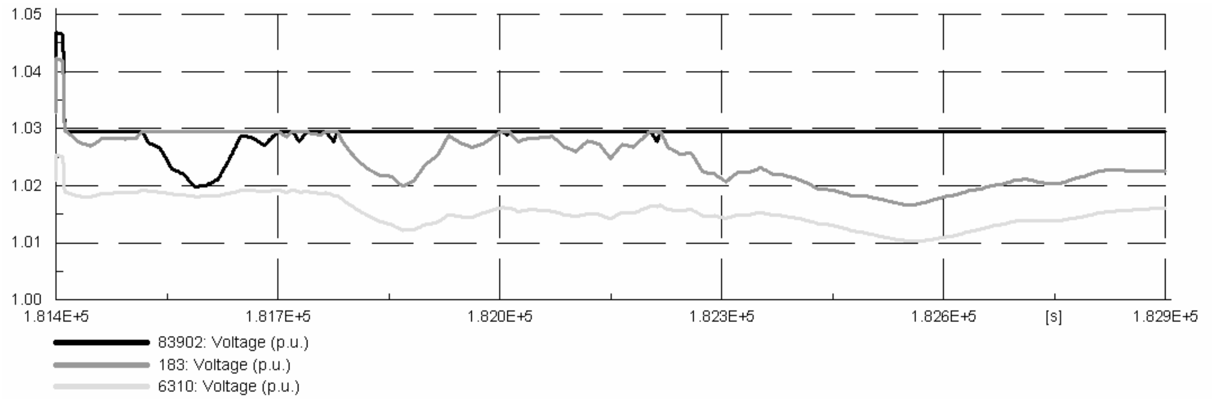


Figure 5.22 – Application of the CVC with SD (Storage Model 1) to overvoltage nodes – SD_83902 contributes to the voltages at the nodes 83902 and 183.

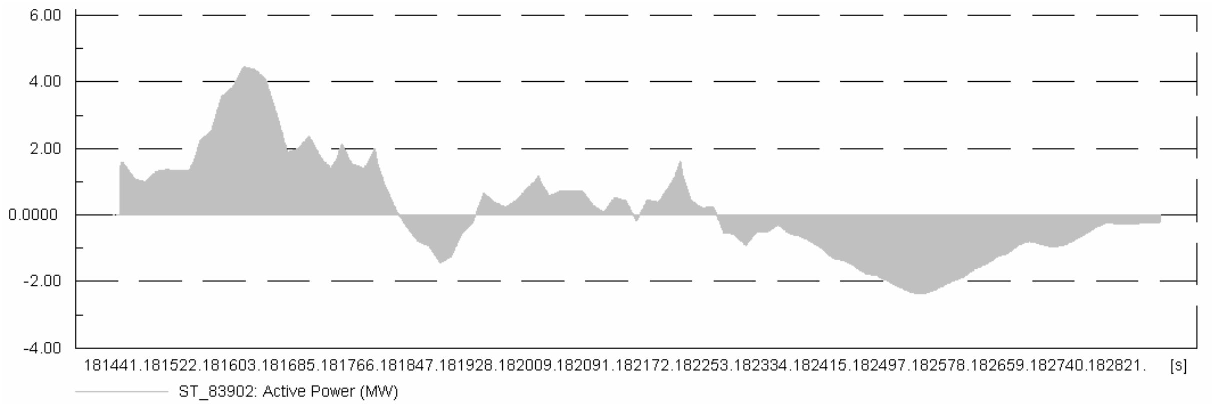


Figure 5.23 – Storage power – SD_83902 (contributes to the voltages at the nodes 83902 and 183)

In this case, the highest P_{max} was 4,45MW and the lowest was again -2,37 MW. P_{max} is the maximum absolute (4,45 MW). There are again periods when the SD is discharged. The SD_Size was calculated this time as 29,92 MWh.

At the undervoltage node 62.905_SS1, P_{max} (4,09 MW) and SD_Size (52,93 MWh) are almost the same as the values obtained for the last case. This was already expected as the contribution of SD_62.905_SS1 on the PQ priority matrix was not altered.

5.3.1.3 Limited Power Output – w/ Q and PQ Control

The next test considers that P_{max} of SD_83902 is limited and is only enough to keep the voltage within the limits if the PQ control is also considered. P_{max} for this test was found, empirically, to be 0,65 MW, for charge and discharge. Figure 5.24 shows the power output of the SD. The value of SD_Size was also calculated and is 8,45 MWh, which is smaller than the value obtained without storage limits.

On the other hand, SD_62905_SS1 had P_{max}= 4,13 MW and SD_Size = 53,73 MWh, which are practically the same values found for the previous example. This is due to the fact that this SD has no constraints, because no DG can help with its control, otherwise the voltage would not be kept between the limits. Besides that, the influence of the other nodes to the node 62905_SS1 seems to be insignificant.

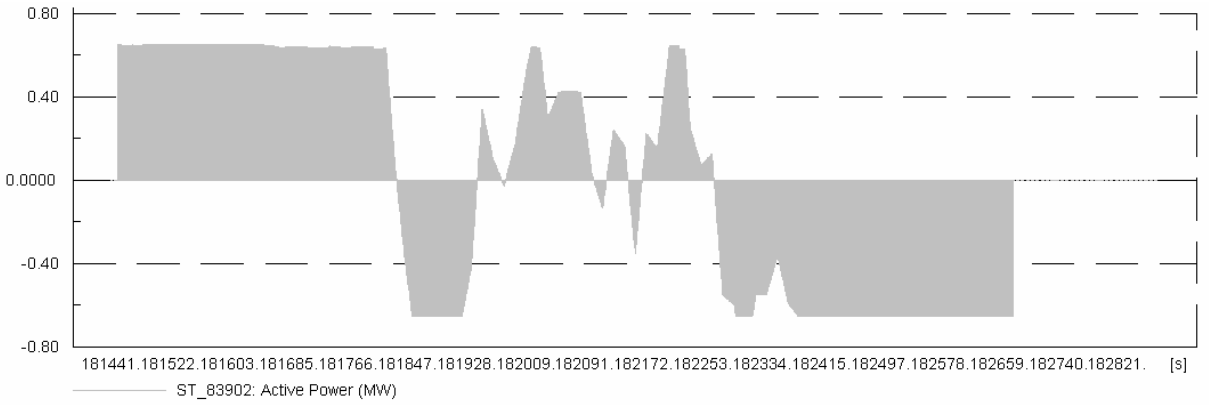


Figure 5.24 – Storage power – SD_83902 (limited power)

Figures 5.25 and 5.26 show the profile of DEA–DG9_W and DEA–DG13_V2_2MW, respectively. The periods when the power curtailment of these DGs is necessary is highlighted by the circles on the figures. On these periods of time, the storage control is not enough to keep the voltage within the limits and, therefore, the PQ control is activated. Alike, when DEA_DG9_W is not enough, DEA_DG13_V2_2MW is activated. It can be seen that, for a period of circa 30min, both DGs have their powers curtailed to keep the voltage within the limits.

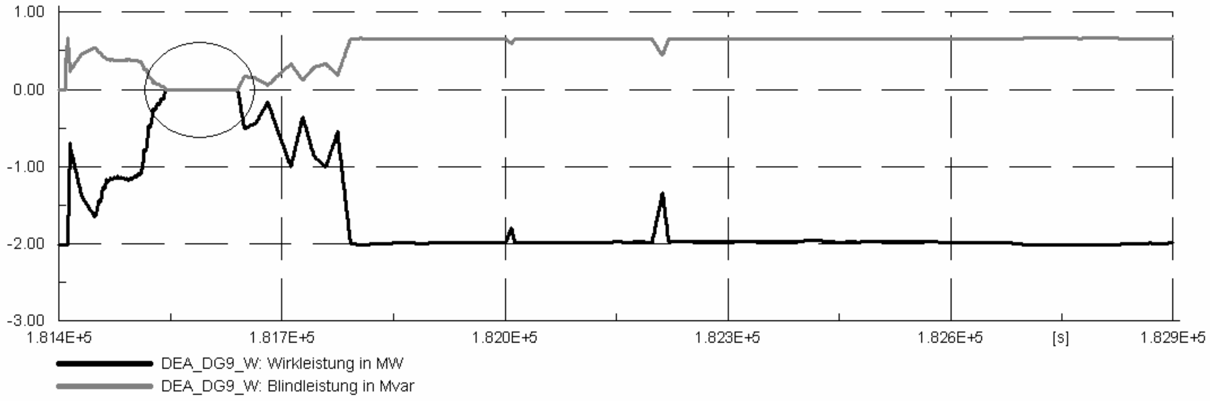


Figure 5.25 – Active and reactive power – DEA–DG9_W

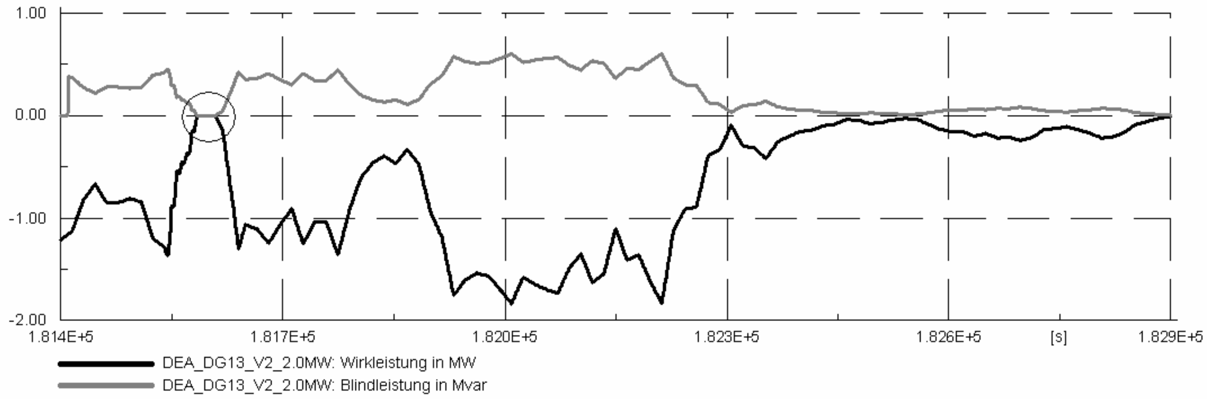


Figure 5.26 – Active and reactive power – DEA–DG13_V2_2MW

Figure 5.27 shows the voltage profile for the overvoltage nodes. While the voltage at node 83902 is kept within the limits, the node 183 presents light overvoltage for a period of time, as only the first one was controlled on this example.

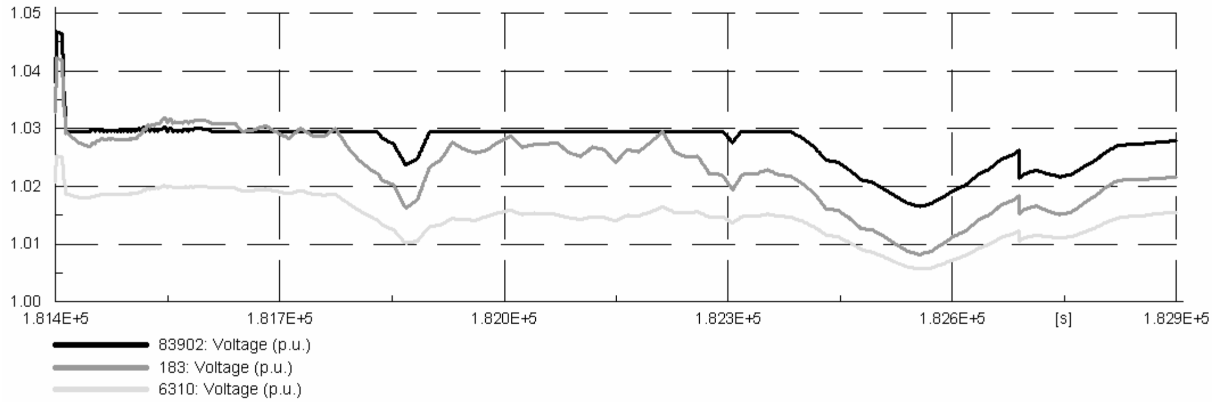


Figure 5.27 – Application of the CVC with SD (Storage Model 1) to overvoltage nodes

An interesting comparison can be made considering the necessary DGs curtailed energy to control the voltage. In this case it is necessary to subtract the PQ control output powers from the DG generation profile. For May 7th, 10,65 MWh were curtailed in order to control the voltage. The sum of all the storage positive outputs (charges) gives how much energy was not necessary to be curtailed by the DGs to control the voltage. This value was 10,61 MWh. If the SD control was not used, the DGs curtailment would be 21,26 MWh. This means that almost 50% of the energy that would be curtailed by the DGs to control the voltage was compensated by the SD control.

5.3.1.4 Limited Power Output – w/ Q and PQ Control (MOC)

On this test the SD_83902 was permitted again to control the voltage at the nodes 83902 and 183. Even though the SD_83902 profile was the same as presented on the Figure 5.23, the DEA_DG9_W and DEA_DG13_V2_2MW profiles present instability as they are turned off when the voltage is between the limits and turned on when it is again outside these limits. Their active and reactive power profiles are shown on Figures 5.28 and 5.29, respectively.

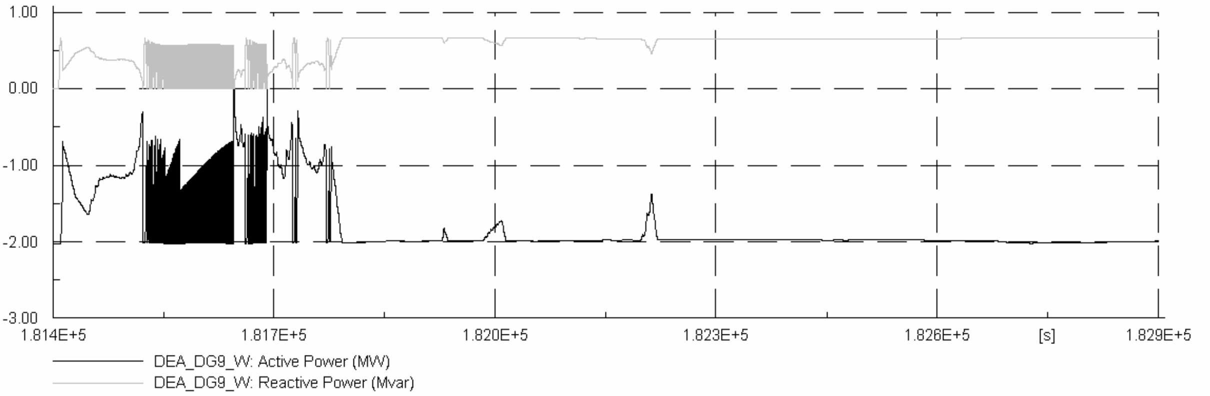


Figure 5.28 – Active and reactive power – DEA–DG9_W

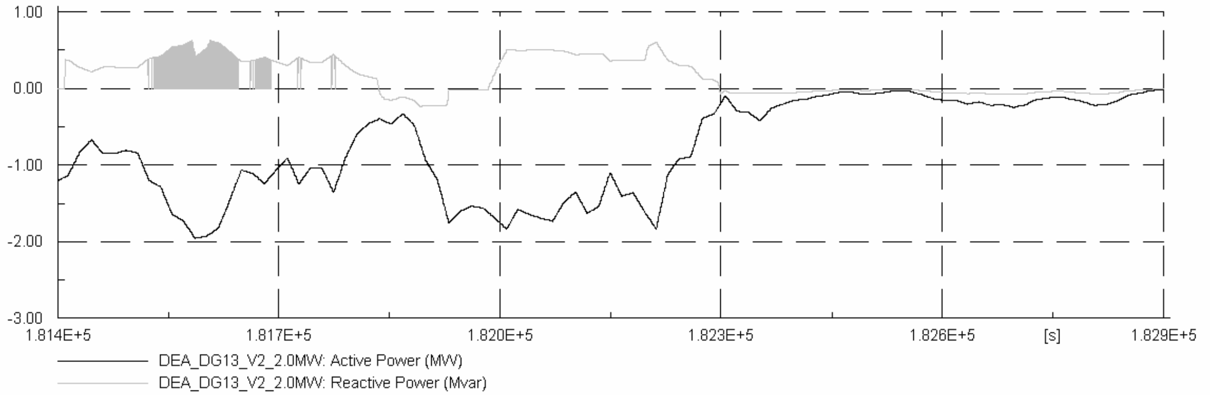


Figure 5.29 – Active and reactive power – DEA–DG13_V2_2MW

On this example, the values for P_{max} and SD_Size were 0,65 MW (empiric) and 7,09 MWh, respectively. The energy curtailed by the DGs in order to control the voltage was 8,94 MWh. Finally, 4,97 MWh was the energy not necessary to be curtailed by the DGs to control the voltage. The percentage of energy that would be curtailed by the DGs to control the voltage, but was compensated by the SD control, was again greater than 50%.

Figures 5.30 and 5.31 show the voltage profile at the overvoltage and undervoltage nodes respectively. Especially for the overvoltage nodes, the control instability causes the voltage to present incongruities.

The SD power and capacity should be greater than on the last case, due to the fact that two nodes are being controlled instead of one; however, they are smaller due to the aforementioned control instability.

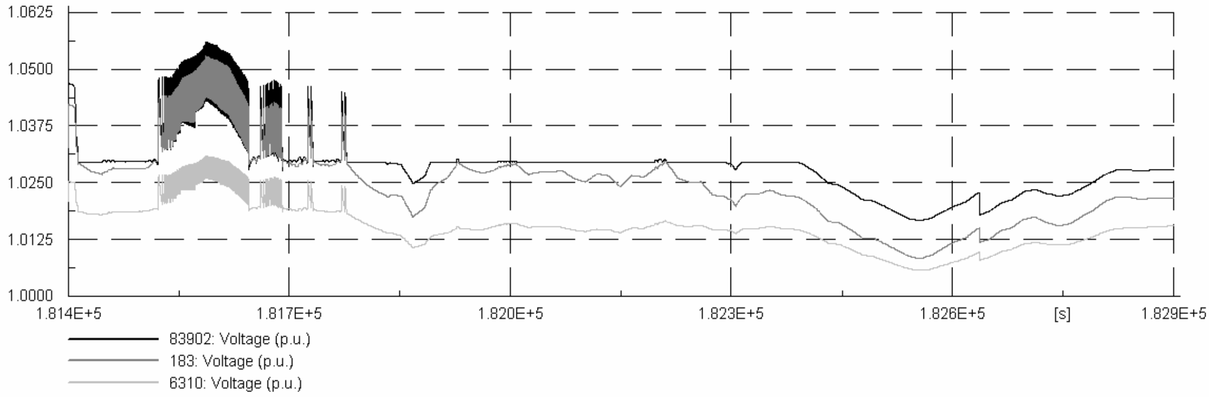


Figure 5.30 – Application of the CVC with SD to overvoltage nodes

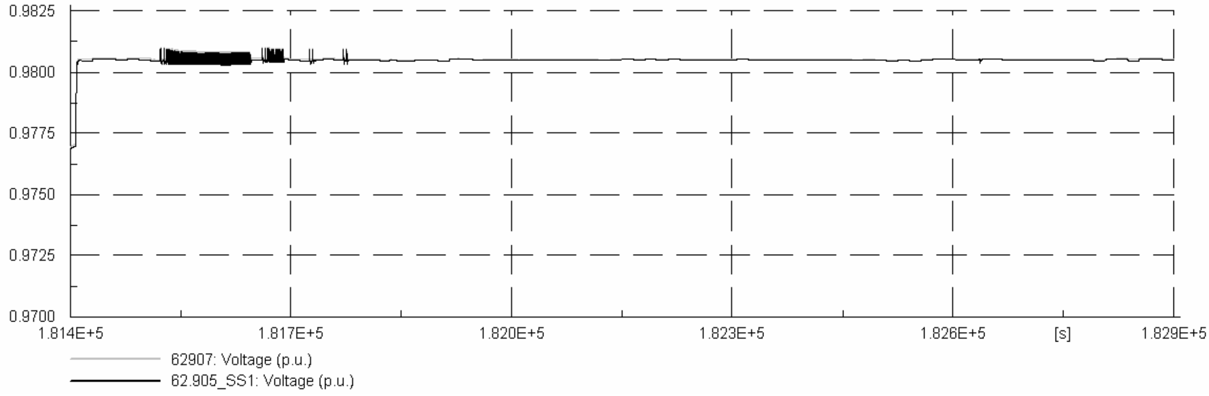


Figure 5.31 – Application of the CVC with SD to undervoltage nodes

It is important to highlight that the SDs don't contribute to these control instabilities as they are always active and are never turned off. When they are not necessary to keep the voltage within the limits, they charge or discharge in order to reach the storage setpoint and, therefore, maximize their control capacity

New methods to control multiple nodes simultaneously with PQ control are being developed and are discussed in chapter 6.

5.3.2 Storage Model 2 – Integrated Storage System

The generator DEA_DG10_W, connected to the node 83902, can be modeled according to the Storage Model 2 presented in chapter 4. In this case, the SD_83902 is disconnected and the storage is the DEA_DG10_W itself. As no generator is connected to the 62905_SS1, it can not be modeled according to the second Storage Model.

Since the Storage Model 2 considers the SD as the generator itself, Pout is equal to the generator output, which is a sum of the required generation and the storage output, but cannot be greater than the maximum production of the generator (See Figure 4.20).

5.3.2.1 Generator Limited Output – w/o Q/PQ Control

The first test considers that no Q or PQ controls are activated. The voltage at the node 83902 is controlled only by the transformer's tapping and the SD control. Figure 5.32 shows the profile at the DEA_DG10_W. It can be seen that the reactive and active power regulation are at their limit, for some hours, but it was not sufficient to keep the voltage within the limits during all the time, as seen on Figure 5.33.

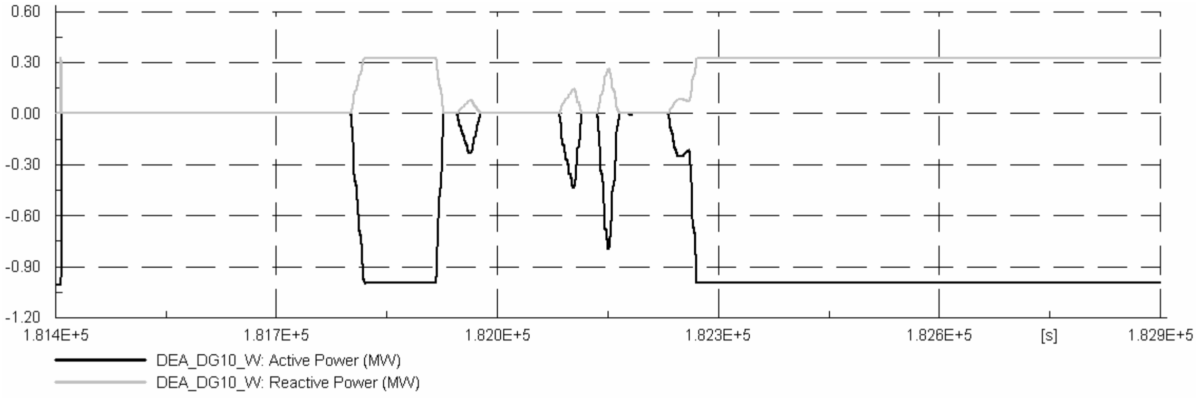


Figure 5.32 – Active and Reactive Power at DEA_DG10_W (Model 2)

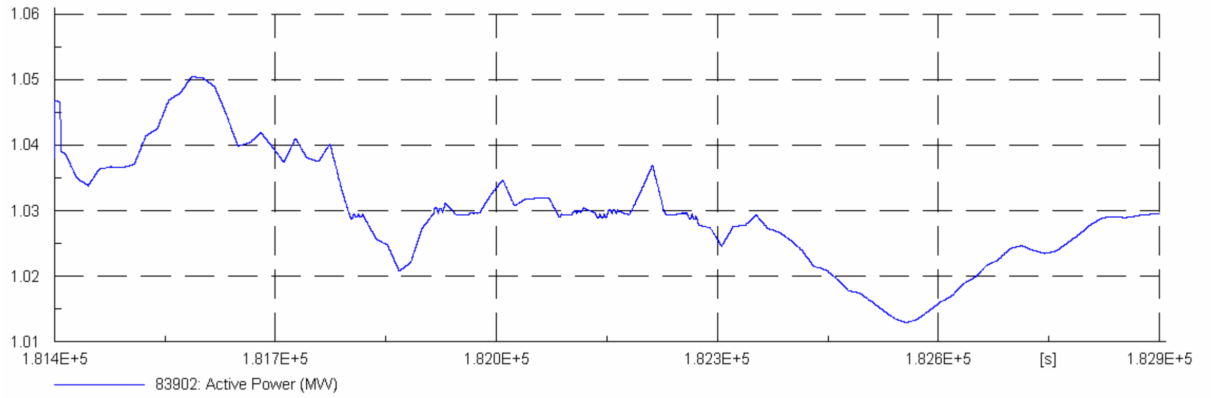


Figure 5.33 – Voltage profile at node 83902 – SD Model 2 control (No Q nor PQ control)

P_{max} was limited by the generator's nominal power (≈1 MW) and the SD_Size was calculated as 11,43 MWh. The amount of energy not curtailed, and stored, was 11,36 MWh.

5.3.2.2 Generator Limited Output – w/ Q Control and w/o PQ Control

Considering also the Q control, the voltage is kept between the limits for a longer time, as can be seen on Figure 5.34. However, there are again periods when the control is not enough to keep the voltage within the limits. Figure 5.35 shows the active and reactive power of the DEA_DG10_W, while trying to control the voltage.

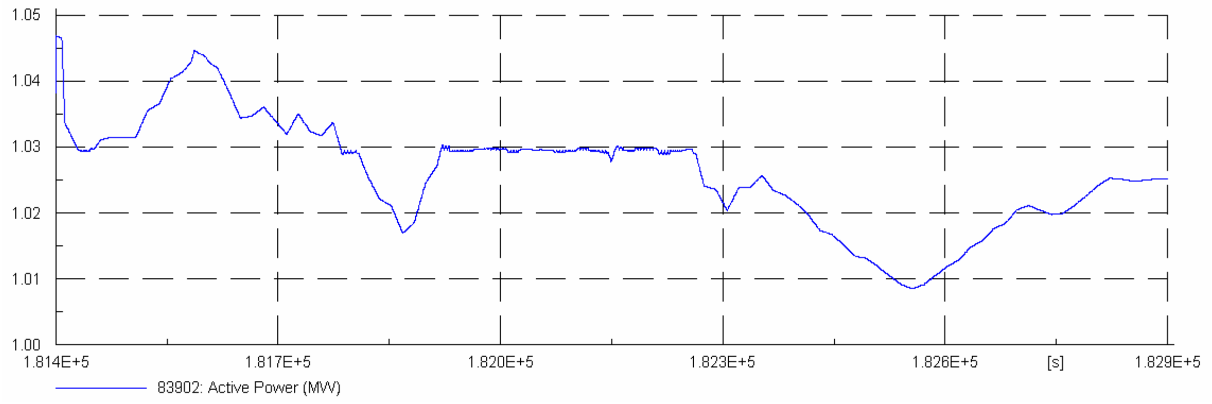


Figure 5.34 – Voltage profile at node 83902 – Storage Model 2 (Q control, but no PQ control)

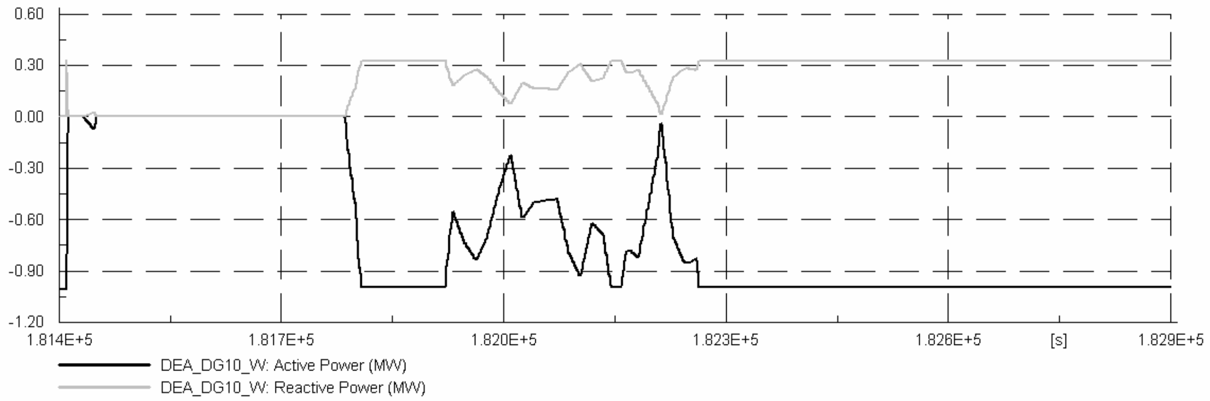


Figure 5.35 – Active and reactive power at DEA–DG10_W (Storage Model 2)

P_{max} is again ≈ 1 MW and the SD_Size was calculated as 8,09 MWh. The amount of energy not generated in order to control the voltage was 8,03 MWh. This energy was again stored and not thrown away.

5.3.2.3 Generator Limited Output – w/ Q and PQ Control

Considering also the PQ control, it was possible to keep the voltage between the limits during all the day, as presented on Figure 5.36. The Figure shows some instabilities around the overvoltage limit, which are caused by turning the controllers on and off.

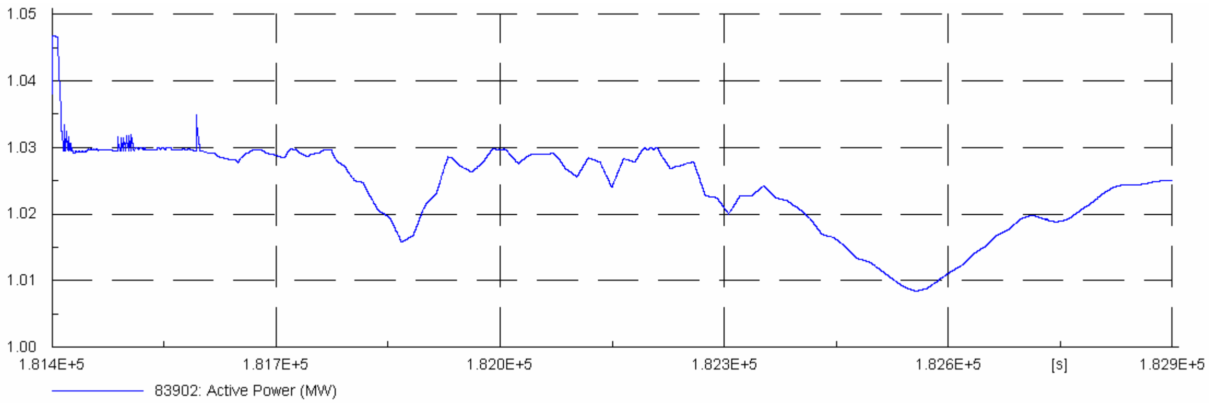


Figure 5.36 – Voltage profile at node 83902 – Storage Model 2 (with Q and PQ control)

Figure 5.37 shows the active and reactive power of the DEA_DG10_W, while controlling the voltage at the node 83902. These powers are at their limit for some period of time.

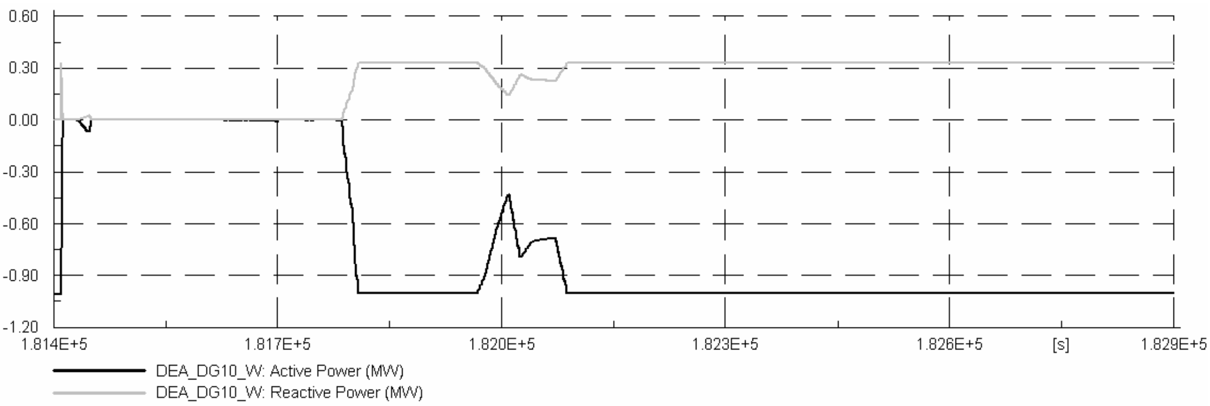


Figure 5.37 – Active and reactive power at DEA_DG10_W (Storage Model 2)

Figure 5.38 shows the active and reactive power profile at DEA_DG9_W, which is also necessary to keep the voltage between the limits. This generator is also at its limit for a short period, marked with a small circle on the figure.

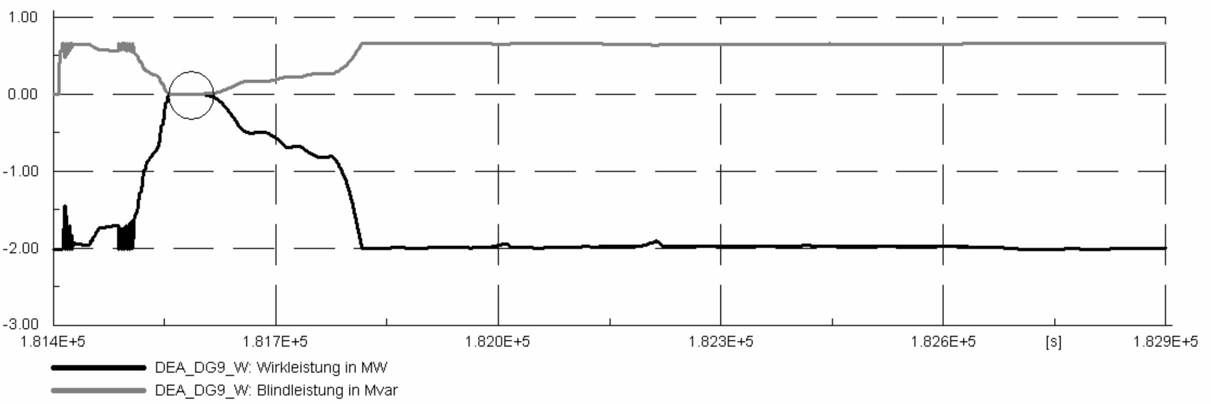


Figure 5.38 – Active and reactive power at DEA_DG9_W

DEA_DG13_V2_2MW was not necessary to control the voltage and could generate according to its normal profile.

The storage parameters were $P_{max} \approx 1$ MW and SD_Size = 4,50 MWh. The amount of energy not generated, and stored, in order to control the voltage was 4,38 MWh.

The table below groups the results obtained for both Storage Models 1 and 2 and the tested control variations. The "SD Control Contribution" and "DG Control Contribution" can be considered as the same for the Storage Model 2, as the storage system is, in fact, the generator itself, with the difference that it stores the energy, instead of curtailing it.

Table 5.6 – Storage Models 1 and 2 – Results summary

			OVERVOLTAGE				UNDERVOLTAGE	
			P_{max} (MW)	SD_Size (MWh)	SD Control Contribution (MWh)	DG Control Contribution (MWh)	P_{max} (MW)	SD_Size (MWh)
STORAGE MODEL 1	1	Unlimited Power Q Control	3,20	26,11	28,84	X	4,09	52,75
	2	Unlimited Power Q Control (MOC)	4,45	29,92	32,65	X	4,09	52,93
	3	Limited Power Q / PQ Control	0,65	8,45	10,61	10,65	4,13	53,73
	4	Limited Power Q / PQ Control (MOC)	*0,65*	*7,09*	*8,94*	*4,07*	4,04	53,00
STORAGE MODEL 2	1	No Q nor PQ	≈1	11,43	11,36		X	X
	2	Q, no PQ	≈1	8,09	8,03		X	X
	3	Q and PQ	≈1	4,50	4,38		X	X

The voltage is kept between the limits for all the four cases of the Storage Model 1. For the Storage Model 2, the voltage is kept between the limits only in the third case. The values in italic for the fourth case in the Storage Model 1 are approximated due to the control instabilities. These values should be in fact greater than those of the third case, since the multiple overvoltage control (MOC) is active.

6 Conclusions and Next Steps

In this work, the application of the storage to control the voltage in distribution networks was presented. This application was based on the coordinated voltage control in the framework of the project DG-DemoNet. The results show that this approach can be a good alternative, but is, of course, strongly dependant on the applied technology.

Some technologies, like the hydrogen storage, are not yet fully developed, but can be in the future a good option for the desired application, or even better than the technologies that were selected. It is also necessary to investigate what would be the requirements of the DNO for the integration of these technologies to the distribution networks.

Obtaining detailed technical information and costs for some of the technologies, particularly those under development, is extremely difficult. As a result, some of the costs may change as the technologies reach full development or as competition with other technologies drives prices down.

The flow batteries are of extreme interest because their capacity and output power are independent from each other. This is very important as there can be a critical node where the voltage is always too high (or too low) but not far from the voltage limit. It means this node needs constant charge/discharge action but not high output power is required. On the other hand, there can be a node where the storage voltage control action is not often required, but it needs a high power to bring the voltage between the limits.

Batteries (of one type or another) can address all application areas, although they are not always the least expensive option. The replacement costs factor is significant into the life-cycle costs of batteries, much more so than other technologies. The batteries connected to nodes that need intensive storage voltage control need to be selected by a rigorous life-cycle criterion.

The CAES technology is very cost-effective for bulk energy storage and can be applied at nodes that need high capacity storage devices.

In almost all applications, particularly for large scale systems, the installations are composed of multiple units or cells that are combined in series and/or parallel arrangements to achieve the system rating for power and stored energy. For example, battery systems almost always have cells in series to form a string with an appropriate operating voltage and multiple strings in parallel to achieve the total stored energy. Similarly, pumped hydro systems have multiple turbines, each of which operates most effectively at a specific power output level.

Regarding the results obtained in chapter 5, the normally accepted undervoltage limit is 0,94, however, there was no voltages under 0,94 during all the year, the undervoltage limit was set to 0,98. This caused the undervoltage nodes, namely 62907 and 62905_SS1 to present undervoltage during all the selected day. Therefore the SD for undervoltage control needed to discharge during twenty four hours leading to the very high storage capacity requirements obtained for undervoltage control.

Another important aspect in this work is the lack of time constants for the simulations presented in this work. Not only the reaction time of the diverse storage technologies should be taken in account, but also all the time constants related to all the distribution network elements, like generators, transformers and loads. A new graduation thesis will start on September, 2008 at arsenal research with the objective to determine the time constants for the voltage regulation concepts in medium voltage networks. This work will take into account the voltage dynamics, transformer switching, determination of time constants for generators and loads (dynamic P and Q). The obtained values will be used to improve the coordinated voltage regulation algorithm to reflect the real response of the system to the active voltage control.

One of the main difficulties in this work was to embed the storage control to the CVC, trying always not to change drastically the behavior of the already existing control. Both the original code and the new code have some issues that need to be solved in order to provide more accurate and efficient simulation results.

Some important modifications are being currently accomplished in order to develop a more readable and clean algorithm, but also with the objective to improve and broader the control concept. These changes can be highlighted as:

- Simultaneous optimization of multiple critical nodes, avoiding undesired effects like those evidenced in chapter 5, caused by the fact that the voltage control is currently performed sequentially. This multiple optimization could be performed by the application of simultaneously control loops. One of the difficulties associated to this solution is that the voltage control in one of the critical nodes can have influences on others and, therefore, the multiple voltage control loops need to be coupled;

- Improvement of the precision of the priority matrix: Unlike the currently qualitative classification of the contribution of DEAs and SDs to critical nodes (only sequential), the new classification will be quantitative; illustrating clearly how important is the contribution of these elements to the voltage at a specific node;

- Improvement of the transition between normal operation and voltage control. In the present coordinated control algorithm, the control is abruptly turned off when the voltage is within the limits, causing control instabilities around these limits. This could be implemented by the coordinated application of open and closed control loops through a states machine. With the system dynamics and the usage of a states machine it will be possible to define the states and temporally activated transitions;

- Development of a simulations environment to test and debug the algorithmic routines. This is important from the developer's point of view, since the integration between MATLAB® and DIgSILENT PowerFactory® doesn't allow any debugging. Therefore, a simulation environment is being already created; using a MATLAB® based toolbox called PSAT®. The idea is to test and validate the routines using PSAT®, and then simulate them with DIgSILENT. It is important to assure that the target network is the same and has the same parameters in both PSAT® and DIgSILENT and to assure a minimal cost for this porting between the two systems.

Still regarding the priority matrix, the selection of the generators which perform voltage control must be done on the basis of detailed analysis through offline studies. The critical nodes have to be selected on the basis of offline studies in order to ensure that compliance with the voltage limits at these nodes imply compliance in the whole network. Of course, the effectiveness of this control is limited by the network characteristic (e.g. different load flow characteristic of medium voltage branches). This solution also supposes a communication infrastructure with limited requirements between selected nodes and the OLTC controller.

Also interesting is the evaluation of the effectiveness of a specific voltage control method in scenarios with different DG penetration rates, or in other words, to what DG penetration rate a method is still valid.

The most critical point of the future integration of the validated CVC to a real network is the communication infrastructure of the network. The control needs to obtain all the necessary inputs to perform the calculations and provide its results. If, however, one of the inputs takes longer than the estimated time to be read, it can delay the control. Therefore, there is also the need to determine the time constants of the communication devices and to figure out how they can be configured and integrated. Depending on the chosen communication technology, a varying delay on these lines has to be expected

Another future investigation can be the application of Demand Side Management (DSM) in addition to the CVC and storage technologies. The following lines give a brief overview about the DSM and how it could be used in addition to the voltage control methods present in this work.

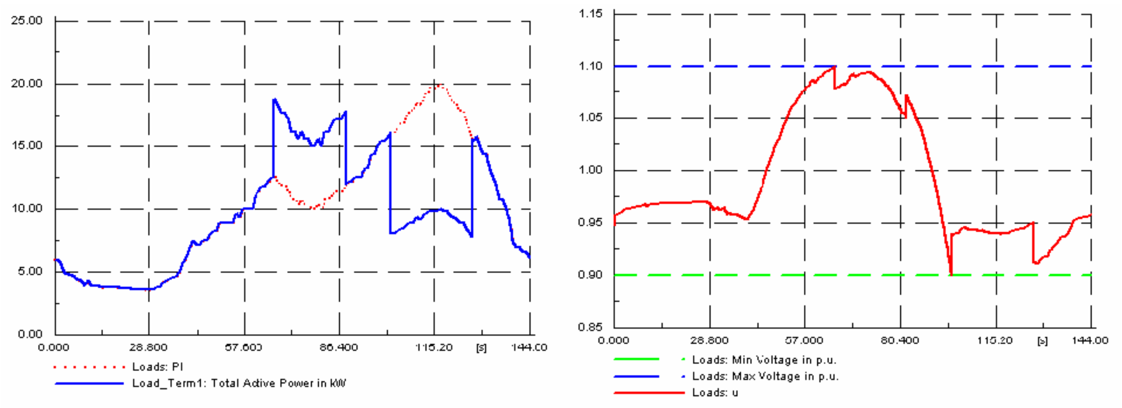
Demand side management can be understood as the planning and implementation of utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the pattern and magnitude of a utility's load. Demand-side management encompasses the entire range of management functions associated with directing demand-side activities. Opportunities for demand-side management can be found in all customer classes, including residential, commercial, industrial, and wholesale (DELGADO, 1985).

The DSM can reduce the demand peaks, shift the loads between times of day or even seasons, fill the demand valleys to better utilize existing power resources, reduce overall demand (strategic saving) in the context of delivering the required energy services by use of less energy (and not a reduction in services) and provide strategic growth especially to shift between one type of supply to another with more favorable characteristics, for example, in terms of the environment.

DSM can also have some positive effect in grids with high share of DG. As the voltage problem presents the main power quality problem in networks with DG, it was identified that DSM techniques can be used to mitigate a voltage rise effect caused by DG and can be also used as a complementary technique in conjunction with a conventional technique to minimize voltage rise effects on distributions networks. The advantages of using DSM are as follows:

- DSM may be able to mitigate voltage rise problems with minimum network reinforcement;
- It may be able to mitigate voltage rise problems on a low voltage network integrated with DG;
- DSM may be able to avoid any voltage rise problems with minimum generation constraint;
- DSM provides a more robust solution to voltage rise problems than a voltage regulator due to the system having no single point of failure and a certain level of redundancy.

Figure 6.1 shows an example of the application of DSM to the voltage control. In (a) two load switching profiles can be seen. A controlled load and a PV unit are connected to the same node. To keep the voltage between the required ±10 % limits (Figure 6.1 (b)) the load is increased by 50 % of its normal value (normal value is represented with dotted red curve in Figure 6.1 (a)). When the voltage reaches the lower voltage limit the load reduces by 50 % of its normal value. It can be seen from Figure 6.1 (b) that DSM can help to keep the voltage between the required limits.



(a) (b)

Figure 6.1 – Voltage control with DSM – load in kW (a) and voltage at the point of common coupling (b)

Another specific further approach would be the usage of storage technologies to fulfill the goals of the load management on distribution level. Load management can be understood as the utility activities designed to influence the timing and magnitude of customer use of electricity. To many people, the traditional load shape objectives of load management include peak clipping, valley filling, and load shifting.

In the case of fast changing load flow patterns or changes in the distribution of the loads or power plants among the grid, the risk of voltage instability increases. One of the solutions could be the injection of an amount of power into the grid, stored earlier during the time that there was no need for peak power, to maintain the voltage. Two possibilities using SMES and Redox Flow Batteries are presented in (SELS *et al*., Sep. 2001) and the results promise an increased overall efficiency of the power plant and on the other hand an increased stability of the electrical distribution grid. Both solutions can act very quickly on peak demands or transients in the load pattern and have stabilizing effects. This will introduce new perspectives for load managing on distribution level.

In any case, if DSM would be used together with the CVC and SDs, a priority order between local voltage control with DG units, SD control and DSM should be introduced, and, for the real application of the DSM concepts, an evaluation of the quantitative potential of DSM would be necessary, both for habitations and for the industry.

Finally, it is important to reinforce that the method developed in this work was intended to determine the most suitable technologies for the application to the voltage control and, despite this is a difficult choice, it is expected that all the improvements currently carried out will help to refine this method and adequate it to play an important role in the voltage control schemes of distribution networks with a high penetration of distributed generation.

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