



Evaluation of Conservation Voltage Regulation Techniques in Microgrids

CLENO RAVAZZI RIBEIRO PAES LEME

Final Report of Dissertation / Project Work / Internship presented to the
School of Technology and Management
Polytechnic Institute of Bragança

To obtain the Master degree in
Industrial Engineering – Electrical Engineering

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Area of Expertise in **Electrical Engineering**

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ABSTRACT

This work has the main objective to present an evaluation of the Conservation Voltage Regulation (CVR) technique applied to a small microgrid based on renewable energy sources.

Conservation Voltage Regulation (CVR) is based on the premise that reduction of the supplier voltage will lead to reduced energy consumption by final consumers without harming their appliances. CVR implementation is one of the cheapest technologies that can be used to provide better resources utilization, demand reduction and efficiency improvement, being this principle already validated when applied in public networks.

The actual trend of Distributed Generation based on Renewable Energy Sources in distribution systems also impacts on voltage control and on CVR schemes. By this way, it is important to analyze the impact of CVR in microgrids.

Experimental tests have been performed on a demonstration project of a small microgrid of the Polytechnic Institute of Bragança in order to evaluate CVR benefits.

Voltage and frequency control strategies involved in this kind of networks are conceptually similar to the ones existing in the public network, but due to intermittency of renewable sources, control dynamics is completely different, with consequences in the application and evaluation of CVR technique. The energy consumption varies with voltage and also with frequency, which do not allow the translation of CVR advantages and evaluation techniques already validated in public networks to small microgrids.

RESUMO

Este trabalho tem o objetivo principal de apresentar uma avaliação da técnica de “*Conservation Voltage Regulation*” (CVR) aplicada a uma pequena microrrede baseada em fontes de energia renováveis.

O CVR baseia-se na premissa de que a redução da tensão do fornecedor levará ao consumo de energia reduzido pelos consumidores finais sem prejudicar seus aparelhos. A implementação da CVR é uma das tecnologias mais baratas que podem ser utilizadas para proporcionar uma melhor utilização dos recursos, redução da demanda e melhoria da eficiência, sendo este princípio já validado quando aplicado em redes públicas.

A tendência atual da Geração Distribuída baseada em Fontes de Energia Renovável em sistemas de distribuição também afeta o controle de tensão e os esquemas CVR. Desta forma, é importante analisar o impacto da CVR em microrrede.

Testes experimentais foram realizados em um projeto de demonstração de uma pequena microrrede do Instituto Politécnico de Bragança para avaliar benefícios CVR.

As estratégias de controle de tensão e frequência envolvidas neste tipo de redes são conceitualmente semelhantes às existentes na rede pública, mas devido à intermitência de fontes renováveis, a dinâmica de controle é completamente diferente, com consequências na aplicação e avaliação da técnica CVR. O consumo de energia varia com a tensão e também com a frequência, o que não permite a tradução de vantagens de CVR e técnicas de avaliação já validadas em redes públicas para microrrede pequenas.

CONTENTS

TABLES LIST	III
ILLUSTRATIONS LIST	V
ABBREVIATION AND SYMBOLS LIST.....	VII
1 INTRODUCTION	1
1.1 MOTIVATION AND OBJECTIVE.....	1
1.2 DISSERTATION STRUCTURE.....	2
2. STATE OF THE ART	3
2.1 CONSERVATION VOLTAGE REGULATION.....	3
2.2 TYPES OF LOADS AND CVR.....	5
2.3 LEGISLATION	9
2.4 CVR TECHNIQUE IN POWER GRIDS	10
2.4.1 Load Tap Changer	11
2.4.2 Voltage Var Control.....	13
2.4.3 Voltage Spread Reduction	14
2.4.4 Voltage and Volt-Ampere Reactive Optimization.....	15
2.4.5 Online Tap Changer.....	17
2.5 RESUME	17
3 MICROGRIDS	19
3.1 CONTEXTUALIZING MICROGRIDS.....	19
3.2 DISTRIBUTED GENERATION AND CVR.....	21
3.3 SMART GRID.....	23
3.4 EXAMPLES OF MICROGRIDS	26
3.4.1 Polytechnic Institute of Bragança Microgrid.....	28
3.5 RESUME	29
4 TECHNICAL VIABILITY OF THE CVR APPLIED TO MICROGRIDS	31
4.1 EXPERIMENTAL	31
4.2 EXPERIMENTAL ANALYSIS	35

5 CONCLUSION AND FUTURE WORK 41
5.1 CONCLUSION..... 41
5.2 FUTURE WORKS 42

TABLES LIST

TABLE 1 - Comparison of energy supply strategies	4
TABLE 2 - Results of CVR tests in terms of CVR factor (economized energy relationship in function of the reduced voltage percentage)	6
TABLE 3 - Tension reduction applications (reducing 122V to 118V)	7
TABLE 4 – Example of tests made on California.....	8
TABLE 5 – Voltage Reduction Techniques.....	11
TABLE 6 – Comparative of Traditional Grids with Smart Grid.....	25
TABLE 7 – Load Characteristics	32
TABLE 8 – Test Designation.....	34
TABLE 9 – CVR factors	40

ILLUSTRATIONS LIST

Fig. 1 - Left image reduction in peak consumption times, the Right image shows the reduction of consumption in a 24-hour period	5
Fig. 2 - Hypothetical Feeder Voltage Profile with an LTC.....	12
Fig. 3 - LTC operating without LDC	13
Fig. 4 - LTC operating with LDC	13
Fig. 5 - Reactive Power Consumption with Capacitor Bank	14
Fig. 6 - Feeder Voltage Profile with LDC, Voltage Regulator and Capacitor Bank	15
Fig. 7 - Avista's VVO configuration	16
Fig. 8 - NOVEC VVO configuration	16
Fig. 9 - Microgrid Integration Diagram	21
Fig.10 - General structure for distributed power system	22
Fig. 11 - Traditional Radial Power Grid	24
Fig. 12 - Future Smart Grid System	26
Fig. 13: Representation CEDER microgrid	28
Fig. 14 - Microgrid DC/AC proposed	29
Fig. 15 - Representation of IPB microgrid	30
Fig 16 - Power Energy Data Logger	32
Fig 17 - Communication options in the stand-alone power grid	33
Fig. 18 - Configure microgrid	34
Fig. 19a - Case A Produced Power vs. Irradiation	35
Fig. 19b - Case G Produced Power vs Irradiation	35
Fig. 20a - Case G: Produced Power vs Frequency	36
Fig. 20b - Case A Produced Power vs Frequency	36
Fig. 21 - Control algorithm in the SMA stand	37
Fig. 22a - Consumed Power, parallel A vs E	38
Fig. 22b - Consumed Power, parallel C vs E	38
Fig. 22c - Consumed Power, parallel D vs G	38
Fig. 23a - Case B: Consumed Power vs Frequency	39
Fig. 23b - Case A: Consumed Power vs Frequency	39
Fig. 23c - Case G: Consumed Power vs Frequency	39

ABBREVIATION AND SYMBOLS LIST

AC	Alternating Current
ANAEEL	National Electric Energy Agency
BPA	Bonneville Power Administration
CEDER	Center for Development of Renewable Energy
CFL	Compact fluorescent lamp
CIEMAT	Center for Energy Environmental and Technological Research
CRT	Cathode ray tube
CVR	Control Voltage Reduction
DC	Direct Current
DD	Day
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management System
DR	Demand Response
EPRI	Electric Power Research Institute
EU	European Union
f	Frequency
f_0	Initial frequency
f_{CVR}	Conservation Voltage Regulation Factor
I_C	Capacitor current
IEEE	Institute of Electrical and Electronics Engineers
IPB	Bragança Politechnic Institute
IRR	Solar Irradiation
I_S	Source current
ITC	Information and communication technologies
I_{VR}	Current on voltage regulator
IVVC	Integrated Voltage and var Control
LCD	Liquid crystal display
LDC	Line Drop Compensation
LDC	Line Drop Compensation
LED	Light-emitting diode
LTC	Load Tap Changer
MDF	Medium density fiberboard

MM	Month
NOVEC	Northern Virginia Electric Cooperative
NYPA	New York Power Authority
OLTC	Online Tap Changes
OMEC	Oneida Madison Electric Cooperative
P	Active Power
PEL	Power Energy Data Logger
PMSG	Permanent Synchronous Generator
PRODIST	Procedures for Distribution of Electric Energy un the National Electric System
PV	Photovoltaic
Q	Reactive Power
R – C – I%	Residential, Commercial, Industrial
R_{line}	Line resistance
R_{load}	Load resistance
RV	Reference Voltage
SCADA	Supervisory Control Data and Acquisition
TV	Television
U_0	Initial Voltage
U_{AC}	Alternating Voltage
U.S.	United States
UK	United Kingdom
V_{AC}	Alternating voltage source
V_p	Primary Voltage
V_s	Secondary Voltage
V_{set}	Reference voltage level
VSR	Voltage Spread Reduction
VVC	Voltage and Reactive Control
VVO	Voltage Variation Optimization
X_{Cap}	Capacitor bank reactance
X_{line}	Line inductance
X_{load}	Load inductance
YY	Year
Z_{REF}	Line impedance

1 INTRODUCTION

This Chapter is dedicated to the presentation of the theme, as well as the motivation of the work documented in this dissertation. It includes a brief resume of the current scenario of energy and their problems, focusing on methods of energy efficiency, particularly techniques used reduce the voltage to save energy on electric networks.

1.1 MOTIVATION AND OBJECTIVE

Control Voltage Regulation or Reduction (CVR) it's a method of energy efficiency applied to utility networks, which consists in reducing the voltage at the levels allowed by the legislation, thus promoting a reduction of the power consumed.

Historically the first complete electric power system (comprising a generator, cable, fuse, meter and loads) was built by Thomas Edison (New York City 1882). It was a DC system to supply 59 costumers [1] and from this idea the entire electrical system was developed to supply the demand of the population.

Moreover the World primary energy demand is projected to increase by 1,2% per year, on average, from now until 2035. Electricity demand is projected to grow by a higher rate, 2,2% per year [2].

Electric energy is essential for the generation of industrial, commercial and societal wealth, energy and it also provides personal comfort and mobility. But its production and consumption place considerable pressures on the environment: greenhouse gas and air pollutant emissions, land use, waste generation and oil spills. These pressures contribute to research of new clean technologies.

The supply of electricity to isolated communities in developing countries, in general, is still done in a precarious way. This situation occurs mostly due to the high cost associated with the expansion of the conventional power grid to these communities [3]

When the electrical system has not been able to serve the entire population, some places can have micro systems comprising energy generation, using alternative sources of energy such as solar, wind or hydro, energy storage systems and loads.

One common trend is the addition of photovoltaic and wind turbines on the distribution system, called by distributed generation which leads to microgrids systems.

Researches and development study have been developed regarding distribution efficiency methods in order to reduce system losses, energy requirements, and peak demand. A technique that has

been studied and aims to increase energy efficiency and reduce peak demand is Control Voltage Reduction (CVR), the subject of this work.

Many companies in the energy industry as Northern Virginia Electric Cooperative (Virginia), BC Hydro (Vancouver), Oneida Madison Electric are examples of companies which have researched and tested the implementation of this method in their networks to evaluate the results.

Observing a growth in the use of renewable energies and the implantation of microgrids, some questions arose:

- Can the CVR be implemented in a microgrid?
- How can this happen?
- What is the effect of this?
- Is it possible to achieve energy savings using CVR inside the microgrid?

Therefore this work tries a different approach which will apply the same method on a microgrid isolated from utility networks. The objective are:

- Check the relationship between voltage reduction and energy savings;
- To analyze the CVR technique applied to various equipment such as lights, televisions, computers;
- To analyze the effects of CVR technique applied to a microgrid.

1.2 DISSERTATION STRUCTURE

The work consists of a brief analysis of the current energy scenario, pointing out the need for energy, the need for expansion of the electric system, energy efficiency and voltage reduction techniques, herewith the objectives of this work.

Chapter 2 presents the Conservation Voltage Regulation method, show a panorama of its use, citing its aspects and characteristics, the legislation involved, also shows the evaluation of this method as a function of different types of loads, presents some variations of the implementation of the method and presents examples of applications.

Third chapter aims at presenting an outlook of microgrids, contextualize the smart grids concept and the distributed generation, by presenting some examples of existing microgrids, and the IPB microgrid, which will be the experimental set up under analysis in the following chapter.

In chapter 4 the technical viability of the CVR applied to the microgrid (IPB microgrid) is explored, the experimental methodology, and a discussion of the results of the experimental tests are presented.

Finally, Chapter 5 is dedicated to the conclusions reached with the work and perspectives for future work that can be done.

2. STATE OF THE ART

The growing global concern about the environmental problems caused by fossil fuel based energy resources in recent decades has given rise to the development of renewable energy sources as wind, solar and geothermal [4].

Losses in powertrain systems and energy efficiency in distribution systems is at the top of the list of issues that power utilities face today. This has forced many utilities to explore new energy-saving avenues, such as energy efficiency programs, demand response, demand-side management, smart metering, and conservation voltage reduction (CVR) [5].

In this chapter, the Conservation Voltage Reduction (CVR) definition, the influence of the CVR application and the behavior of the loads, the relevant legislation, the CVR techniques applied to the electric networks, will be discussed. Additionally, several studies on CVR implementation are presented.

2.1 CONSERVATION VOLTAGE REGULATION

CVR is defined by [6] as a method of energy conservation based on the premise that reducing the voltage at the load terminals decreases the consumption of active and reactive power.

According to [7], [8], Conservation Voltage Regulation (CVR) it is a reduction in the energy consumption resulting from the reduction of the supply voltage, which translates in reducing the consumed power in the distribution system. The reduction of the supply voltage is performed within the allowed values in order to obtain a reduction of the final consumption of energy.

CVR was born in the United States, the first wide-scale implementation of CVR was in 1973, during the oil embargo, when the Public Service Commission of New York ordered their utilities to implement 3%–5% reduction in voltage in order to reduce energy consumption [6], [9]. However, the order was lifted and the effects of CVR were not properly documented.

A project developed in California in 1976 reported savings of 2,686 GWh (1,7%) on their system for one year [9], based also on a 1% voltage reduction.

In the 90's three independent studies [10] [11] shown that, typically, it was possible to lower the feeder voltage 1 percent without affecting loads. The studies also found that a voltage reduction of 1 percent led to energy savings between 0,5 and 1 percent. This technique was called by Conservation Voltage Reduction or Conservation Voltage Regulation (CVR).

In 2007, Plum Creek Timber Company (Plum Creek), Flathead Electric Cooperative (Flathead Electric), and the Bonneville Power Administration (BPA) teamed up with PCS UtiliData (PCS) to

evaluate Plum Creek's Medium Density Fiberboard (MDF) facility in order to optimize its distribution voltage, resulting in a voltage reduction between 1,9% and 4,8%. This reduction provides over 6.000.000 kWh per year of energy savings [12].

Many utilities and public service commissions have tested to implement CVR on their systems as can be seen , for example, in [13], [14] and [7].

The Conservation Voltage Reduction Factor (f_{CVR}) is the term which allows an evaluation of the effects of the technique, it expresses the reduction of the energy consumption by reduction of the voltage, which is defined as the percentage of consumption reduction per 1% of voltage reduction [15]. This quantitative indicator presents typical values between 0.4 and 1.0, values greater than 1.0 in the case of purely resistive loads and depending on how long they are in operation [16]. Being calculated by the following formula:

$$f_{CVR} = \frac{\Delta P\%}{\Delta V\%} \quad (1)$$

Where $\Delta P\%$ means the difference of the consumed power on nominal voltage in relation to the consumed at reduced voltage, and $\Delta V\%$ is the voltage difference applied in the CVR (values in percentage)

The implementation of the CVR technique can cause a deterioration of the voltage profiles along the network, which is why the voltage drop in the circuits will need to be compensated by corrective methods such as capacitor banks to compensate for the voltage drop along the line, or autotransformers in case of very long lines [17]. A capacitor bank can be controlled through many schemes, e.g. time control, voltage and vars control, etc [18].

In [17] it is possible to find a comparison of the strategies of energy distribution between the methods named by the author as Basic strategy, intelligent and intelligent with CVR (Table 1).

TABLE 1 - Comparison of energy supply strategies.

	Basic Strategy	Smart Strategy	Smart Strategy with CVR
Total Consumption (kWh)	20.747,46	20.747,46	18.631,70
Total power supplied by the grid (kWh)	10.570,99	10.987,96	9.454,91
Total power provided to the grid (kWh)	0,57	913,20	1.718,15
Network power balance (kWh)	10.570,41	10.074,56	7.736,76
Total cost (€)	1.560,53	1.298,37	941,06

Source: [17]

The Basic Strategy for the operation of microgrid had the follows principles, not being equipped with intelligent mechanisms and processes of management and optimization. In this case, the

main difference is that there is no possibility of purchase and / or sell electricity to the distribution grid, since the connection to the same network is prevented [17].

In the intelligent operation strategy of microgrid, used mechanisms for optimization and control in the power supply, in particular through the anticipated loading of the storage the request of consumer (and taking into account the average values of their needs and production), and also controlling the succession of requests for supply, i.e. based on the time of day, to manage energy demand consumers in the most economically advantageous way [17]. The smart strategy with CVR has the same characteristics of the smart strategy plus the use of the CVR.

Analyzing Table1 it can be observed that the smart strategy with the use of the CVR a reduction of the costs and the saving of energy is obtained its better than others applied methods.

A consumption profile in energy distribution systems without the use of the CVR and with CVR as proposed in [17], highlights one of the benefits of using the CVR, which in periods when the peak consumption can occur, the CVR allows reducing the need to increase the generation to meet the demand (Fig.1).

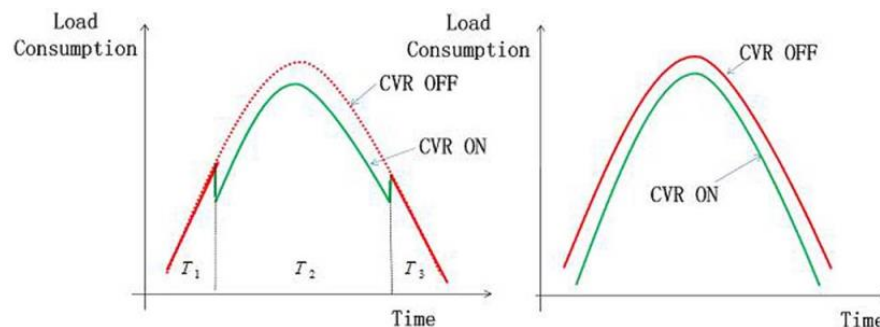


Fig. 1 - Left image reduction in peak consumption times, the Right image shows the reduction of consumption in a 24-hour period.
Source: [19]

2.2 TYPES OF LOADS AND CVR

The loads can be subdivided into 4 groups with different characteristics [18].

The first group is composed by loads with constant impedance without feedback loop, based on purely resistive equipment such as electric showers, incandescent lamps, freezers, electric ovens, etc.

The second group is designated as loads with constant impedance and feedback loop, which can also be termed as constant energy loads; in this group can be found equipment that have a temperature control and have feedback.

The third group is those of constant power loads such as computers, television sets, etc. For these devices when the reduction on the supply voltage is applied there is an increase in current.

In the fourth group, called constant current loads occurs the reduction of the energy consumed for the loads; in this group there are the compact fluorescent lamps, e.g..

Prabha Kundur in his book “Power System Stability and Control”, separates loads into three groups: Constant Impedance , Constant current and Constant Power [1].

Regarding reactive loads, they usually have a high inductance absorbing active and reactive energy, including loads such as motors, electric pumps and compressors. In these loads, when reducing the voltage below its specifications, it does not always lead to the reduction of active power. This effect is more pronounced in industrial consumers with large induction motors particularly for those that have speed adjustment [20].

The importance of knowing the load model for the CVR analysis is based in the fact that the efficiency of energy saving using the CVR method is different for different kind of loads [21].

Table 2 shows the experimental results obtained with the use of CVR in the various sectors, based on [12].

TABLE 2 - Results of CVR tests in terms of CVR factor (economized energy relationship in function of the reduced voltage percentage)

Year	Residential	Commercial	Industrial	Overall
1973	0,61%	0,89%	0,35%	0,62%
1977	0,76%	0,99%	0,41%	
1979	0,73%	0,84%	0,49%	0,71%
1989				0,62%

Source: adapted [21]

Doing the analysis of specific loads according to [22] could be observed in Table 3, a study conducted by the Electric Power Research Institute (EPRI) in Palo Alto, California, examples of some applications of the use of the CVR and their economy shown in terms of power and percentage for various equipment that can be found in residential sector.

TABLE 3 - Voltage reduction applications (reducing 122V to 118V)

Appliance	Conserved Power (Watts)	Conserved Power (%)
INDUCTION MOTOR		
Fan	4,2	6%
MONITORS		
CRT TV	2,1	4%
LCD TV	0	0%
PLASMA TV	-2	0%
DESKTOP LCD	-0,6	-2%
LIGHTING		
13- W compact fluorescent lamp (CFL)	0,9	8%
20 W - CFL	1	6%
LeD (low quality)	0,2	6%
75 – W incandescent	3,4	5%
42 – W CFL	0,8	2%
LED (high quality)	0,1	1%
LED (médium quality)	-0,1	-1%

Source:[22]

The reduction of the consumption of electric energy through the regulation of the voltage is performed in [23] and it points out that the reduction is dependent on the type of load, the percentage they represent in the load diagram, the time of use of the apparatus, such as the type of equipment being used and the time at which the equipment is used.

In the case of induction motors it is generally detrimental to the voltage decrease since it causes the increase of the absorbed current, but this only happens in case the power of the load is constant, increasing the losses in the form of heat [16]. In order to reduce the voltage in these cases, it is essential to ensure that the equipment does not suffer any malfunction.

These devices operate within a range of voltage values, being in this range their safe and efficient operation. Within these specifications there may be considerable variations and must therefore be studied in order to verify the conservation of energy using voltage reduction [23].

If the load has a thermal cycle, there will be more complex to model the load, as it needs an additional control loop to determine when the load is energized, and for how long [7]. The loads that have thermal cycles are heaters, fans, air conditioning systems, e.g..

In California, in the 1970s and 1980s, tests were performed on substations in order to study the effect of reducing the distribution voltage on power consumption [24]. In these tests, the types of

loads are separated into Residential, Commercial and Industrial classes due to their different characteristics (operating hours, types of equipment used, etc.). Table 4 below shows the results obtained by these tests.

TABLE 4 – Example of tests made on California

Load mix on test circuit (R-C-I%) ^a	Number of months in test	% energy savings per 1% voltage reduction
80-20-0	4,1	1,44
98-2-0	18,0	1,24
80-20-0	17,2	1,61
90-10-0	16,4	1,61
75-25-0	15,3	0,65
0-100-0	16,4	1,69
10-10-80	14,8	0,58
60-40-0	1,1	1,57
32-14-54	2,4	1,03
49-27-24	2,4	0,52
14-21-65	0,5	0,36
54-4-42	0,5	0,46
0-8-92	18,9	0,46
77-16-7	4,7	0,80
91-5-4	5,0	1,54
55-45-0	1,8	0,84
Mean (weighted by months)		1,12
Standard error of mean		0,126
T-ratio		8,89 ^b

^a Residential, Commercial, Industrial. Industrial includes Agriculture.

^b Significant at 95% confidence level

Source: [24]

Analyzing the results, it is observed that in the residential sector the reduction in consumption would reach 0,76% for each 1% of voltage reduction, while in the commercial and industrial sector this reduction would be 0,99% and 0,41% respectively.

2.3 LEGISLATION

One of the more complex and demanding activities for energy companies is to maintain voltage and frequency levels of all network connection points within an acceptable operating range [25].

Regulatory bodies in each country and standardization organizations are responsible for establishing those ranges, which reflects acceptable technical and operational limits.

In Brazil, the regulator is the National Electric Energy Agency (ANEEL), according to [26], the voltage variation allowed for consumer units with a rated voltage of less than or equal to 1 kV (220V / 127V) is 5%, the values considered adequate are in the range of 202 to 231 Volts and 117 to 133 Volts respectively.

For consumers with nominal voltage greater than 1 kV and less than 69 kV, 0,93 RV (Reference Voltage) to 1,05 RV, is considered suitable. For rated voltage greater than 69 kV allowed voltage values are between 0,95 RV(Reference Voltage) e to 1,05 RV [26].

In the United States, the legislation requires that the voltage available to consumers is 120V +/- 5%, meaning that the voltage is in the range between 114V and 126V. However, system managers tend to maintain the voltage always above 120V in order to have a greater safety margin during the peak hours of the load [23], preventing the voltage to decrease below its minimum far away from the points with voltage regulation.

European legislation stipulates that the permitted voltage variation in the public distribution networks is 10% more or less than the nominal value of the voltage, i.e., if the nominal voltage for the residential supply is 230V the allowed range for Voltage range is between 207V and 253V [27]

Another aspect that should be considered is the frequency. Variations in the frequency of an electric system are defined in [1] and [28] as being deviations in the value of the fundamental frequency of this system (50 Hz or 60 Hz). The frequency of the power system is directly associated with the speed of rotation of the generators that supply the system.

In systems connected to the utility grid, frequency is controlled automatically by the generators themselves through the regulation equipment that inject more or less water (or steam or gas, e.g.) into the turbines that drive the generators, depending on the increase or decrease in demand [29].

Small frequency variations can be observed as a result of the dynamic balance between load and generation in case of some change. Frequency variations that exceed the limits for normal operation at steady state can be caused by faults in transmission systems, the failure of a large load block or of a large generation source [1].

In order to analyze the Electric Power Quality, the PRODIST - Module 8 [26] (for Brazil) has been analyzed; referring to this document, it is stated that:

- 1- The distribution system and the generation facilities connected to it must, operate, under normal operating conditions and at steady state, within the frequency range of 59,9 Hz to 60,1 Hz.
- 2- It may not exceed 66 Hz or be less than 56,5 Hz under extreme conditions;
- 3- It can remain above 62 Hz for a maximum of 30 (thirty) seconds and above 63,5 Hz for a maximum of 10 (ten) seconds;
- 4- It can remain below 58,5 Hz for a maximum of 10 (ten) seconds and below 57,5 Hz for a maximum of 05 (five) seconds;

The European legislation Establishes 50 Hz as standard frequency, [27] recommends that the frequency remain between -6%/+4% (47 to 52 Hz) for 100% of week.

The IEEE - Recommended Practice for Monitoring Electric Power Quality, shows that in isolated systems, however, e.g. the case of the own generation in the industries, in the event of a disturbance, the magnitude and the dwell time of the machines operating out of speed, result in deviations of the frequency in more significant proportions [28].

2.4 CVR TECHNIQUE IN POWER GRIDS

Electricity supply normally uses a "Supervisory Control and Data Acquisition" (SCADA) system to provide monitoring and control of power generation through downlink substations to detect the need to increase or decrease generation and to respond to instabilities of the electrical system [30].

Firstly, in order to design a CVR, it is always necessary to maintain the minimum voltage limit for customers at the end of the lines.

Each electrical equipment is designed to operate within a certain range of voltage values, but not necessarily with optimum performance for all these values. When the voltage level is out of its operating range, the device may be unable to turn on or operate, may malfunction or may even be damaged [23].

Consistent with [25] the CVR can be implemented using several strategies, such as Line Drop Compensation (LDC), load tap changer (LTC), Voltage Spread Reduction (VSR) and voltage and reactive control (VVC).

According to [31] with improved technology available with smart grids, integrated voltage and reactive control should become much more effective than traditional technologies such as Online Tap Changes (OLTC) transformers, automatic voltage regulators and capacitor banks operating autonomously. Table 5 resumes the percentage of voltage reduction which can be reached according with the methodology of voltage reduction adopted.

TABLE 5 – Voltage Reduction Techniques

CASE OF STUDY	VOLTAGE REDUCTION TECHINICQUES	ADVANTAGE	DISADVANTAGE
#Case 1	LTC	easy and economical	small volt reduction, without volt feedback, may result in low volt
#Case 2	LDC	end-of-line voltage is controlled, larger volt reduction than LTC	complicated settings, without volt feedback, can't adapt to dynamic changes
#Case 3	LDC		
#Case 4	LDC		
#Case 5	LDC		
#Case 6	LDC, Capacitor	end-of-line voltage is controlled, larger volt reduction than LDC, less power losses, flattened volt profile and improved power factor	capacitor placement is complicated, can't adapt to dynamic changes, high cost
#Case 7	LDC, Capacitor		
#Case 8	LDC, Capacitor		
#Case 9	LDC, Capacitor		
#Case 10	VVO	larger volt reduction, more reliable with volt feedback, adaptive to dynamics changes	complicated and high cost
#Case 11	VVO		
#Case 12	VVO		

Source: Adapted from [19]

2.4.1 Load Tap Changer

Load Tap Changer (LTC) and Line Drop Compensation (LDC) are the most commonly used methods to implement voltage reduction. They control the voltage at the secondary of the transformer substation and are available in most substations, which means that there would be no additional costs for the implementation of this system, meanwhile the circuits that will be applied to the voltage reduction should be carefully selected [19].

In 2002, a study using a CVR with a Tap-Change Operation found energy savings between 0,3 and 1,1 %, depending on the feeder [4].

During 2009 and 2010, OMEC (Oneida Madison Electric Cooperative), in conjunction with the New York Power Authority (NYPA) participated in the EPRI (Electric Power Research Institute) Green Circuits project; in a study that attempted to identify effective methods for improving system

efficiency and reducing losses through modeling and simulation of specific feeders. Voltage optimization (CVR) through the use of LDC was simulated as a loss-reduction and energy reduction technique on two OMEC feeders. These simulations indicated that OMEC could potentially reduce its annual energy consumption by 0.9—1.1% (an energy efficiency improvement realized through reduced consumer consumption) by implementing the recommended LDC settings with the regulator controls in the circuits in question [32].

The assumption of uniform charge distribution to calculate the set point is not always accurate [33]. One of the problems is that more efficient LDC methods require reliable communication links and sophisticated techniques for efficient optimization [34].

The circuit of a Load Tap Changer is usually constituted by a control circuit, a servo-motor, a transformer and an autotransformer which adjusts its output automatically to provide the voltage regulation [23]. Fig. 2 below exemplifies a voltage profile of a network operating with LTC, the “M” on figure are not explain by the author, but could be understood how a measure point.

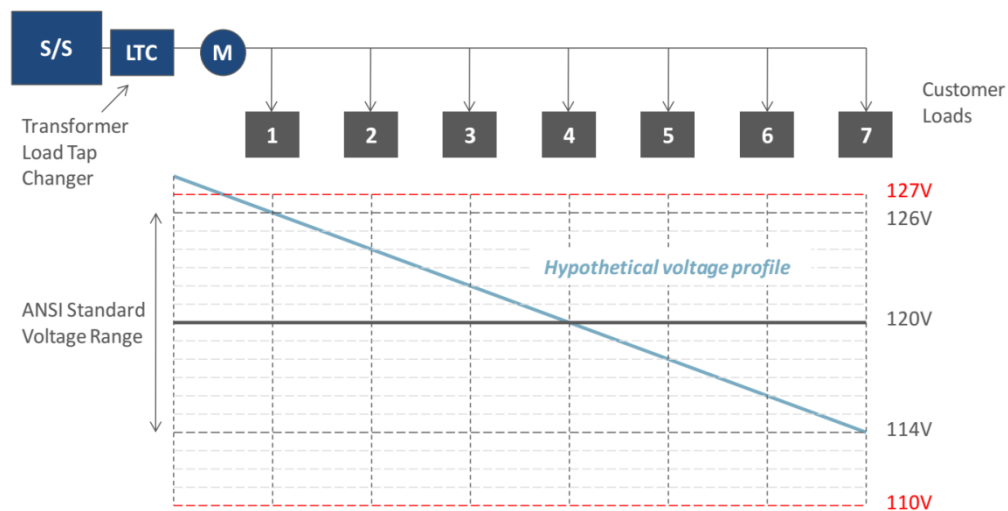


Fig. 2 - Hypothetical Feeder Voltage Profile with an LTC
Source: [35]

When the LDC is not used for voltage control (see Fig. 3), the voltage regulator reads the voltage at its own terminals and compares it with a reference voltage level V_{set} , where V_p and V_s are the voltages on the primary and secondary voltage regulator and B it's an bandwidth (see equation 2). It may be noted that the loads do not influence the voltage regulation.

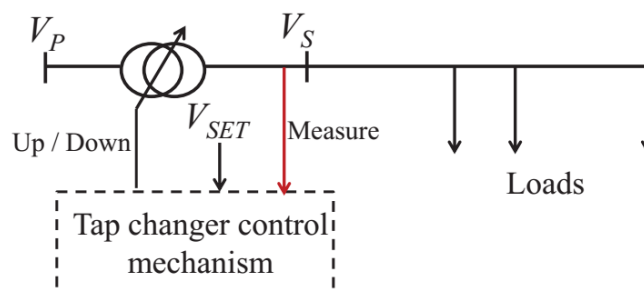


Fig. 3 - LTC operating without LDC
Source: [34]

In agreement with [34], to calculate the voltage that the regulator must emit for the loads the following equation (2) is used:

$$V_{set} - 0,5B \leq V_s(t) \leq V_{set} + 0,5B \quad (2)$$

In voltage control with the use of the LDC [34] (see Fig. 4), the stated objective is to keep the voltage at the constant set point in proportion to the current.

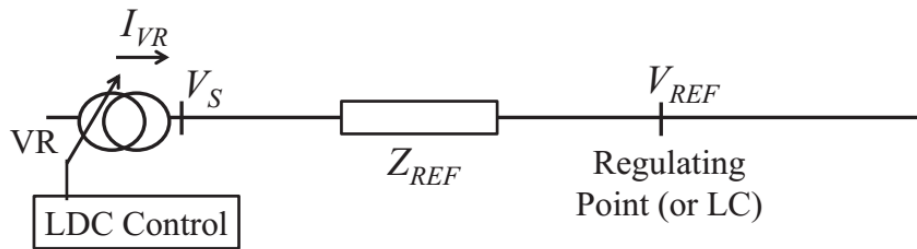


Fig. 4 - LTC operating with LDC
Source: [34]

The voltage V_s can be determined by (3), where Z_{REF} equals the line impedance between the regulator and the setpoint. When the difference between the voltage sent and received at the set point is high, the autotransformer changes its number of turns to correct the error [34].

$$V_s(t) = V_{ref} + I_{VR}(t)Z_{REF} \quad (3)$$

2.4.2 Voltage Var Control

The term Voltage Var Control (VVC) refers to the use of reactive power devices and controls in the utility grid to maintain acceptable voltages at all power points along the line under any load condition [31]. Capacitor banks are also used to reduce electrical losses along the feeder by providing a source of reactive power that is closer to the load, thus enabling the utility to avoid the losses incurred when the sole source of reactive power is the transmission and centralized generation system (Fig. 5).

Where I_s is the source current, I_C is the capacitor current, V_{AC} is the alternated voltage source, R_{line} is the line resistance, X_{line} is the line inductance, X_{Cap} is the capacitor bank, R_{Load} is the load resistance and X_{Load} is the load inductance

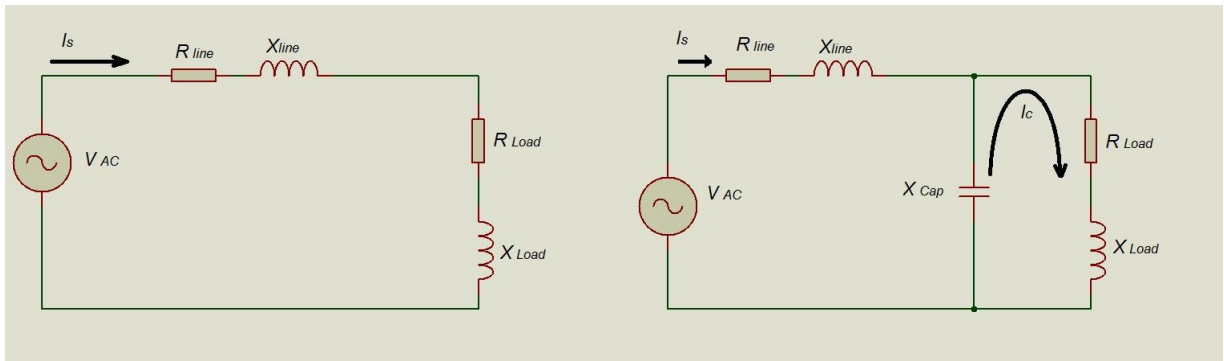


Fig. 5 - Reactive Power Consumption with Capacitor Bank
Source: Adapted from [31].

The advantages of closed-loop VVC application are evident, optimal voltage reduction, improved energy savings and can adapt system dynamics changes, while its disadvantage is the high complexity and high cost [17].

2.4.3 Voltage Spread Reduction

Usually the Voltage Spread Reduction (VSR) is implemented through LDC and VSR, as addressed in the following. With the use of VSR the voltage limit is stipulated in a certain range $\pm 5\%$ or less (usually $2,5\%$, e.g.) using the regulator or Load Tap Changers controller, this requires investment in the improvement of transmission lines, balancing charge and addition of capacitors [10].

VSR is used to minimize voltage variation along the line, by using capacitors to provide voltage support across the network, and will later allow CVR operators to reduce substation voltage [33].

VSR provides greater uniformity of voltage to consumers throughout the distribution network. According to [36] the VSR to regulate the power line voltage profile by combining voltage regulators and capacitor banks installed at strategic points in the line for Attenuate the degree of line voltage drop.

The voltage profile of grid with LTC, voltage regulator and capacitor bank can be observed in Fig. 6.

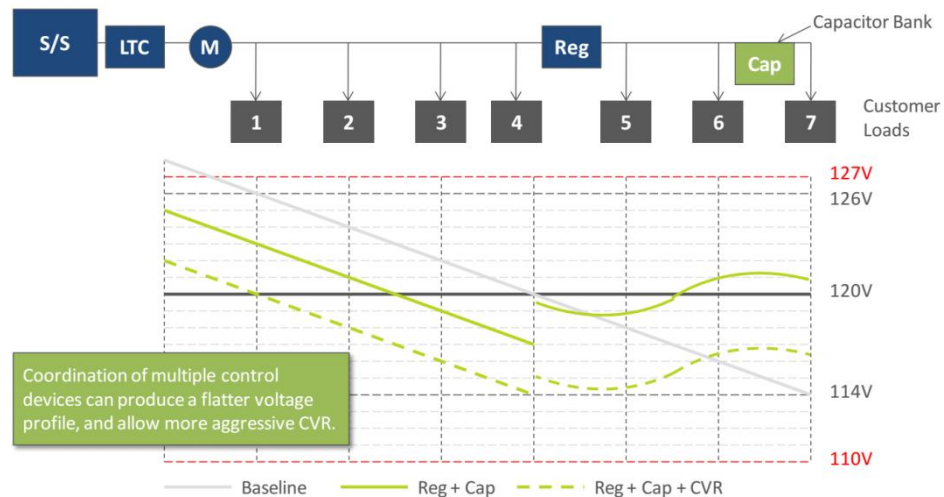


Fig. 6 - Feeder Voltage Profile with LDC, Voltage Regulator and Capacitor Bank
Source: [35]

2.4.4 Voltage and Volt-Ampere Reactive Optimization

With the development of Smarts Grids and SCADA the possibility of controlling and monitoring the conditions of the power supply system has been enhanced, where values such as active power, reactive power and supply voltages can be easily collected and analyzed by system operators, thus allowing a connection between the voltage and reactive power, called volt-ampere reactive optimization (VVO) and SCADA systems, optimization and real-time control of the network [37].

The VVO method is an evolution of the VVC, and according to [35] it aims to lower distribution voltage levels during peak periods to achieve peak demand reductions, reduce voltage levels over longer periods to increase energy savings, and reduce energy losses in the electric distribution system.

VVO projects generally fall into three main categories [35]:

- Reduce peak demand (CVR for Peak)
- Reduce electricity consumption (CVR for Energy)
- Reduce distribution line losses

BC Hydro is one of the leaders in the North America in the implementation of Voltage VAR Optimization (VVO) in distribution systems, and implemented in 1990 the first demand response and distribution automation project which allowed deferring new investments in transmission capacity, and providing energy conservation as a side benefit [38].

The primary benefits of VVO are better network voltage and reactive control, easier system operation and maintenance and better integration with distributed generation [32].

Other benefits associated with implementing VVO technologies, are for instance, a higher level of visibility into system operating parameters and a greater degree of control to optimize energy efficient and reliable electricity delivery, increase the system optimization in utilities facing a dynamic operating profile [39].

Some examples of VV project will be presented below [35]:

Avista's VVC project, in Washington, coordinates substation voltage regulators and line capacitor banks using a distribution management system (DMS). The objective is to flatten voltage profiles on distribution feeders in order to safely lower the voltage levels and achieve energy savings with CVR. Avista also expects to reduce line losses by improving feeder power factor. Fig. 7 shows Avista's equipment configuration.

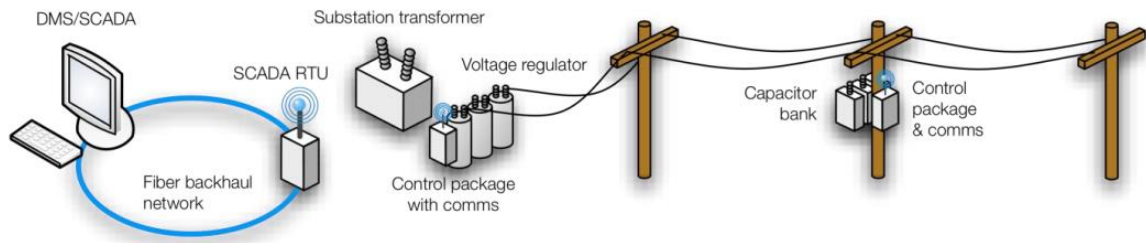


Fig. 7 - Avista's VVO configuration
Source [35]

The Avista DMS includes an Integrated Voltage and Var Control (IVVC) algorithm that automatically monitors and controls individual capacitor banks to minimize feeder losses while maintaining voltages and power factor within specified limits.

Other project is applied by Northern Virginia Electric Cooperative (NOVEC), this project has as objective improving feeder power factor with switched capacitor banks, and lowering feeder voltage on substation. The equipment configuration of NOVEC is showed on Fig.8.

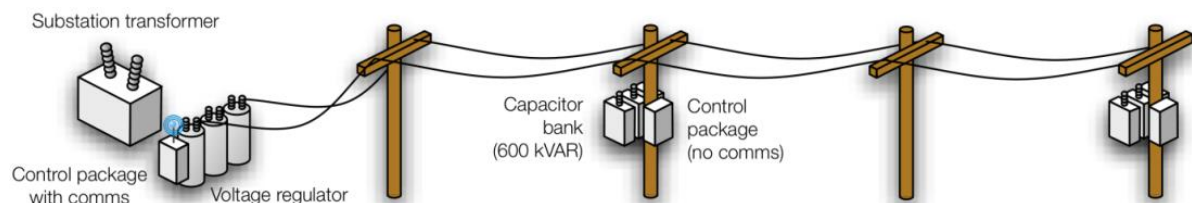


Fig. 8 - NOVEC VVO configuration
Source [35]

2.4.5 Online Tap Changer

In the UK and in many countries in the world with European style network designs, LV circuits are typically equipped with off-load tap changers which means that the fine tuning of the ratio between the primary and secondary of the transformers can only be changed when disconnecting the load [40].

The adoption of on-load tap changer (OLTC) is increasingly being considered, particularly in the context of residential-scale Photovoltaic systems [40]. However, depending on the control strategy, tap operations can be significant, leading to the wear and tear of the OLTC.

The performance of an low voltage OLTC-fitted transformer was analyzed in [41] considering a load-based control algorithm. The OLTC set-point was changed depending on the total load variation.

In 2016 a paper of University of Campinas UNICAMP, describe a serials of simulations to increase a photovoltaic hosting capacity with OLTC technology and photovoltaic var absorption in a medium voltage/ low voltage rural Brazilian distribution system [42].

2.5 RESUME

This chapter presents the state of the art regarding the potential of using the CVR as a tool of energy saving. It has been shown how loads interact with the CVR, the legal parameters for variation of the voltage and frequency and how the CVR is applied in the Electrical Networks.

It was showed through various papers that the CVR method is very advantageous for the energy saving when the loads used are not purely resistive. There are many studies where the CVR method are applied to electrical networks or substations (see [35], [7]), and several studies analyzing the impact of the use of the CVR with penetration of distributed generation (see [19, 43, 44], but there are not found many studies of case that apply the CVR method in isolated networks.

3 MICROGRIDS

The traditional electrical system is characterized by a strongly centralized model and traditionally very dependent on fossil fuels. Currently, there is a change of mentality: the improvement of renewable technologies and the development of Smart Grids have opened a new horizon of improvement allowing a greater control of the electrical system and the introduction of distributed generation [45].

The need of finding alternative energy resources is already established and is being implemented in a considerable scale [46]. The development of efficient technologies that allow the use of renewable and clean energy sources, such as photovoltaic conversion, which is one of the alternatives with the best relation between cost and benefit. It has become a significant energy source of the energy matrix of countries such as Germany, Spain, Portugal and Switzerland. The integration of this energy source, among others such as wind energy and cogeneration systems, in the network allows the exploitation of energy systems organized in microgrids.

One of the missions of smart grids is to contribute positively to the environmental impact and reduce social costs by using energy more efficiently and utilizing more renewable and distributed energy. This is reflected in the increasing use of renewable energy and the consumers enfoldment which can sell the energy they produce and also use it for their own consumption. In this scenario, there was the opportunity of the emergence of microgrids.

According to EU estimates, there are more than a billion people in the world living without electricity. Due to high investment costs for expanding the public grids and low power requirements, it would be uneconomical to connect these remote areas to the utilities in the medium run. Under these circumstances stand-alone PV systems present a logical alternative [47].

In this chapter we will introduce the microgrids, distributed generation and smart grid concepts. The microgrid, whereas the analysis of the impact of CVR techniques will be studied, will also be presented.

3.1 CONTEXTUALIZING MICROGRIDS

It is possible to define microgrid as a semi-autonomous group of generation sources and loads, which are placed and operated in order to serve clustered or dispersed clients belonging to the micro-network, which may be connected to the main network or explored as a standalone system [48]. The microgrid concept is a set of loads and micro-sources operating as a single controllable system that provides power and/or heat to the local area [48]. Typically, it is a low voltage

Microgrid network (e.g., a small urban area, a shopping center, or an industrial park)

A Microgrid can operate in two ways according to [49]

- Normal Interconnected Mode - the microgrid is connected to a main network, either being supplied by it or injecting some amount of power into the main system.
- Emergency Mode - the microgrid operates autonomously, in a similar way to physical islands, when the disconnection from the upstream network occurs.

Whatever operation option is adopted, some characteristics should be observed [49]:

- When the microgrid is connected to the electrical network, the system should offer support for the integration of renewable energy sources and optimization for the economical operation of them.
- When the system is operating in isolated mode (off grid), it is necessary to have a high organization and control of the microgrid system itself: because if the system cannot feed all the loads of the network it will be necessary to make the separation of the loads, maintaining the loads considered of major importance.

The benefits of microgrids are [50]:

- Enhance local reliability,
- Reduce feeder losses,
- Support local voltages,
- Provide increased efficiency through using waste heat and combined heat and power, e.g.
- Voltage sag correction and,
- Provide uninterruptible power supply functions.

The components of a microgrid depend heavily on the available energy sources and the type of use. The diagram (Fig. 9) shows how the energy resources from a microgrid can be integrated on a electrical network.

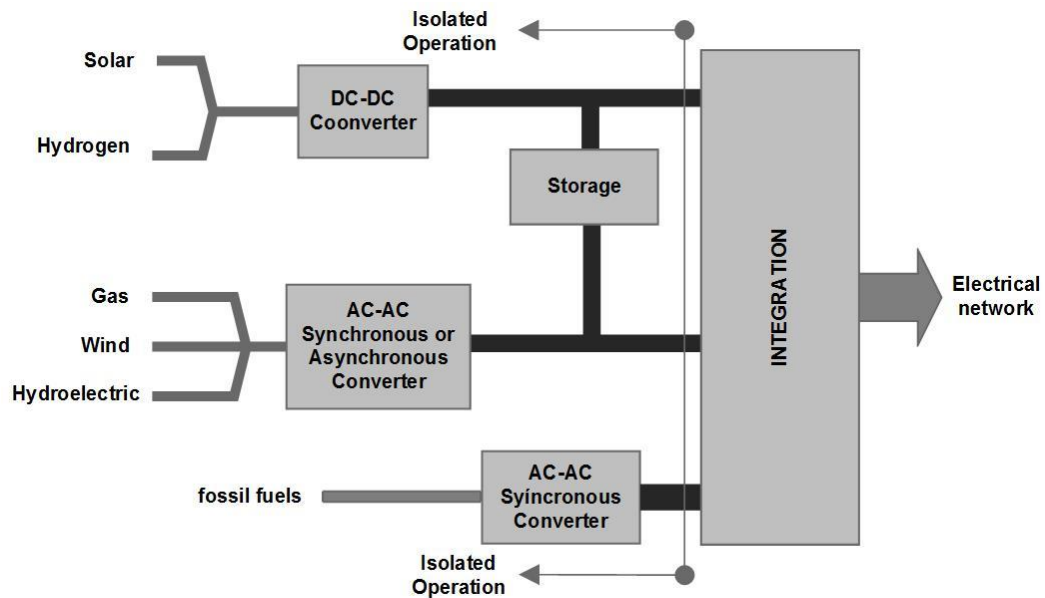


Fig. 9 - Microgrid Integration Diagram
Source: Adapted from [51]

The components of the microgrid may be sets of micro turbines, fuel cells, photovoltaic panels and other small power generators, storage devices and controllable loads.

3.2 DISTRIBUTED GENERATION AND CVR

A distributed generation characterized by the installation of small generators usually based on renewable sources or even using fossil fuels, located near the centers of electric energy consumption as explained in [52].

The IEEE define distributed generation as an electric generation facilities connected to an electrical power system through a point of common coupling; a subset of distributed resources [53].

A general structure for distributed systems is illustrated in Fig. 10 the input power is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network, depending where the generation system is connected. The control tasks can be divided into two major parts, being one of them Input-side controller, with the main property to extract the maximum power from the input source, and the other is the grid-side controller responsible for control of active power generated to the grid, control of reactive power transfer between the Distributed power generation systems and the grid, control of dc-link voltage, ensure high quality of the injected power, grid synchronization [54].

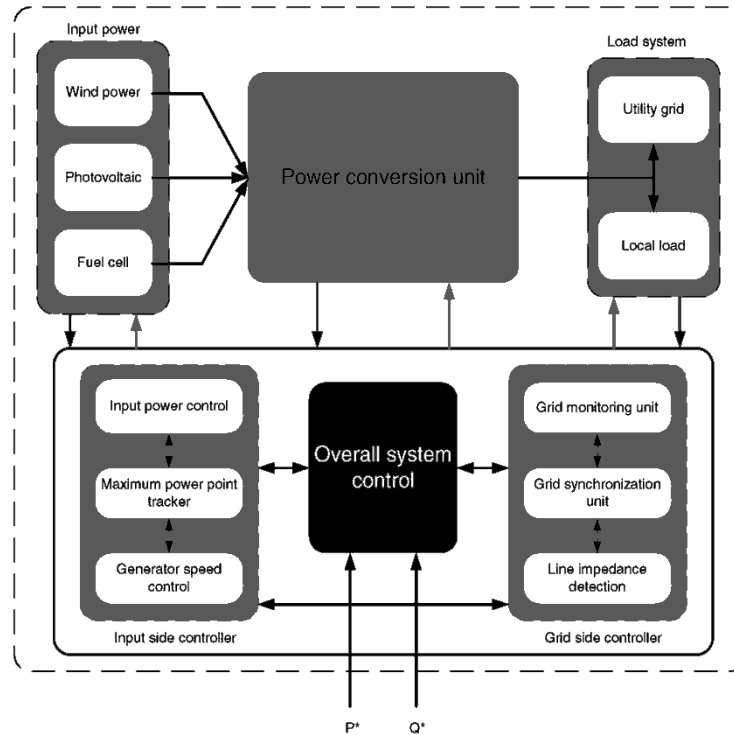


Fig.10 - General structure for distributed power system
Source: [54]

Distribution system configuration is usually designed as a radial rather than a network or loop system. The radial circuit has many advantages, e.g. easier voltage and power flow control and lower cost. However, the radial system, if designed to have only one utility power generation source at the beginning of the feeder, leads to two major problems, i.e. voltage drop at the feeder end and higher system power loss [18]. Distributed generation allows the elimination of these disadvantages, since generation is distributed along the radial network.

Distributed generation (DG) in power system networks has rapidly increased. This increase can be justified by factors such as environmental concerns, the restructuring of electricity market, because some countries disabled their nuclear plants, and the development in technologies for small-scale power generation.

The integration of information and communications technologies (ICT) into the grids allows the optimized integration of the Distributed generation with the distribution networks. Installation of DG can help decentralize power generation, defer transmission system upgrade, support system voltages, and reduce system power loss.

The connection of DG to the utility network can lead to grid instability or even failure, if these systems are not properly controlled. Moreover, the standards for interconnecting these systems to the utility network are stressing more and more the capability of the Distributed Generator System to run over short grid disturbances. In this case, both synchronization algorithm and current controller are essential to solve this problem.

These integrations were studied in [55], e.g., showing that the voltage profile along the line change more quickly with the increasing of DG sources, and a lower percentage of photovoltaics is not of major concern, but penetration equal to, or greater than, 20% can dramatically affect the feeder voltage profile.

It is explained by [56] that a high penetration of different kinds of Distributed energy resources (DER), demand response (DR), and electric vehicles in the distribution systems will make the distribution system a highly active and complex, and may have adverse impacts on the power system in some situations, as well as positive ones in other situations.

Conventional synchronous generators are able of both generating and absorbing reactive power. Therefore, the use of DGs utilizing overexcited synchronous generators will allow on-site production of reactive power. The local generation of reactive power, which can be addressed also by capacitor banks, reduces its import from the feeder, thus reduces the associated losses, and improves the voltage profile. As a result, the voltage security is also improved, the same could not be said about the Asynchronous Generators, when the DG are directly connected to the distribution system they always consume reactive power, thus contributing to the factors increasing the probability of encountering voltage stability problems. The reactive power consumption of asynchronous generators is commonly compensated by shunt capacitor banks [57].

The utilization of CVR in Photovoltaic (PV) Systems are discussed in [58] and it is not found any negatively influence of its use, since power inverters can be set to generate constant power. But when it is used renewable energy like solar and wind energy, the system depends on the weather conditions, and output of DG such as PV cannot be anticipated accurately.

3.3 SMART GRID

The concept of a smart grid, differs according to who defines it. Some experts focus on the concept in the automation network part, others in the energy supply chain, others in the improvement of interaction channels and services for the consumer. The reason for this is that this definition varies according to the needs (reduce losses, operational costs) and with the optics (financial, environmental, among others) of the author.

The U.S. Department of Energy [59] said the smart grid it's not a "thing" but rather a "vision" and to be complete, that vision must be expressed from various perspectives, values, characteristics, and efforts must be made to achieve it.

That "Vision" must be built according to the needs of the market where it will be implemented and taking into account multiple perspectives, such as technological, environmental, socio-economic and political-regulatory.

In the past, the grids systems are blind, i.e., it was not possible to have a total view of what was happening in the system.

A key technology in order to transform the actual grids is the information and communication technologies (ICT). This means that advanced management, automation, control and communication concepts had to be developed to attend the requirements of smart grids systems; especially for the large-scale integration of distributed power systems. The electric energy system, especially the distribution networks are on the verge of a profound change with Smart Grid solutions enhancing efficiency and flexibility [60]. Fig. 11 Can presents a flowchart of how the traditional power transmission system works.

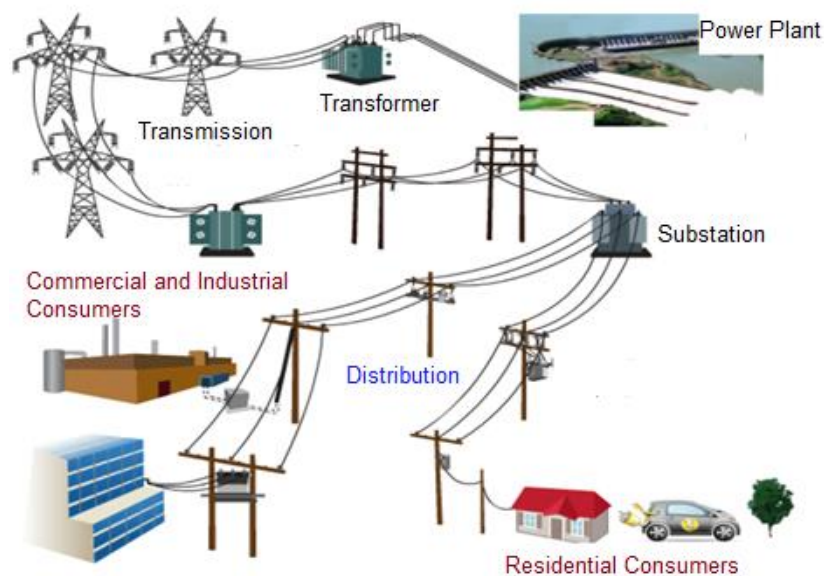


Fig. 11 - Traditional Radial Power Grid
Source: [60]

In general, the future grids are characterized by new network and communication components (e.g., inverters, smart meters, charging units, controller devices, switches, breakers, etc.) with enhanced and advanced services.

In this way a comparison can be made between the current distribution network model and the Smart Grid model as showed on Table 6.

Table 6 - Comparative of Traditional Grids with Smart Grid

TODAY'S GRID	PRINCIPAL CHARACTERISTIC	SMART GRID
Consumers are uninformed and do not Participate with the power system	Enables Consumer Participation	Full price information available, choose form many plans prices and options to buy and sell
Dominated by central generation, very limited distributed generation and storage	Accommodates All Generation & Storage Options	Many "plug and play" distributed energy resources complement central generation
Limited wholesale markets, not well integrated	Enables New Markets	Mature, well-integrated wholesale markets, growth of new electricity markets
Focus on outages rather than power quality	Meets Power Quality Needs	Power quality a priority with a variety of quality and price options according to needs
Limited grid intelligence is integrated with asset management processes	Optimizes Assets & Operates Efficiently	Deep integration of grid intelligence with asset management applications
Focus on protection of assets following fault	Self-Heals	Prevents disruptions, minimizes impact, and restores rapidly
Vulnerable to terrorists and natural disasters	Resists Attack	Deters, detects, mitigates, and restores rapidly and efficiently

Source: [61]

In the future it is expected that the system will have all the features mentioned above with the implementation of smart grids (Fig. 12).



Fig. 12 - Future Smart Grid System
Source: [62]

3.4 EXAMPLES OF MICROGRIDS

Microgrids are used in many places in many different ways, we looked for some examples of how this technology is being used.

A place that worked with research and development in the area of Renewable Energies is CIEMAT (Center for Energy, Environmental and Technological Research) - CEDER (Center for the Development of Renewable Energies), located near the city of Soria in Spain, as a national center for research, development and promotion of renewable energies. Dependent of CIEMAT and assigned to the Department of Energy of this Public Research Agency, it is considered as a pioneer center in Spain in the field of energy use of biomass, in addition to being a national and European reference in minieolic energy [63].

The CEDER, which provides services to groups of the CIEMAT itself as well as to other public and private institutions in the field of business and research, has been providing, developing and attracting R&D&I activities, started their activities at the end of 1986, are assigned for the carrying out of research activities in 3 areas related to renewable energy sources as Wind energy, Biomass and solid waste energy, Bioclimatic architecture and Energy Efficiency in Buildings [63].

Currently the CEDER-CIEMAT microgrid counts on a total of 5 wind turbines, being 3 single-phase and 2 three-phase, making a total of 69.2 kW of power. Has two types of photovoltaic panels: first in the ground, producing a total of 30 kW of energy, with the following characteristics [45]:

- 24 panels of polycrystalline silicon associated to a 5 kW PV inverter.
- 32 monocrystalline silicon panels, associated to a 5 kW PV inverter.
- 32 monocrystalline silicon panels, associated to a 5 kW PV inverter.
- 64 monocrystalline silicon, associated with an inverter PV of 15 kW.

And covered Photovoltaic on the roofs of three buildings, producing a total of 40 kW of power, with the following characteristics:

- 64 monocrystalline silicon panels, associated with a PV inverter of 10 kW.
- 54 monocrystalline silicon photovoltaic panels, associated with a PV inverter of 10 kW.
- 238 First Solar FS-397-Plus Thin Film Panels, associated with a PV inverter of 20 kW.

The use of hydroelectricity is also present in this microgrid, with a hydropower mini-plant with 2 types of turbines.

A system pump/turbine group with a maximum output of 40 kW and an output voltage of 400 Vac, can operate for 6 hours uninterrupted. A pump system consisting of two 18.5 kW hydraulic pumps running in parallel, pumping the turbine water into the lower reservoir toward upper [45].

And a turbine based on the Archimedes screw, with the aim of maximizing the use of water resources, this turbine is in the characterization phase, but a production of between 1 and 1.5 kW is estimated [45].

The renewable resources described above, it is necessary to add a total of four battery banks, three of them Lead-Acid and a fourth of Lithium-Ion, which complement the Distributed Generation (DG) to storage the energy resources [45]. The Fig. 13 below shows the operating scheme of microgrid.

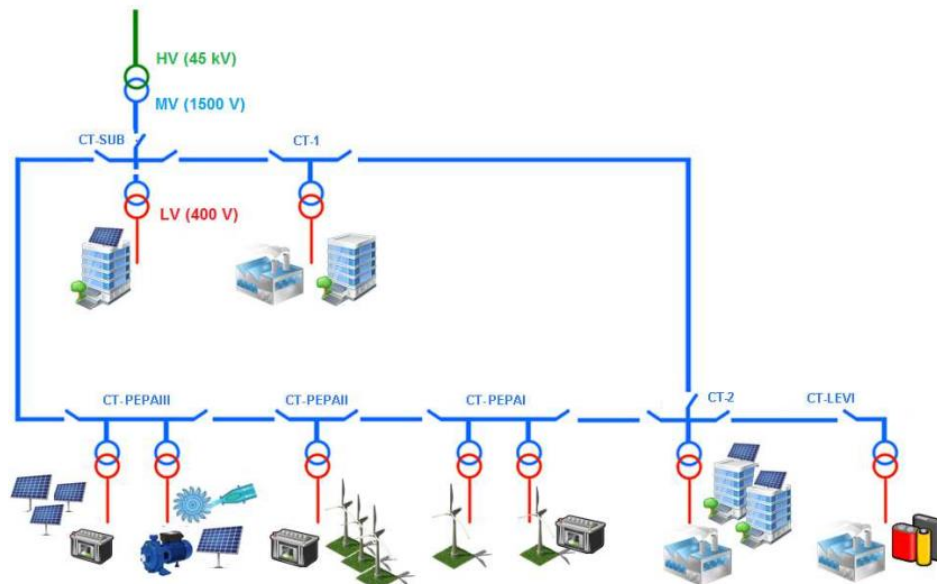


Fig. 13 - Representation CEDER microgrid
Source: [45]

Other example, it's a project of a hybrid microgrid DC/AC situated on Juiz de Fora - Minas Gerais – Brazil in the Federal University of Juiz de Fora and it's based on renewable power sources, the

hybrid term is based In fact that a DC microgrid, losses per conversion can be reduced from 32% to up to 10% second [64]; so the essential idea of this microgrid is to take advantage of the loads that require a DC power, seeking this energy directly from the DC bus, and the loads that need an AC power is made the conversion by means of inverters.

Part of the proposed microgrid in the project is already in operation (photovoltaic panels are already active). The microgrid is composed of photovoltaic, wind power and fuel cells to store energy. Photovoltaic production is generated by 264 photovoltaic panels grouped in 11 independent arrangements (24 panels each) with a capacity of 404 V / 7,12 A per arrangement (under maximum power conditions). The panels are installed in the Solar Laboratory Photovoltaic of University, and part of the generated power (15 kW) will be available to the 320 V DC bus of the microgrid [64].

The wind system integrated to the microgrid system consists of a permanent magnet synchronous generator (PMSG), a three-phase bridge rectifier and a boost converter operating as a Maximum power point, obtained by measuring voltage and current at the output of the rectifier. The wind generator at the point of maximum power will generate about 2 kW of power (simulated) [64].

To meet demand at times when the system operates in isolated mode or when the network is unavailable, diesel generators or gas micro turbines may be used. The proposed microgrid diagram can be seen in Fig. 14 below.

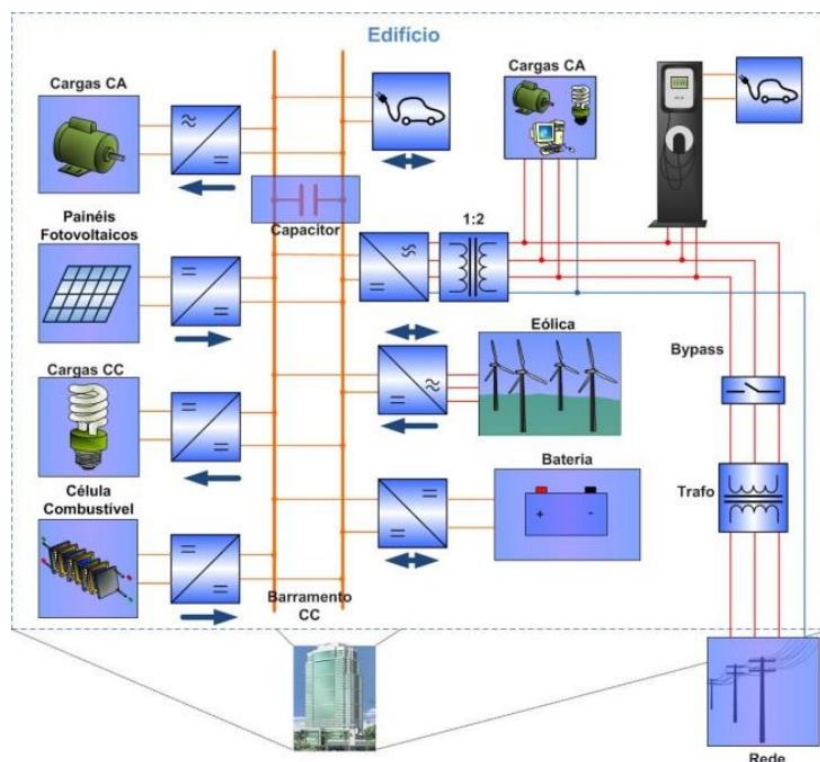


Fig. 14 - Microgrid DC/AC proposed
Source: [64]

3.4.1 Polytechnic Institute of Bragança Microgrid

Since 2007, the Polytechnic Institute of Bragança (IPB) has developed a project called VERCampus – Alive Campus of Renewable Energies, which aims to implement a "Live Park" dedicated to the dissemination of Renewable Energies in its University Campus: solar photovoltaic, solar thermal, wind, hydro, hybrid systems, smart grids, electric vehicles, biofuels and energy efficiency [65].

The microgrid deployed in the IPB was developed for an isolated and self-sustaining system and has a nominal power of 5 kW integrating renewable energy sources, aiming to be a demonstration platform in terms of technology evolution and applied research [66].

The microgrid showed in the Fig. 15 represents the microgrid implemented in IPB and used to test the CVR effects in the experimental study (Chapter 4). The system is composed by 2 groups of photovoltaics panels, 1 wind generator, a group of 8 batteries (200A/h), a Sunny webbox (data control), 1 inverter (Sunny Island), 2 solar inverters (Sunny Boy1 and Sunny Boy 2), 1 wind inverter (Sunny Wind), 2 meters (Power quality analyzer and power energy logger) used to collect information and save data during tests, and loads (composed by 2 lighting circuits and 1 load circuit).

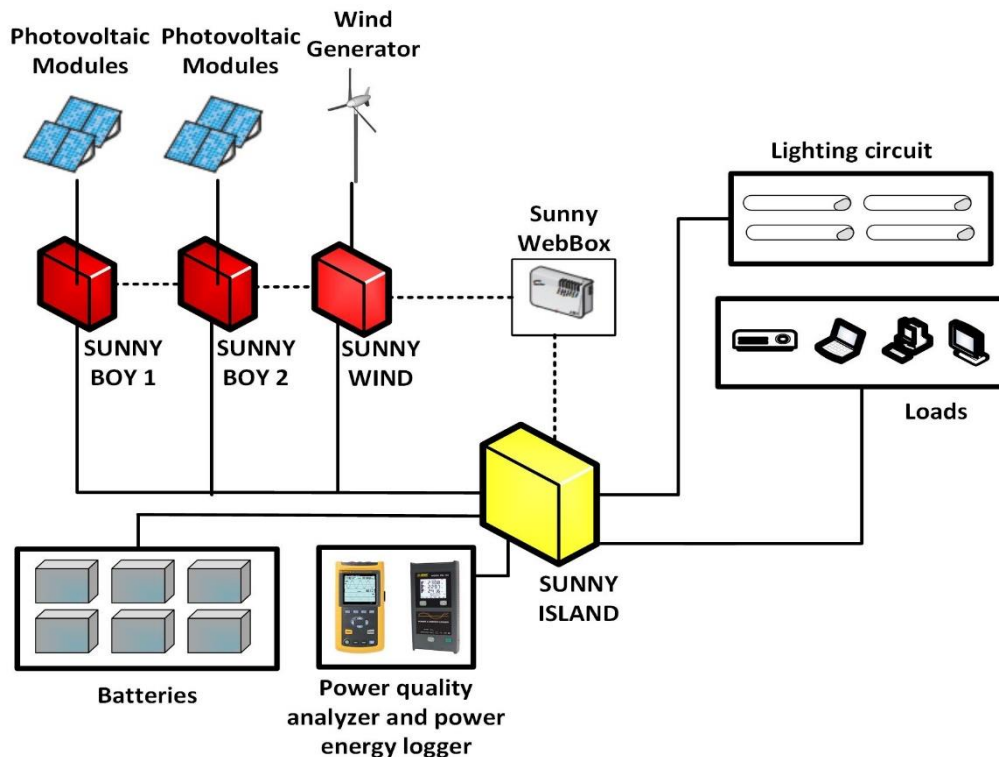


Fig. 15 - Representation of IPB microgrid
Source: adapted from [67]

The IPB allowed the studies related to this work to be developed within their microgrid, and the results will be presented in chapter 4.

3.5 RESUME

In this chapter the topic of microgrids was discussed, the need of the evolution of the technologies for the incursion of microgrids and Distributed Generation in the current system, the importance of the Smart Grids for the integration of these systems to the electric network, it was mentioned examples of implanted microgrids and their characteristics.

It has been found that the number of microgrids have grown due to improved technologies and the spread of renewable energies, which is a new scenery for future distribution networks.

4 TECHNICAL VIABILITY OF THE CVR APPLIED TO MICROGRIDS

In order to analyze the energy saved in a microgrid with CVR technique applied, based on the study of the state of the art of CVR, several laboratory tests were carried out in the IPB microgrid, feeding different loads, particularly at lighting level (an area where active energy is more evident), to test the real viability of the voltage reduction methodology.

The tests were carried out in the Laboratory of Electromechanical Systems (LSE), located in ESTiG, of IPB.

4.1 EXPERIMENTAL METHODOLOGY

Test experiments were performed using a fixed set of loads and the voltage of the microgrid set for two different values: first with 230V - rated value, and the second with reduced voltage to 207V – CVR. The voltage level is established through the Sunny Island, the bidirectional inverter of the microgrid. The collected results are then analyzed to evaluate the possible reduction of energy consumption and/or dependencies between loads, voltage and frequency.

The experiments are divided in 4 tests with the voltage regulated at 230 V (days 30 May, 07 June, 25 July, 08 August) and 3 tests with voltage regulated at 230 -10% V (days 23 May, 02 August and 07 August). During the tests the loads were maintained, except for the tests on 07 and 08 August, where the rated load was reduced to 1,5 kW, in the others tests the rated load was approximately 3,2 kW.

The loads used for the validation of the method are described in Table 7 below.

TABLE 7 – Load Characteristics

AMT	EQUIP	I [A]	VOLT. [V]	TOTAL POWER CONSUPTION
1	Monitor 27" LED	4A	14	69W
1	Monitor LCD 19"	0,8A	100/240	34W
1	LCD TV 47"		320	300W
2	Slide Projector	2,5A	230	290W
2	CPU	6A	230	480W
1	Oscilloscope		90/250	20W
1	Oscilloscope		120/230	15W
1	Oscilloscope		230	60W
1	Oscilloscope	2A	250	(5W) 110VA máx
2	LAMP CSRAM L36W		230	72W
1	FLUORESCENT LAMP		230	7W
1	FLUORESCENT LAMP		230	10W
1	HALOGEN LAMP		230	50w
1	LED LAMP		230	9W
4	TLD LAMP 28W		230	112W
1	FHE LAMP 25W		230	25W
21	REACTORS 4W			84W
32	T8 LAMP 58W		230	1856W
		TOTAL		3506 W

All tests were performed at the microgrid of the Polytechnic Institute of Bragança (see Fig.15), with the structure presented earlier in this paper (Section 3.4.1).

During the tests, the microgrid was configured in isolated mode; after the connection of the described loads, the measurements were taken via different tools.



Fig. 16 - Power Energy Data Logger
Source: MegaTester [68]

The measurement of the power and energy of the loads was carried out through the PEL (Power Energy Data Logger - model PEL 103 manufactured by Chauvin Arnoux) are designed for electricians to record electrical or energy use over time, see Fig. 16, the data logger was placed on the electric distribution board of Laboratory such as all the energy coming out of the inverter was measured, and the remaining measurements were provided through the existent communication tools from inverter. In stand-alone power systems communication equipment can be used for three different purposes, as follows [47].

Function-related communication these function is responsible for the intern communication between systems parts our equipment, for example, if several battery inverters are connected in parallel or operated in a three-phase stand-alone power grid, they will need to communicate with each other in order to exchange data or comply with electrical parameters such as phase shifts.

Supportive communication, these type of communication serves to evaluate data so that optimum plant operation can be verified and controlled (see Fig. 17). For this purpose, communication with Sunny Island is usually sufficient, since the Sunny Island can simultaneously collect data from the batteries, external sources and loads. This data can be recorded and stored by a Sunny WebBox. If required, Sunny WebBox will send the data to Sunny Portal where it will be available online from anywhere in the world [47].

To do a General diagnostics the inverter had to communicate with all most every component of the system. Each individual device can be detected and the data recorded. Via a communication bus, you can link up a Sunny Island, Sunny Boy and Windy Boy to the Sunny WebBox. [47].

All communication tasks mentioned here can also be carried out locally with a laptop or PC by these processes the data were save can be subsequently analyzed.

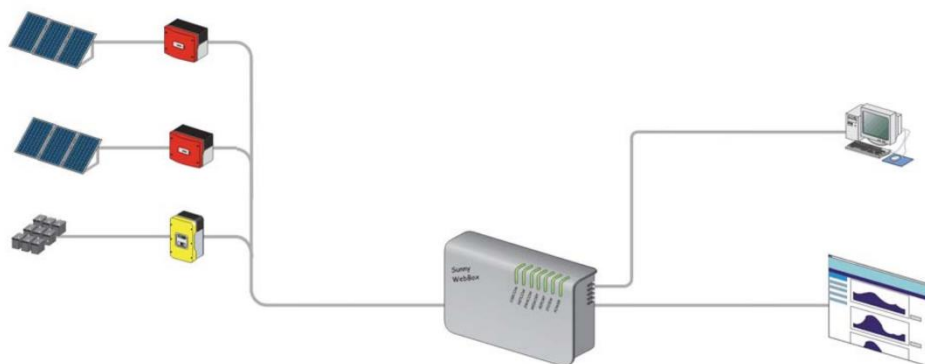


Fig 17 - Communication options in the stand-alone power grid
Source: adapted from [47]

Another important point was the configuration of the system so that it operated at the desired voltage. To configure the microgrid voltage it's needed to log in the Sunny Portal (see Fig. 18) and there it's possible save the data stored and change the configuration voltage of the inverter.

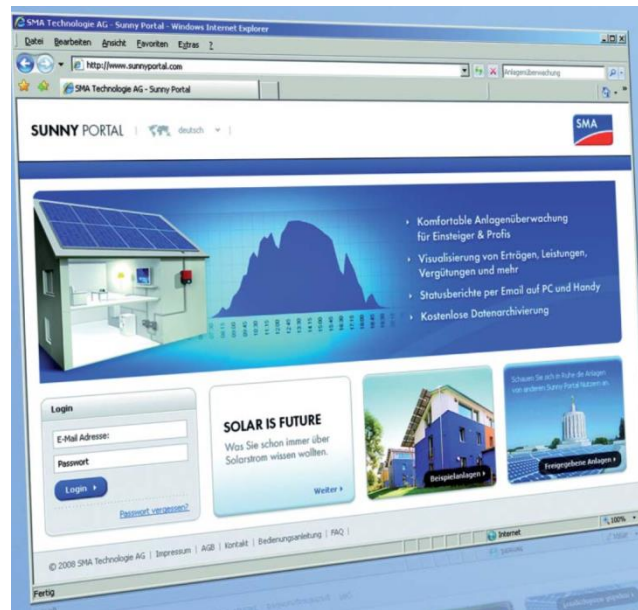


Fig. 18 - Configure microgrid
Source: [47]

After everything is set up the tests have been performed and the results are shown below. To facilitate the reference to different tests, the following designation has been established.

TABLE 8 – Test Designation

Test Designation	Date [DD/ MM/ YY]	Applied Voltage [V]	Load Power [kW]	Frequency [Hz]
A	30/05/17	229,9	3,5	50
B	07/06/17	229,9	3,5	50
C	25/07/17	229,9	3,5	50
D	08/08/17	229,9	1,5	50
E	23/05/17	211	3,5	50
F	02/08/17	211	3,5	50
G	07/08/17	207	1,5	50

4.2 EXPERIMENTAL ANALYSIS

Aiming to analyze the possible advantages of using of the CVR in microgrids and their results, parameters such as irradiation, voltage, produced power, frequency and power consumed were analyzed.

There are many factors that have a direct effect on the energy production of photovoltaic panels, such as heat, solar radiation, ambient temperature, system components, the mounting of the PV array and their position. Among them, it can be highlighted solar radiation [67, 69]. The intensity of the solar radiation changes at any moment depending on the rotation of the earth and its translation around the sun, clouds, etc.

One of the factors that interferes directly in the energy production of photovoltaic panels is the irradiation, thus Fig 19 shows the relation between irradiation and power produced during some tests.

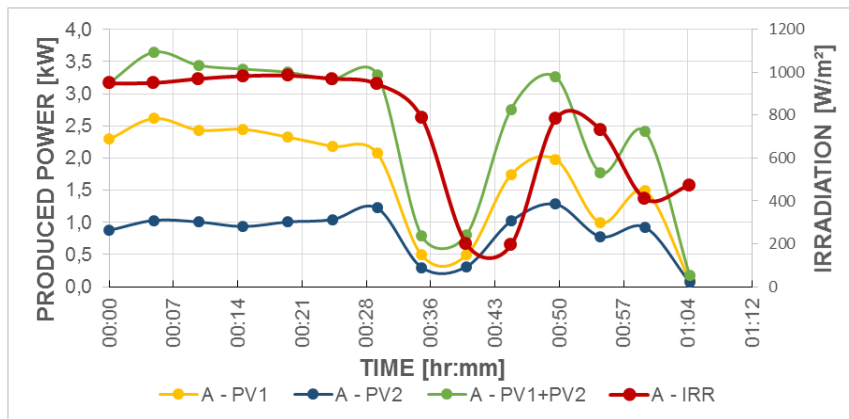


Fig. 19a – Case A Produced Power vs. Irradiation

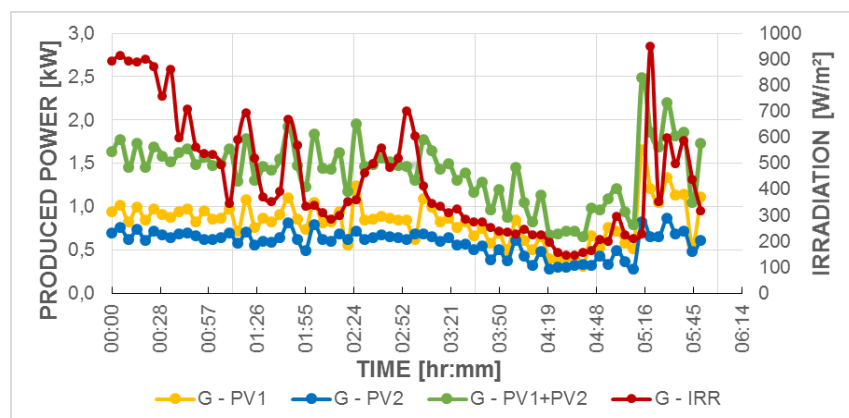


Fig. 19b – Case G Produced Power vs Irradiation

As can be seen in tests A and G, it is verified that the power produced by the photovoltaic panels follows the irradiation.

In G-test, the load used was 1.5 kW, and it can also be observed that the main inverter (Sunny Island) controls the power produced according to its demand.

It has been noticed in some tests that when the power produced has been reduced also occurs the reduction of the frequency of the inverter. As can be seen in Fig. 20a and 20b.

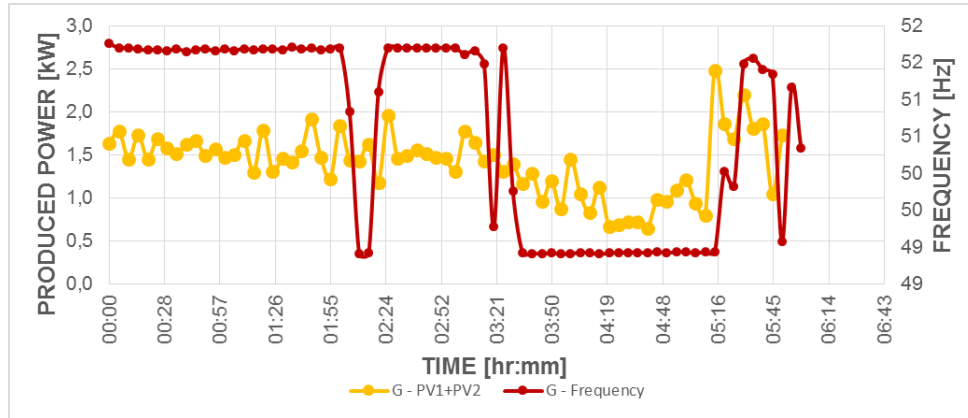


Fig. 20a – Case G: Produced Power vs Frequency

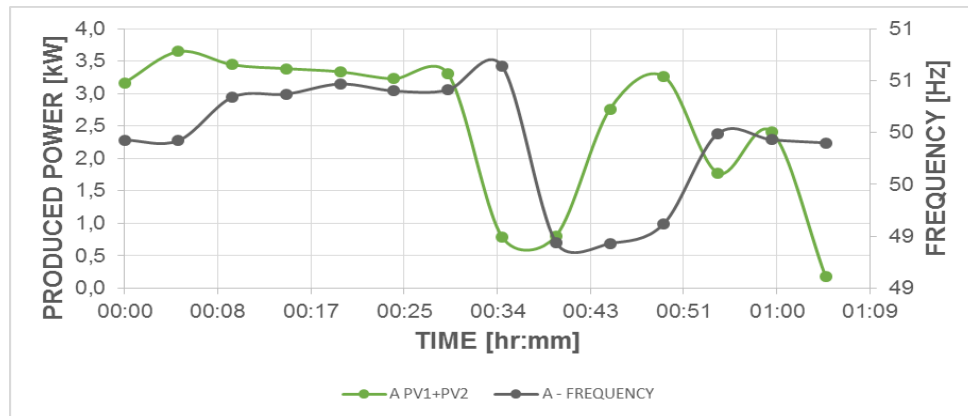


Fig. 20b – Case A Produced Power vs Frequency

This could be justified according with algorithms implemented in the inverter which describes that in order to enable the parallel operation of the AC coupled voltage sources without involving any communication, is used a method called “drop mode”. This method uses active and reactive power statics as a basis for coordinating the performance of the various coupled converters (see Fig. 21). To achieve optimum power flow, the grid parameters voltage and frequency are both influenced [47]. The stand-alone power inverter is equipped with various management systems which guarantees the stable operation of the power supply system.

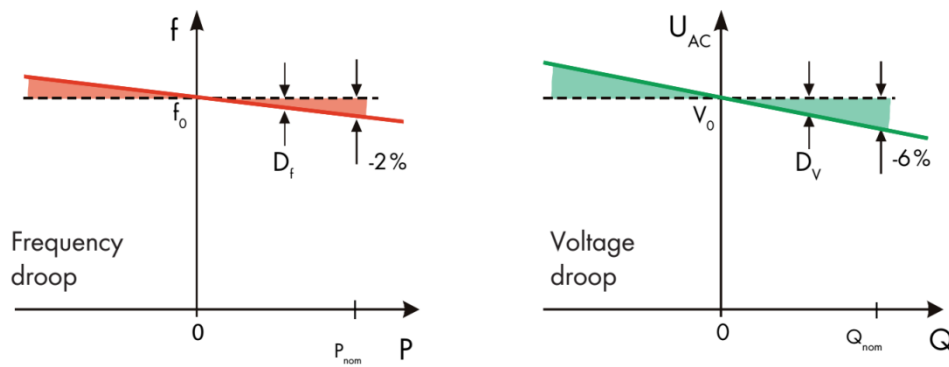


Fig. 21 – Control algorithm in the SMA stand
Source: [47]

Each converter operates by using a cascade controller as its voltage source. In this way, the consumption and output of active power of each individual parallel converter is independently controlled as a function of the stand-alone power grid frequency. If the frequency increases due to a sudden reduction in load, all converters will reduce their power input, and thus the system will remain balanced [46].

Sunny Island inverter has the ability to “interpret” the frequency level in the stand-alone power grid. In the same way as large power plants in the public grid, they are able to adjust to the given energy demand based on the measured frequency – i.e., to regulate the energy flow of the stand-alone power grid [43].

In a microgrid based on photovoltaic generation systems, it can occur sudden increases/decreases in input power, which causes the system to not be able to stabilize the frequency. Thus, the inverters control the power through the frequency, which deviates from the behavior of the utility grid, whereas the frequency is also used to control the balance between produced and consumed energies, but, due to the higher scale of the system, frequency deviations are not as frequent nor as higher as the ones observed in the microgrid under analysis.

As stated earlier (chapter 2.1) the validation of CVR benefits may be performed through CVR factor (sensitivity of load to voltage change, i.e., capacity that the load has to change its power consumed by changing the voltage on it), which is mainly decided by load composition. The factors that influence directly the CVR factor are the voltage and power consumed. By analyzing the data collected (with the use of PEL) during the tests, the power consumed by the loads over time were obtained, as presented in Fig. 22.

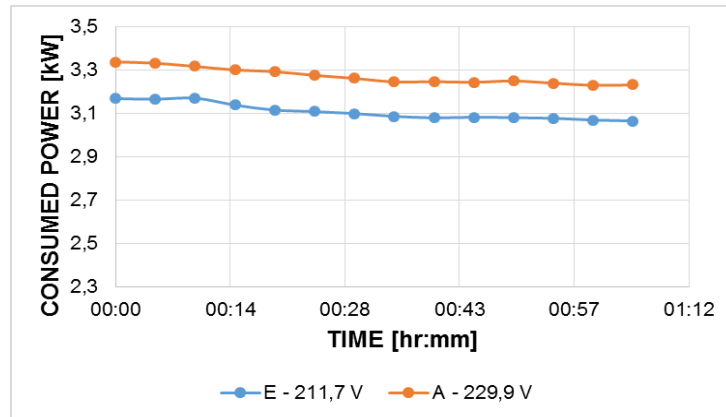


Fig. 22a – Consumed Power, parallel A vs E

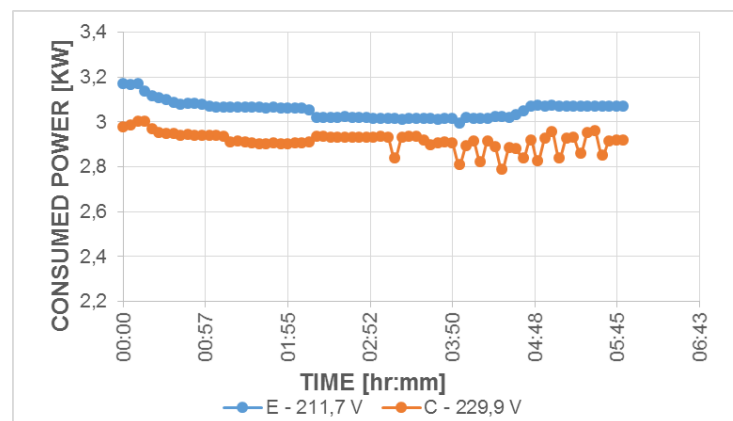


Fig. 22b – Consumed Power, parallel C vs E

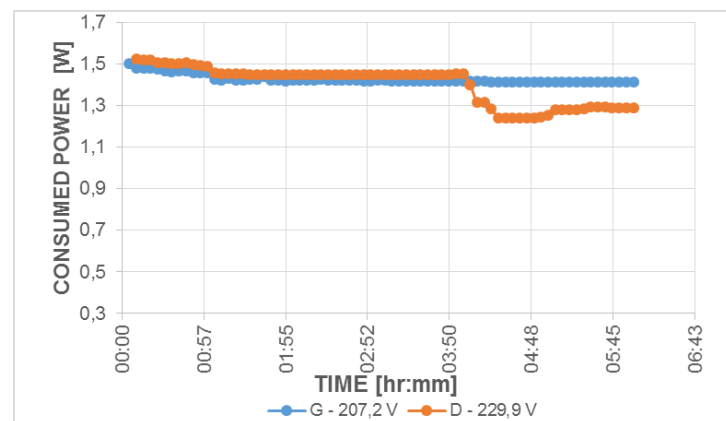


Fig. 22c – Consumed Power, parallel D vs G

The figures above show 3 different situations, first (Fig. 22a) a reduction of the power consumed occurs when the applied voltage decreases. Second (Fig. 22b) the power consumed under a voltage of 230 V (C – LOAD) is lesser than 210 V (E – LOAD), third (Fig. 22c) until complete 4 hours of the test, the experiment behaves as the first one, and then, a sudden reduction of the power consumed occurs.

In order to further analyze this behavior, it was verified by data processing that the non-maintenance of the frequency in a range close to the ideal ($50 \text{ Hz} \pm 0,5$) may have interfered in the power of the loads as shown in Fig. 23.

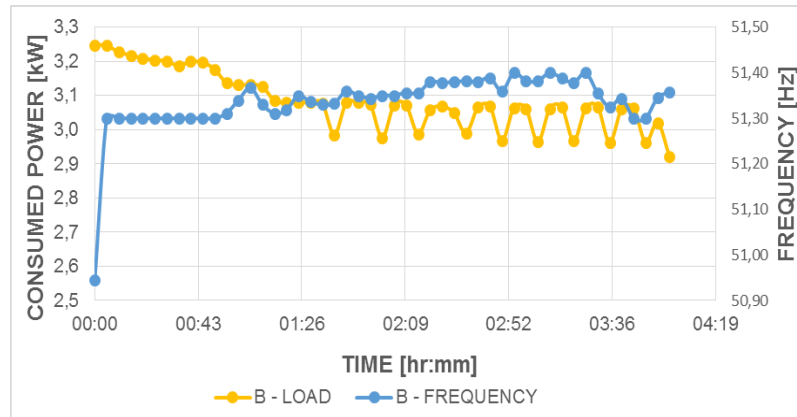


Fig. 23a - Case B: Consumed Power vs Frequency

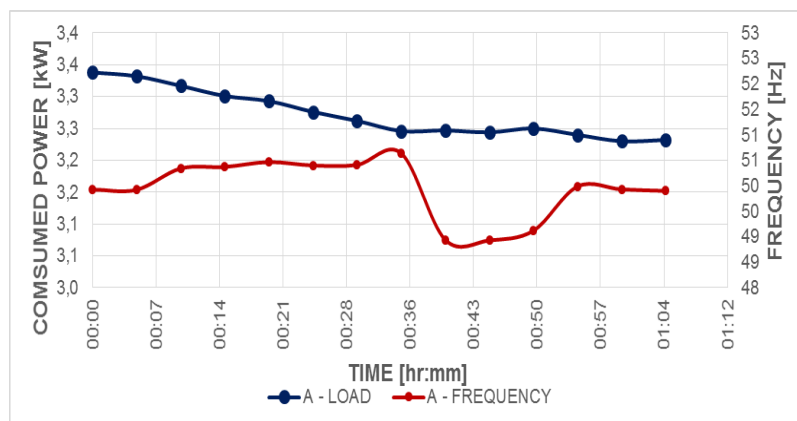


Fig. 23b - Case A: Consumed Power vs Frequency

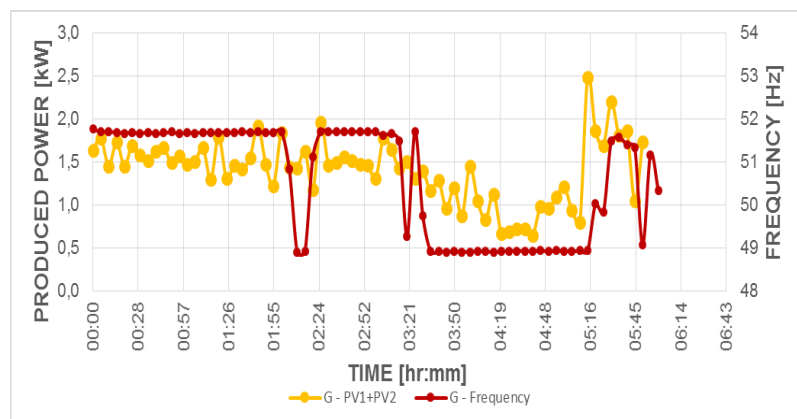


Fig. 23c - Case G: Consumed Power vs Frequency

In Fig.23a there was great variation of the frequency and power consumed in a large time span. In the next Figure (Fig 23b) it is noted that when a frequency reduction occurs (00:30 hours) the power consumed rises. In “G” case (Fig. 23c) the frequency decrease at 03:25 hours and the consumed power it’s reduced.

Analyzing these results it is evident that the behavior of power consumed as a function of frequency is not linear, and this conclusion leads us to consider that it is not possible to calculate f_{CVR} by the traditional methods and applied by calculations in the public networks explained by [15], [19].

It is necessary to keep the frequency constant and equal to its nominal value for some reasons. For example, the performance of most industrial AC motors is a function of frequency; nominal frequency is also required by noble loads, such as computers. But the most important reason is the fact that it's an indicator that the active power balance is being properly performed. In other words, the active power supplied by the system sources is equal to the active power requested by the loads.

Combining these factors it is necessary to look for new ways of evaluating the CVR technique on microgrids decoupled from the public network. Besides that, it explains why the values obtained from f_{CVR} , presented in Table 9, varies from tests to tests, by varying the energy produced by the sources, and are even negative, which indicates that there is no energy saving by lowering the voltage, due to the load variation with frequency.

TABLE 9 – CVR factors

Case studies	CVR factor (f_{CVR})
B (229,9 V) vs E (211 V)	0,121
C (229,9 V) vs E (211 V)	-0,595
A (229,9 V) vs E (211 V)	0,630
C (229,9 V) vs F (211 V)	-0,189
D (230 V) vs G (207 V)	-0,181
A (229,9 V) vs F (211 V)	0,956

The case studies shown in the table are the comparisons made between the tests of the nominal mains voltage and the reduced voltage to obtain the f_{CVR} , the letters (from A to F) are how each experiment was defined as previously explained.

It was expected that in all case studies the power consumed by the loads when reducing the voltage will always be lower as shown in the state of art. When the f_{CVR} is negative it indicates that there was no energy saving.

The classical formulation on the evaluation of CVR, specifically the CVR factor, f_{CVR} , cannot be applied to a microgrid such as the one under study, i.e., very low power and only depending in energy sources which have an intermittent character, such as photovoltaic energy sources. The variation of the power consumed is highly dependent on the voltage but also on the frequency of the microgrid, when in isolated mode. Since the frequency varies considerably in order to maintain the energy balance, it is not possible to evaluate the dependency of the power consumed on the supply voltage in the same way as it is applied to public networks, whereas, due to the inertia, the higher scale and control methodology, the frequency do not vary in the same extent as observed in this microgrid.

5 CONCLUSION AND FUTURE WORK

This chapter is intended to resume the content of the work documented in this dissertation, emphasizing the main points, ending with a vision and proposals for future work.

5.1 CONCLUSION

In this work it has been presented a brief analysis of the energy scenario, technologies that increase efficiency and aim to reduce the demand for energy. It has been also presented a panorama of distributed generation leading to the microgrid concept and the CVR method applied to the public network and microgrids. In order to reach the objectives, an investigation was carried out on different CVR techniques.

In chapter 2, the main aspects related to CVR application and characteristics are presented through some examples of CVR implementation. The main focus of his work was the analysis of CVR techniques and their effects on microgrids. Chapter 3 contextualized microgrids, distributed generation and introduced the smart grid concept. The experimental analysis is presented on chapter 4, which includes the methodology, the results and discussion of the CVR technique applied to a microgrid.

The CVR method was successfully implanted on IPB microgrid, the loads operated at nominal voltage and reduced voltage. In order to analyse the energy savings the CVR factors, f_{CVR} , were calculated and the obtained values were compared to those obtained in studies of public networks. The energy savings cannot be verified due to non-maintenance of frequencies near 50 Hz, because the frequency depends on the balance between the power consumed, produced and the storage system (batteries).

It can be concluded that the traditional methods for evaluating the CVR technique, based on CVR factors, f_{CVR} , do not address the savings in microgrids, whose sources are controlled through frequency variations implemented by the inverters connected to the PV sources and the main bi-directional inverter.

Due to the complex algorithms involved in the control of the energy balance between the production, storage and consumption in a microgrid with Intermittent renewables, which is mainly performed through frequency control, the energy consumption varies with voltage and also with frequency, which do not allow the translation of CVR advantages and evaluation techniques already validated in public grids to small microgrids.

The fact that reduction voltage conservation led to an increase of the power consumption as verified in some case studies of the experimental tests, demonstrated the above.

5.2 FUTURE WORKS

VERCAMPUS is always looking for innovations and improvements in the field of renewable energies and energy efficient use, so future work can be developed by improving this work by searching for other methods to evaluate the possible advantages of CVR techniques in microgrids, and to integrate CVR methodology in the control algorithms of microgrids.

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