UNIVERSITY OF THESSALY
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

DIPLOMA THESIS

with title:

" Synchronization of Wind Turbines on a Microgrid with PLL methods"

"Συγχρονισμος Ανεμογεννητριών σε ενα Μικροδίκτυο με μεθόδους PLL"

Author:
Kosmas Makridis

Head Supervisor
Dr. Leuteris Tsoukalas

Second Supervisor
Dr. Fotios Plessas

VOLOS 2017

UNIVERSITY OF THESSALY
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

"Synchronization of Wind Turbines on a Microgrid with PLL methods"

"Συγχρονισμος Ανεμογεννητριών σε ενα Μικροδίκτυο με μεθόδους PLL"

By
Kosmas Makridis

Graduate Thesis for the degree of
Diploma of Science in Electrical & Computer Engineering

Approved by the two-member inquiry committee at ______

Head Supervisor
Dr. Leuteris Tsoukalas

Second Supervisor
Dr. Fotios Plessas

Diploma thesis in Electrical & Computer Engineering for the graduate degree of Diploma of Science in Electrical & Computer Engineering, at the University of Thessaly, Department of Electrical & Computer Engineering, Volos Greece.

....

Kosmas Makridis

Electrical & Computer Engineer, University of Thessaly

To my family and my friends

Acknowledgements

Foremost, I would like to express my sincere gratitude to my advisors and mentors professor Dr. Leuteris Tsoukalas and Dr. Fotios Plessas for the motivation, the immense knowledge and the continuous support on my postgraduate studies in electrical and computer engineering. Their guidance and our excellent corporation during these 5 years, not only helped me to complete my studies in the most efficient way, but also motivated me to choose my own technical fields of RF Engineering and Power Engineering.

I could not also forget, to express my sincere thanks to the rest of my professors, cooperators and friends for their support, assistance and patience the whole time.

Last but not least, I would like to thank my family for their invaluable support all these difficult academic years and in my life in general.

Contents

List of Figures

List of Acronyms

RES - Renewable Energy Sources
DG - Distributed Generation
SG - Smart Grid
MG - Micro Grid
DER - Distributed Generator
PCC - Point of Common Coupling
MGCC - Microgrid central controller
SCADA - Supervisory control and data acquisition
MS - Micro Sources
LC - Load Controller
MC - Micro Source Controller
PLL - Phase-locked Loop
VCO - Voltage Controlled Oscillator
PD - Phase Detector
PFD - Phase Frequency Detector
LF - Loop Filter
TSO - TSO Transmission System Operator
EMS - Energy Management Systems
CHP - Combined Heat & Power
MAS - Microgrid multi-agent system
FACT - Flexible AC transmission systems
WT - Wind Turbine
HAWT - Horizontal axis Wind Turbine
VAWT - Vertical axis Wind Turbine
CSI - Current source inverter controller
VSI - Voltage source inverter controller
MEM - Microgrid Energy Manager
GSC - Grid Synchronizing Controller

ΠΕΡΙΛΗΨΗ

Όσο αυξάνονται οι παγκόσμιες ενεργειακές απαιτήσεις και προστίθονται όλο και περισσότερες παραγωγές, πάροχοι και φορτία στο δίκτυο ηλεκτρικής ενέργειας, νέες αποδοτικότερες μέθοδοι διαχείρησης τόσο της παραγωγής όσο και της ζήτησης, καθίστανται απαραίτητες, φαινόμενο το οποίο οδηγεί όλο και πιο δυναμικά σε μια πιο καταναναμημένη παραγωγή και μεταφορά της ηλεκτρικής ενέργειας. Η κεντρικοποιημενη παραγωγή μεγάλων ποσών ενέργειας παραγκονίζεται απο μια διεσπαρμένη παραγωγή, σαφώς μικρότερης ενεργειακής απόδοσης και ισχύς αλλα αφετέρου πολύ πιο φιλικής προς το περιβάλλον καθώς βασίζεται κατά το πλήστον σε ανανεώσιμες πηγές ενέργειας.

Στα πλάισια αυτών των δραματικών αλλαγών μια νέα αρχιτεκτονική δικτύων αυτή των Έξυπων Δικτύων, αποτελόυμενα απο επιμέρους αυτοελεγχομένα Μικροδίκτυα, αφήνει πίσω της το παραδοσιακό ιεραρχικό μοντέλο παραγωγής και μεταφοράς ενέργειας.

Παρόλο αυτά, όπως κάθε τεχνολογική εξέλιξη, αυτή η αλλαγή δημιουργεί μεγάλες προκλήσεις τόσο στον σχεδιασμό όσο και στον έλεγχο τέτοιων συστημάτων. Ειδικότερα, λαμβάνοντας υπόψην την διακοπτόμενη φύση των εναλλακτικών πηγών ενέργειας, η μεγαλύτερη πρόκληση έγκειται στη διατήρηση της ευστάθεις τέτοιων συστημάτων, αποφεύγοντας διαταραχές τόσο της τάσης όσο και της συχνότητας.

Στην παρούσα εργασία, αναλύονται οι πιο συνηθισμένοι μέθοδοι και συτήματα συγχρονισμού ανεμογεννητριών μέσα σε Μίκροδικτυα, αφου προηγηθεί μια ουσιαστική μελέτη στις δομές τόσο του παραδοσιακόυ όσο και των νέων δικτύων ενέργειας. Για την τελική ανάλυση, επιλέχθηκαν ανεμογεννήτριες και μέθοδοι συγχρονισμού PLL, καθώς το μεγαλύτερο ποσοστό εγκατεστημένης ισχύς ανανεώσιμων πηγών ενέργειας προέρχεται απο ανεμογεννήτριες, ενώ οσον αφορά τους PLL, κατα κόρον τα συστήματα χρησιμοποιούν την παρακάτω μέθοδο για την ανίχνευση και τον συγχρονισμό των συχνοτήτων.

CHAPTER 1

INTRODUCTION

Since Industrial Revolution the basic energy supplier of the worldwide industry and economy has been fossil fuel. Conventional energy sources based on oil, coal and natural gas have proved to be highly effective drivers of economic and most importantly technological progress. However, since these traditional energy sources are considered one of the main causes of environmental problems and a major threat to human health and quality of life, the research on greener and safer power generation resources become more than necessary. Moreover the continuous increase of global population and the tremendous technological improvement creates a more electrical power based society, with the energy demands growing rapidly day by day [1].

These economic, social and environmental incentives are changing the face of electricity generation and transmission leading to a new age for energy generation industry based on more flexible and more environmentally friendly, renewable sources [2] (consider for instance the Kyoto Protocol [3]). Several researches and studies have taken place and several articles have published the past years [4][5][6], analyzing the potential of clean energy technologies. Biomass, wind, solar hydropower can meet many times the worlds energy demand with the effectively one the wind energy [7]. In the past decades many countries globally formed a political strategy which is aiming at fast development of wind technology considering the wind energy both as widely available and as a zero pollution one. In European nations in recent years, there has also been a big transition to renewable energy sources, supported by political and economic strategies, which all have the same goal: to build a new innovative renewable energy system. In the same direction, Greece has managed to increase by 500% the wind capacity energy, exploiting the remarkable wind resources, the climate and the geomorphology of Greece [8].

On the other hand, the increased penetration of renewable energy sources generation plants (like wind farms) encourages the emergence of distributed generation. Distributed Generation is the new modern industrial trend to store and generate electricity power by a variety of small power plants and small power stations, typically plants based on renewable energy sources [9]. Centralized generating facilities are giving way to smaller more distributed generation, creating more and more separate grids operating in parallel to the main grid.

Due to that fact, more restrictive standards for both voltage and frequency are requested in order to ensure a proper operation of the whole grid network and avoid temporary or even worst permanent failures on the grid (e.g. damage on plants, transformers or transition lines). The problem is that in contrast to conventional generation stations, the availability of renewable energy sources has strong daily and seasonal patterns. Plants like wind farms do not operate at a fixed point [9], but instant power, voltage and frequency fluctuate according to the speed of the wind produced by the turbine's propeller (speed of wind). As a consequence an instant (over a specified fixed value) divergence from standard values of the main grid would lead to an unsynchronized micro grid. In a problematic situation like that, the continuously uncontrolled power would inject to the grid, leading to main grid instability and even worse to a failure or even a black out, unable to satisfy the customers energy demands [10].

For this reason, live time controllability, stability management and synchronization is one of the most important challenges in micro grid analysis, requiring a quick and accurate frequency, voltage, current synchronizing between grid-power plant [10].

Much research has been done in how stability in such systems can be ensured through grid generation plant synchronization. Despite that, among the numerous published works there are only few studies which specifically focus on micro grid synchronization and could be categorized, according to the proposed method, to mathematical analysis methods and Phase Locked Loop (PLL) algorithms.

Mathematical analysis methods based on signal processing techniques e.g. Fourier Transform, Hilbert transformation, DFT [11] [12] which are commonly implemented in a digital controller and, thus have a strict requirement of the sampling rate. In contrast, a Phase locked loop synchronization technique or also called PLL is an electronic circuit that used to generate, stabilize, modulate, demodulate, filter or recover a signal. In fact, it takes an input signal with an A-frequency and transformed it to a specified B-frequency signal. They are commonly used in telecommunications and Radio Frequency systems, but the past years there has been a growing trend to use PLL's and PLL algorithms on grid systems for frequency synchronization, or inverter connections.[13]

There are several PLL algorithms and techniques with various characteristics, performance and behavior presented in the literature over past years. One key example is the novel approach in digital implementation of PLL's for grid application by F.D Freijed et al. [14], in which they proposed a notch filter inside the closed PLL loop for better steady state filtering and a low resource consuming voltage control oscillator to optimize the implementation of trigonometric functions. Their project performance has been proved both for single phase and three phase PLL systems, as they present fast transient responses and accurate estimations of phase.

The remaining of this paper is organized as follows. In the following section the transition from traditional power system to smart grid and its potentials are analyzed. Next a brief outline of Renewable Energy Sources and its main generation plants is provided with emphasis on Wind power plants. The analysis continues with Stability factor and Microgrid control examination. In addition, PLL structure and most common grid synchronization methods based on PLL are studied. In the same sphere an ideal PLL using IC565N designed and simulated, and the results are given in the next section. The paper concludes with a discussion of the results, the benefits and the challenges of RES and Microgrids.

CHAPTER 2

REVIEW ON ELECTRIC POWER SYSTEMS

Energy Markets, technological progress and environmental incentives are changing the face of electricity generation, transmission even of consumption. New technologies are arising in energy transmission and new more environmentally friendly and more efficient generation methods are examined, leading to a matter of speech to a new world for energy systems. Although there is no doubt that for many years a powerful electric power system has been established all of the world able to cover the extremely growing energy demands of people of 20th century. In Greece for instance, from the beginning of 20th century, a centralized electric power system based on coal plants has been designed and constructed, following the patters of the technological progress both in USA and Europe [15].

In this section a brief review of electric power grid will be examined, starting with the examination of traditional power system.

SECTION 1

Traditional Power System

Traditionally in the electrical engineering field, the term Electric Power System or Electric Power Grid is used to describe an electric system or an electric power network that is responsible to support one or more of this operations: electricity generation, electricity transmission, electricity distribution and control of power flow and the whole operation [16]. The main and ultimate purpose of this process is to ensure the energy supply (electric or heating energy) of a region or even a whole country. In 20th century and in most cases since now, this power chain has a specific infrastructure and specific characteristics which are based on the following statement. The cost of energy production is inversely proportional to the size of generation plant. According to that fact, traditional energy power systems are centralized and are mainly based on fossil fuels due to their efficiency (the big energy production in small region). Few number of big power plants (size of MWs) can cover the demands of individual customers and big industries of a country [17]. Geographically these plants are being installed in such places that can exploit local energy sources. For example Greece has a centralized power grid based on coal and with the majority of the power plants installed in Western Macedonia, a region with a large stock of minable coal [15].

The core of typical electric power systems consists of a number of power plants, step-up transmission substations, step-down transmission substations, distribution substations and distribution lines. The process is actually the same and can be categorized in the four operations which was outlined above (generation, transmission, distribution) [16]. First stage is the electricity generation: energy generated from the big scaled centralized power plants. Traditional power plants are those based on fossil fuels, coal, gas, nuclear energy and in recent years in more greener energy sources like wind energy, solar or marine energy and biomass. Also there is a growing trend on hydro power and fuel cells. This is the generated energy that will be transferred and distributed to the customers. Although the fact that customers can be distributed in a whole country, far from the power plant, growths the need for long-distanced transmission network. Thus, the next stage of this chain is the transmission of energy.

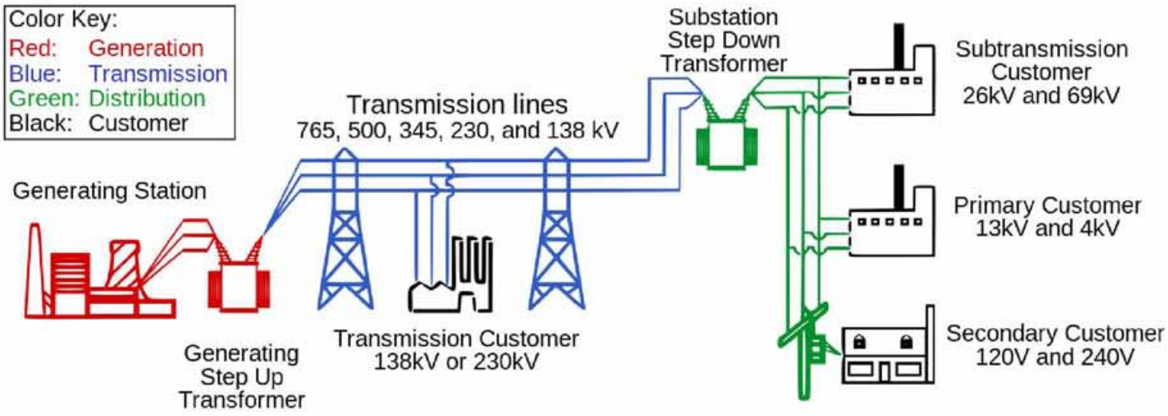


Figure 1. Traditional generation-transmission-distribution chain [1]

The transmission network is responsible to transfer this energy to the pre-distribution network. In contrast with the two other energy transfer systems this grid connect all the power plants and all the hubs with pre-distribution network. It is probably a loop network and manages to handle big amounts of power as it is the backbone of the transfer network. This procedure is done at high values of voltage in order to minimize the losses from the energy transfer. According to the Joule's law, for a standard fixed value of resistance (the resistance of transmission wires) power losses are linearly proportional to voltage but also proportional to the square of the current. Taking consideration and the Ohm's law it is obvious that a double voltage leads to the half current and for this reason to half power. Based on this theory the voltage levels of transmission grid is between 150kV to 400kV. Step-up transmission substations connecting between generators and transmission grid taking charge of step up the voltage at these levels [18].

After many kilometers of wire the energy reach the pre-distribution network. Step-down transmission substation manage to step down voltage levels at 15kV-22kV as the distances in this stage are geographically restricted. The pre-distribution grid not only transfer energy to the distribution network but also supply power to customers with big power needs (e.g. a big industry). Similarly before the connection with the distribution grid there are step-down pre-distribution substations to secure that the voltage level are the desirable ones. The distribution and final stage now is responsible to distribute energy to the final points – the customers. The transmission is restricted two the boards of a city and that explains the low voltage of the transmission. Looking on the graph below, it is obvious that according to the energy demands of the customer there could be a hub on every transfer system. For example an individual energy production industry based on oil can connect to the transmission high voltage system of the main grid to cover its demands or a smaller industry or a campus can connect to the 150kV system [18].

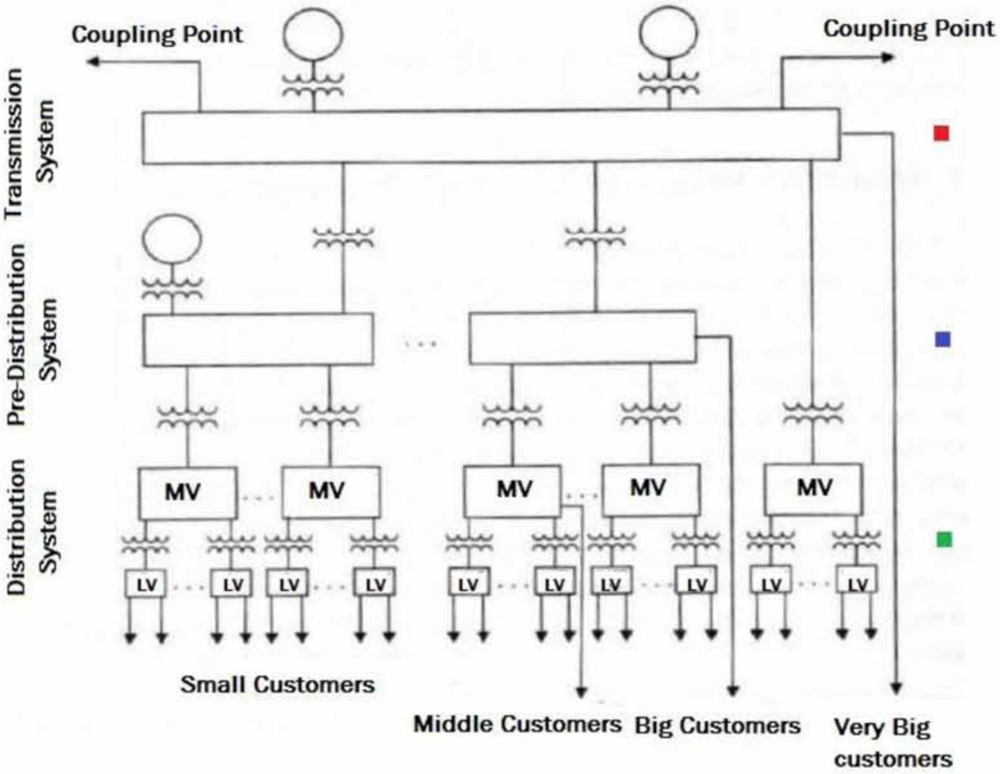


Figure 2. Transmission, pre-distribution, distribution system

In order to make a brief synopsis of the above process we can summarize the above common characteristic of all Electric Power Systems.

- Operation in multiple voltage levels: High Voltage (150kV-400kV), Middle Voltage (15kV-22kV) and Low Voltage (220V – 2kV).
- Generation Process : centralized plants based on efficient sources (gas, fossil fuel, coal, nuclear)
- Transmission System: 150kV-400kV, connects all plants and pre-distribution grid
- Pre-distribution System: 15-22kV, transmission and industries supply
- Distribution System: 220V, customer supply through low voltage distribution
- AC transmission in high voltages at 50~60Hz (for very long distances DC lines can be used –HVDC)

The fourth and one of the most critical operations in a typical electric power system is the control of the above process. The power transmission from the early generation to the final consumption point supervised by the Transmission System Operator (TSO). The main duty of a TSO is to ensure the reliable and specified operation of the whole grid. For this reason the installation of a proper supervising and data collection system is crucial. SCADA – Supervisory Control and Data Acquisition System [19] is the most used system in power grid control and is responsible to collect data from sensors installed in the whole chain of transmission, process this data and present results through a human interface. Fault detection, energy flow, outages, natural disasters in equipment can not only be detected but also predicted. Last decades Energy Management Systems (EMS) [19] are also installed parallel to SCADA systems. These systems predict energy demand curves through the data from SCADA but also from saved data from past similar states of the grid. Last but not least there are circuit breakers distributed in the whole grid which they check the continuous flow of energy on the grid, able to detect faults and disconnect wires.

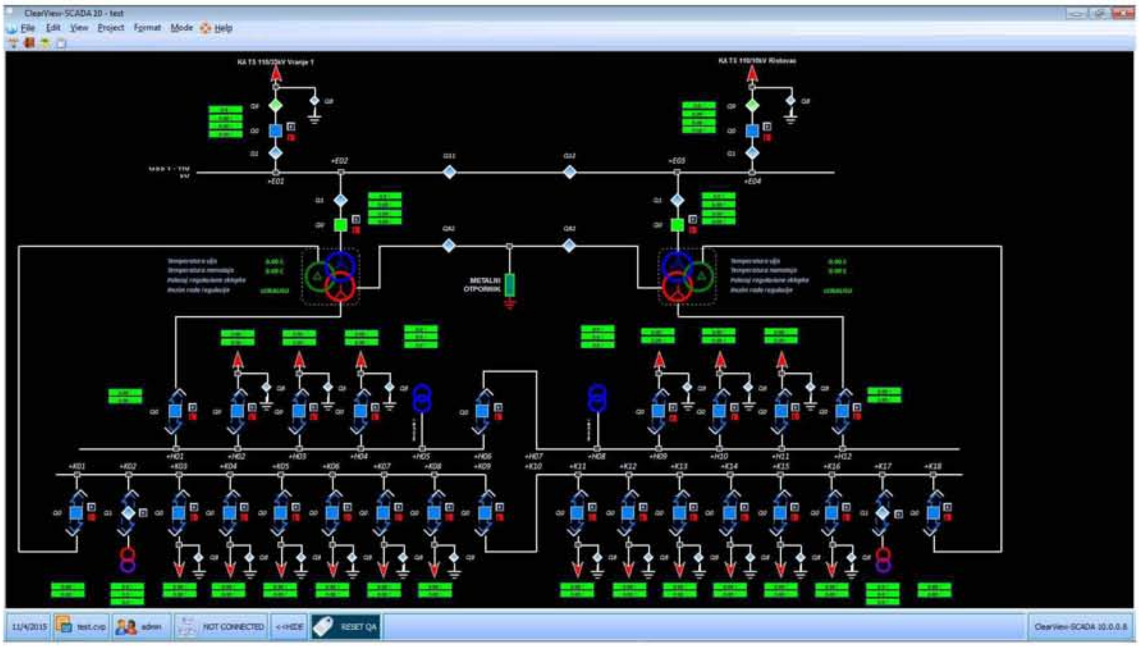


Figure 3. SCADA system human interface [2]

Taking under consideration the above study, it is obvious that it is very difficult and complex to expand the infrastructure of such centralized power grids, as the whole chain in every level must be examined and reconfigured. In fact, and electrical grid in such a huge scale has planned to operate for almost 100 years. Below a summary of the main parameters under examination for a new generation plant are provided:

- Power System efficiency
- Steady-State voltage fluctuations
- Transient voltage fluctuations
- Flicker & Harmonics
- Short circuit current fluctuations
- Implications in TSO operation

SECTION 2

Distributed Generation

A system similar to that described above seems to be able to cover the power demands of whole countries with minimum faults or losses. Although past two decades many factors tend to change the face of electric power systems from scratch [2]. There is no doubt that the global energy consumption growths continuously, and the customer's need for better power quality of electric energy is unsatisfied. The traditional system of 20th century cannot meet the demands of customers and new power plants are designed and installed to the main grid. PV's, wind farms, power plants based on biomass are some of the examples of such plants. In addition to that environmental incentives for cleaner and "greener" energy production forcing governments to minimize CO2 emissions by installing greener power plants (Kyoto protocol is a great example of this state).

All this factors leading to a new trend in grid industry. Centralized power plants are giving way to distributed power sources with smaller capability but with many potentials [2].

A definition for Distributed Generation can be summarized as the process of generate and transfer electricity locally in small scale and geographically distributed. In contrast to big centralized power plants distributed generators are probably small scale independent energy producers (1kW ~ 40MW) which they are locally near to customers that will serve, and mainly owned by individuals [20]. The generation plants are mainly based on renewable energy sources and this is one of the main reasons of the distribution itself as the energy stocks of such sources are commonly distributed in certain regions of a country. Although the distribution may be mandatory not only for the character of the plant, but also for the profile of the customer that will supply. Remote, of-grid regions, like islands or rough villages in mountains cannot connect to the main grid for economic and complexity reasons. In such cases distributed generators is the best and economical solution for the customer but also for the grid itself. Last but not least distributed generators can also operate parallel to a weak grid with many outages and faults as an emergency one.

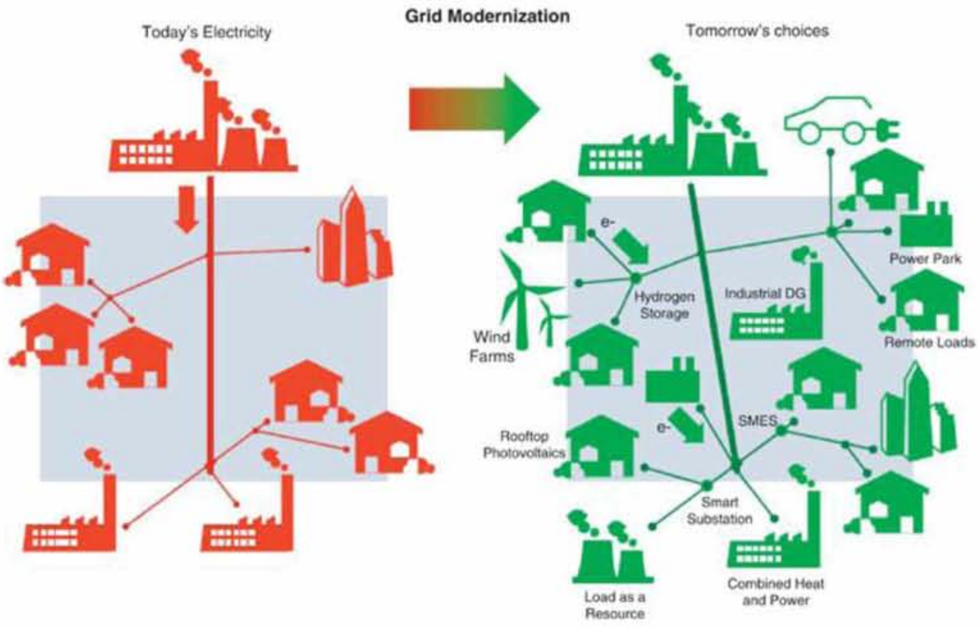


Figure 4. Today's electricity vs tomorrow's electricity [3]

Distributed generators (DERs) can be divided into two categories according to its plants: Conventional type DERs and Renewable Energy Sources based DERs. It is now obvious that the Distributed Generator character is entirely based to the region's local energy sources that will serve. Below the most common generators of these two categories are provided [21].

CONVENTIONAL TYPE	RES BASED TYPE
Micro turbines	Wind farms
Diesel Engines	PVs (solar)
Steam or gas Generators	Hybrid systems
Stirling Generators	Biomass plants
Fuel Cells	Marine Technology

Furthermore, Distributed Generators can also be categorized according to the deliverable power as follows [21]:

- Very Small Scale : 1~5kW
- Small Scale : 5kW~5MW
- Normal Scale: 5MW~50MW
- Big Scale: >50MW

ABSTRACT

Global energy demands are growing rapidly with customers of 21th century demand more and more power quality from energy suppliers. Numerous generators, power supplies and loads are connecting on the utility grid making the management and the supervisory of it more complex and the whole structure more vulnerable and unsecure. In this sphere, new, more efficient management methods not only for the generation side but also for the customer side are arising, methods that also lead inevitably to a more distributed energy generation and transmission. Centralized big-scale plants, are being replaced by distributed generators, maybe with lower efficiency but on the other hand more ecological friendly, as they are probably based on renewable energy sources.

In the same frame, modern grids instead of the traditional ones are arising also called Smart Grids, which are mainly consists of self-healed, sub-grids the Micro Grids. Although, as any other technological progress, this change on the generation's and transmission's electricity face, arise many challenges not only on the design but also on the controllability of such a system. In addition, the intermittent nature of renewable energy sources brings the most crucial challenge of synchronization and stability of the power system, a system able to avoid and protect itself from fluctuations, disturbances and errors.

In this thesis, the typical most used synchronization methods for Wind Turbines in a Microgrid are analyzed, after a brief study of the traditional and modern power system. The analysis focuses especially in PLL methods and wind turbines, due to the big installed capacity of wind energy globally, and due to the fact that PLL is a state of art for synchronization methods on grid.

KEYWORDS: Microgrid, Smart Grid, Phase-Locked Loop, Wind Turbine, Renewable Energy Sources, Stability, Grid Synchronization

The majority of DERs although is actually based on sources like wind or sun energy and for that reason one of the biggest challenge that a Distributed Generation System must overcome is the continuously fluctuation of such generation plants in addition to randomness. Systems like them are extremely depend on weather conditions. Not only fluctuations on the output voltage and frequency cannot be stopped, but also output power cannot be predicted or estimated. Theses fluctuations can cause static voltage stability due to the increase of reactive power, or even voltage harmonics and flicker.

Hopefully this challenge has partially overcome by the parallel progress in electronics technology, and storage devices. Power electronics and especially inverters are electronic circuits based on semiconductor's technology and their main task is to regulate currents and voltages. Typically in power grid systems dc/ac inverters are used on generation plants before the connection with the substations. In addition, storage devices parallel to distributed generators, manage to store the surplus of the deliverable power of the plant or to cover the energy demands in conditions where the power balance between energy production and energy consumption is lost.

Furthermore, taking advantage of the locality of Distributed Generation, such a system can also supply local customers with heat energy except electricity. In the procedure of energy production two thirds of energy are wasted as heat. In a Combined Heat and Power (CHP) system except of producing electricity, hear recovery devices capture the wasted heat energy from the turbine and convert it to useful thermal energy [22]. As the DER is close to consumer, CHP systems can also cover the thermal demands of them (e.g. a whole city or a big customer like a Hospital).

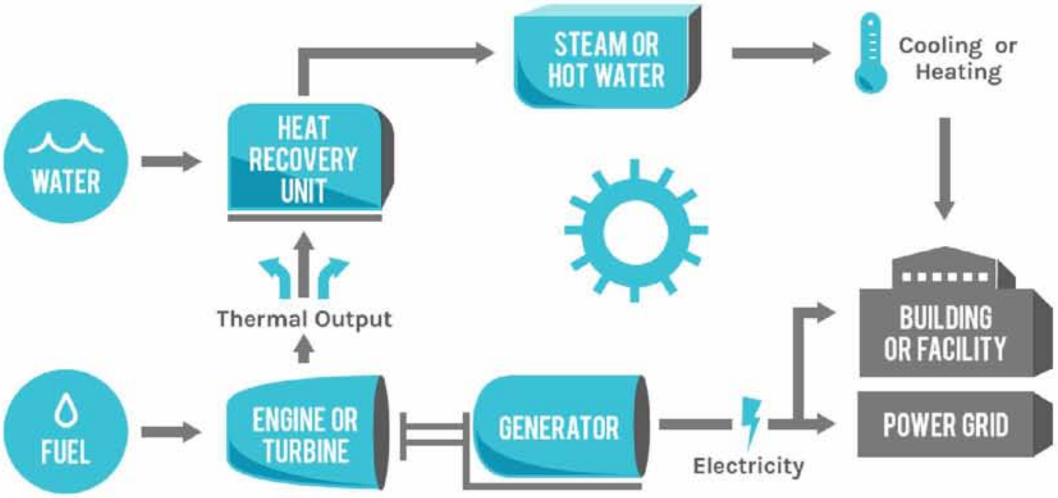


Figure 5. Combined Heat and Power schematic [4]

Through the above examination there is no deny that they are plenty of major differences between centralized generation and distributed generation. Below an outline of these differences is provided:

- From big scale production to small scale (size of KWs)
- From long transmission two locally placed generation near customer
- From conventional plants to environmentally friendly ones
- From one direction power flow from central generation plants to customers narrow down, to bidirectional current flow from distributed generators to the main utility grid. This phenomenon caused due to the fact that DERs are connected on medium or low voltage system in contrast with classic centralized plants.
- Generators can become energy consumers or energy producers according to the need of the utility grid.
- From public corporation industries to individual ownership due to the energy markets

Actual and expected distributed generation challenges have been analyzed by various authors. The following paragraphs summarize the related benefits and implications of DERs against Traditional Generation and Transmission:

Advantages:

- DERs are basically based on Renewable Energy Sources so eco2 emissions are extremely eliminated.
- Countries economic strategies become more independent of a specific energy source (e.g. fossil fuels with restrict supplies) due to the various power sources that used to generate electricity.
- Price of energy is reduced also due to the above reason.
- Power losses from wires in transmission and distribution lines are minimized as generator plants placed near to consumers and less wires are needed. Up to 7.5 % are the transmission losses [17].
- Additional economic benefit are secured due to the above factor.
- Higher performance and more reliable power system is ensured through optional generation supply.
- Utility grid enhance its security as DGs can be used for emergency circumstances (outages in base generator plants).
- Distributed Generators offer the ensuring the stability of power system in "black start". Black start [23], is the ability of a generation plant to go from deactivate mode to operational mode, and generate electricity without any extra energy from the main grid. This is very helpful in states after faults, outages or reconfiguration.

- Better power quality in regions where voltage fluctuations and harmonics are dominant.
- DERs can cover power demands of of-grid regions where main utility grid was unable.
- Reduction of overload in transmission lines.
- Efficiency growth via Combined Heat and Power Systems [23].

Disadvantages:

- High total cost of distributed generation in contrast with cost/kW in centralized plants [17].
- Lack of custom engineering
- Lack of plug and play characteristic in traditional grid. Without any extra reconfiguration of traditional grid it is impossible to connect and disconnect distributed generators on the utility grid and overcome disturbances.
- Installation of new transmission lines and distribution lines. In classical transmission and distribution grid there is one direction flow of current and power, so it is unable to serve the bidirectional needs which created by the connection of distributed generators on other voltage levels than high voltage of 400kV.
- Change to voltage levels of utility grid causing voltage fluctuations.
- In high voltages resistance value of wires are small in contrast with small voltages where the wires have high value of resistance. Despite of that, by connecting a distributed generator in distribution grid (with low voltage levels) will produce high voltage drops and high contribution currents in fault current.

SECTION 3

MICROGRID

Under brief examination and bearing in mind the above study, there is no deny that distributed generation has a lot of emerging potentials and benefits to offer to the society at many aspects of life (ecological, economical, power quality, safety etc.). Many efforts and much research has taken place last decades, knowing that the only way for fully penetration of Renewable Energy Sources in power generation, demands crucial changes in the energy production chain and the grid itself, as the traditional power system is unable to cover smart energy goals and the challenges of DERs of 21th century.

In this sphere, a new subsystem has reemerged in the power systems field, the Microgrid. Even though it seems to be something innovative and new for 21th century, Microgrid was the first and only type of power grid in the early steps of power systems and energy transmission. In the very begging of electrification, Micro grids supply locally distributed regions and the energy production based on local energy supplies. Except from the lack of proper network, the restricted DC transmission forbade transmission and distribution in long distances (and the extension of the grid) as the transmission losses are prohibitive. Later, economic benefits, AC transmission technology and large power plants lead to the typical centralized power system infrastructures.

Coming closer, micro grids are part of the typical grid for years [24]. Decades now, remote sites where utility grid support and service is a forbidden option regarding economic cost, micro grids was installed in order to cover locally energy demands. Furthermore, one not so recognizable type of micro grid, even though it's fully interconnected to the main grid, is combined heat and power system (CHP). Many industrial owners also install their own generators for economic benefits or for emergency conditions in main grid failures.

A Microgrid (MG) is a regionally limited energy system, like a small scale typical electric power grid, operating although as a single controllable system in clearly defined geographical boundaries [25]. In other worlds, an MG is a cluster of distributed generators called Micro Sources (MS), loads (consumers), network assets and in most cases storage devices. In a similar way with a typical power grid, MG's main task is the generation and distribution of energy (both power and heat) to its local area with the most efficient way. It can optimize one or more of the following parameters: power quality, reliability, sustainability, pollution and production cost.

Micro Sources (MS) are small scale generation units (<100kW) with power electronic interfaces [20]. Micro turbines, wind turbines, PV panels, fuel cells, biomass plants are some of the common types of generator plants being used in Micro Grid structure. In fact the new trend, considering the environmental restrictions, is the fully RES based Micro Grids. The common characteristic although of all is the installation on the customer side.

As far as storage devices, except from the conventional energy supply and storage, these devices are necessary for a different reason. When a load or a cluster of loads connect in the grid, the grid itself must ensure the initial energy balance of the system. In traditional centralized power grids with big scale generation plants, this is provided by their inertia. In a Microgrid although, micro sources have probably very small inertia, so an alternative way to secure energy balance must be ensured. Storage devices like batteries, capacitors, super capacitors or a dc bus (especially in island mode where energy is locally supplied) secure the balance.

It was mentioned that the micro grid can stand independently, but there is also a physical connection with the main power grid. For this reason, Microgrid has two different operation conditions: normal interconnected mode and emergency islanded mode.

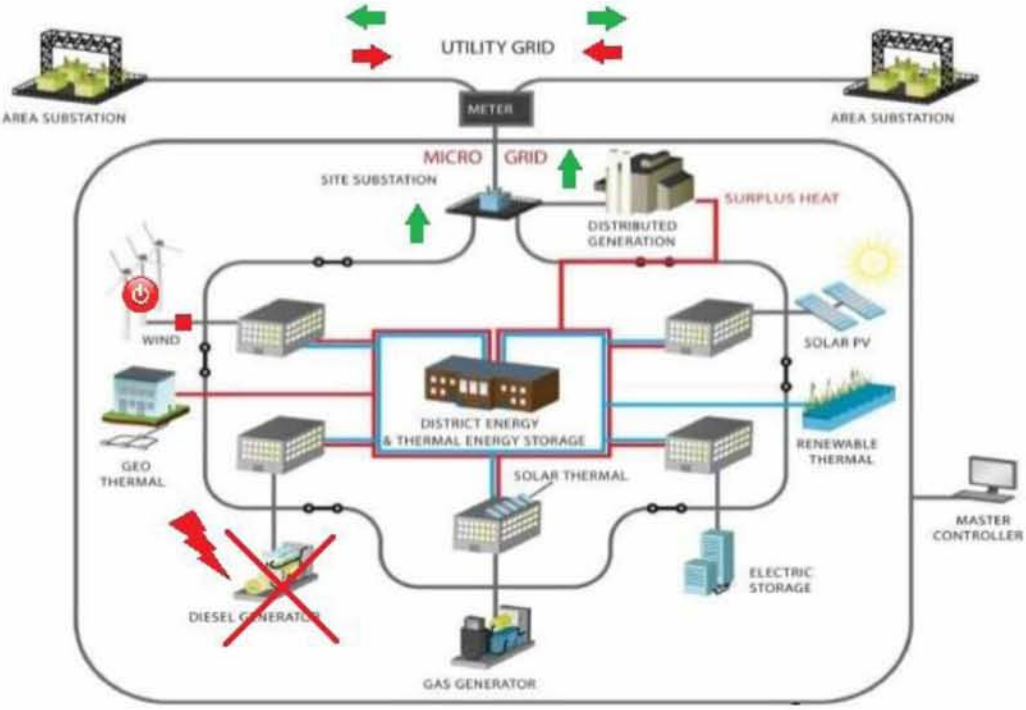


Figure 6. Interconnected Microgrid due to local faults [5]

Interconnected mode:

In grid connected mode, energy can flow through the two systems through a Point of Common Coupling (PCC). In case of a local failure for example or a maintenance of a turbine, micro grid can cover its local energy demands by the main utility grid. On the other hand, in a big outage on the main grid, micro grid can supply with its surplus power the main grid [26]. Additionally, micro grid can work as a balance parameter of reactive power of the power grid when it is necessary, instead of using big costly clusters of capacitors, or synchronous generators.

Although all these function provided above are important, the actual and most important benefit of this connection is different and more crucial nowadays and it is not other than the peak-demand time shifting which will be examined in a following section. In interconnected mode also, many decisions can be taken from intelligent agents and control systems for optimal operation of the grid. Summarizing, as energy flows between two systems, energy balance of active and reactive power, voltage and frequency synchronization must be ensured all period.

Islanded mode:

In emergency conditions, Microgrid can be dispatched from the main grid, through the breaker of PCC and operate independently, supply its local loads by the local Micro Sources. Under an outage or a failure of the main grid on the micro grid's supply line, the MG can be disconnected and cover its local demands independently with Micro Sources. The micro grid plants operate in predefined fixed operation parameters. Storage devices are necessary in this state in order to store or supply energy to the system according to the fluctuations of RES. An alternative way to solve the randomness problem of RES plants is the installation of conventional type generators for emergency conditions like that.

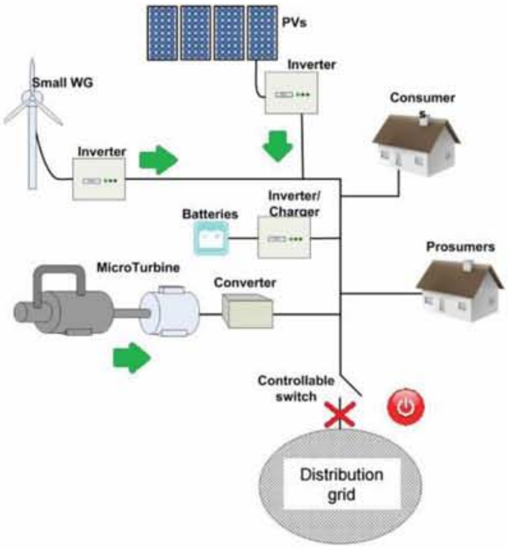


Figure 7. Microgrid in islanded mode due to outage of main grid

According to the customer, the main predefined operation, size and location Micro Grids are categorized in the below types [26]:

a. Institutional and campus microgrids

This system consists of a certain number of buildings so the load is restricted and limited in certain boundaries. Characteristics and expectations may differ according to the type of institution (the need of a college or a university differ from those of a government research center). The example below presents a university campus microgrid based on biomass wind and solar energy. Connection to the utility grid is only for back up reasons as the grid stand alone independently.

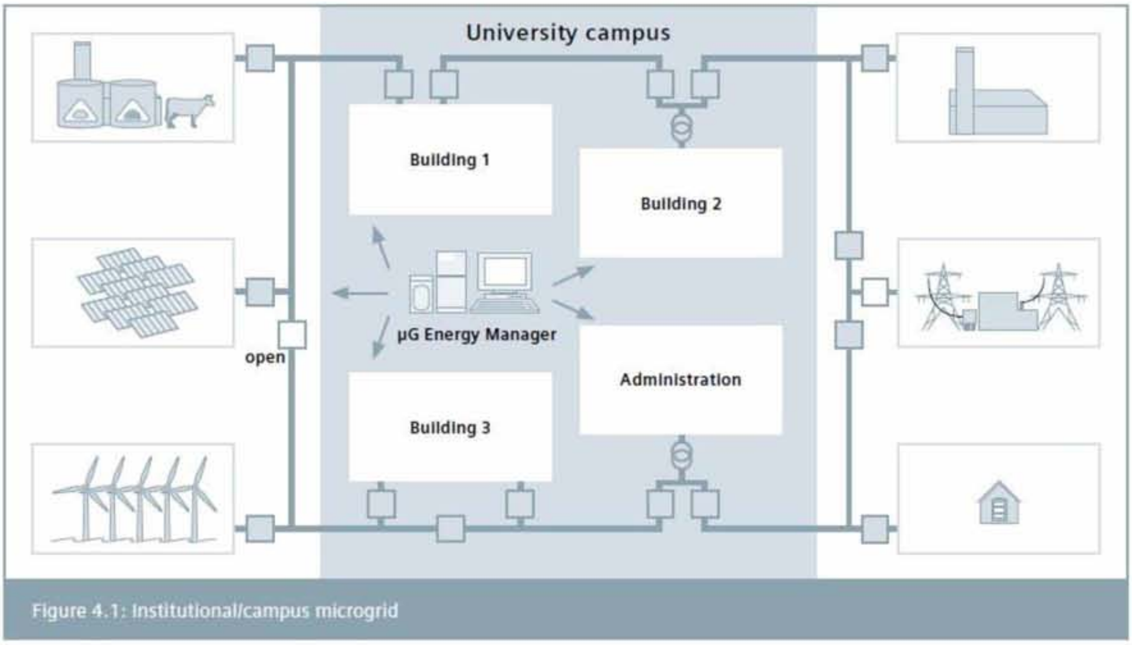


Figure 8. Campus microgrid example structure [6]

b. Commercial & Industrial microgrid

These are probably self-owned systems by industry owners. They are self-supplied systems able to cover the electricity or/and heat demands of a factory. Main drivers for commercial microgrid installation except safety and reliability are economic reasons (the energy cost of an industry can be minimized, especially in countries with high price fuels like Greece), and a weak main utility grid with many outages and faults. Of course, there is a hub with main grid for emergency conditions.

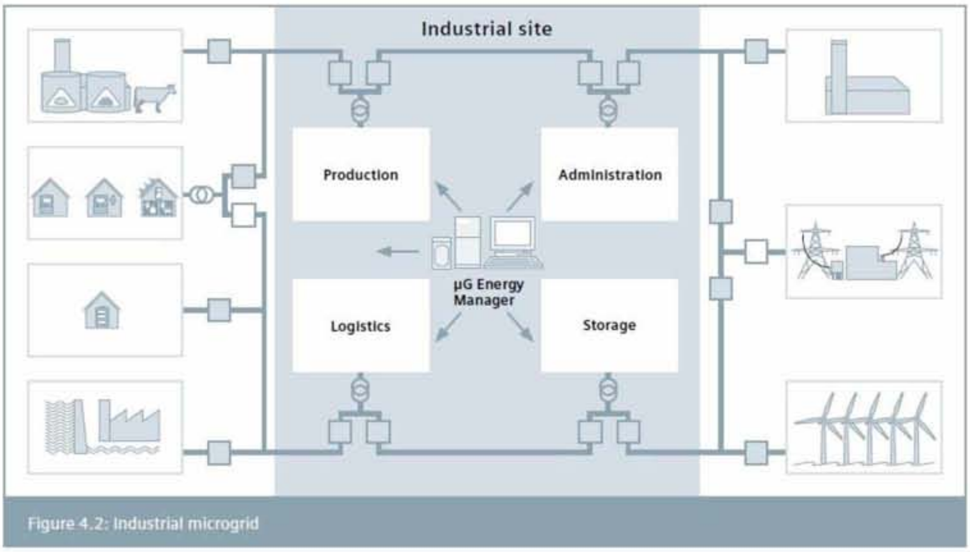


Figure 9. Industrial microgrid example structure [6]

c. Utility and community microgrids

Community microgrids are mainly constructed for private pre-customers, probably in of-site regions, in cases where the main utility service is unacceptable (urban areas, rural communities). Due to profile of the customers and the region most community grids based on biomass plants as there is plenty of local supplies. Instead a utility microgrid is a small scale of transmission system of a typical utility grid. It may include medium and low step-up step-down distribution substations, a distribution feeder and control systems like SCADA in a large area. Main task is the connection and distribution of many local generators and loads within the microgrid.

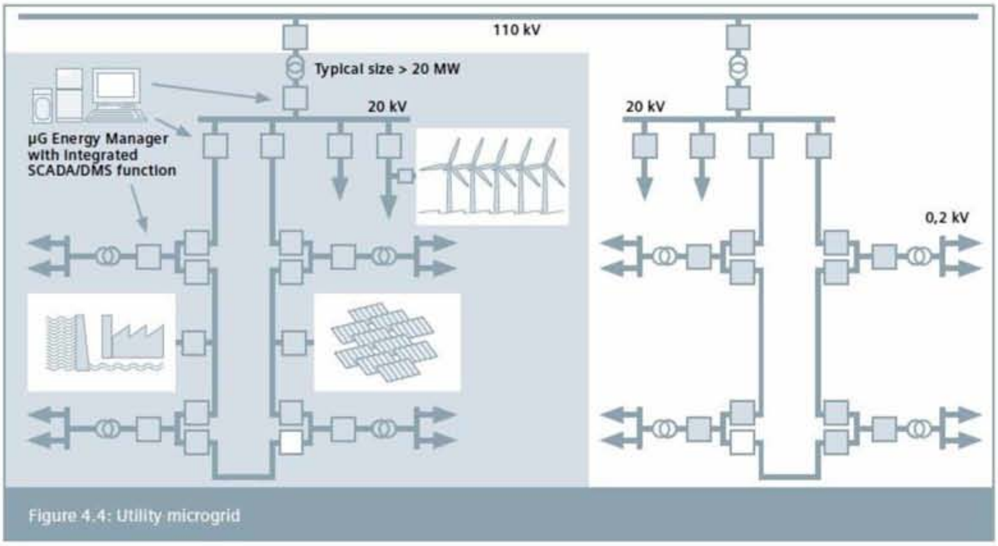


Figure 10. Utility microgrid example [6]

d. Island and off-grid microgrids

The name itself explains the structure of this type of microgrid. They are usually built in areas of-site regions far from main transmission system so there is no any connection with the utility grid. The grid is always in island independent mode and local micro sources cover the local energy and heat needs. It is obvious that storage devices are mandatory to secure not only the energy balance, but also black start of generator plants.

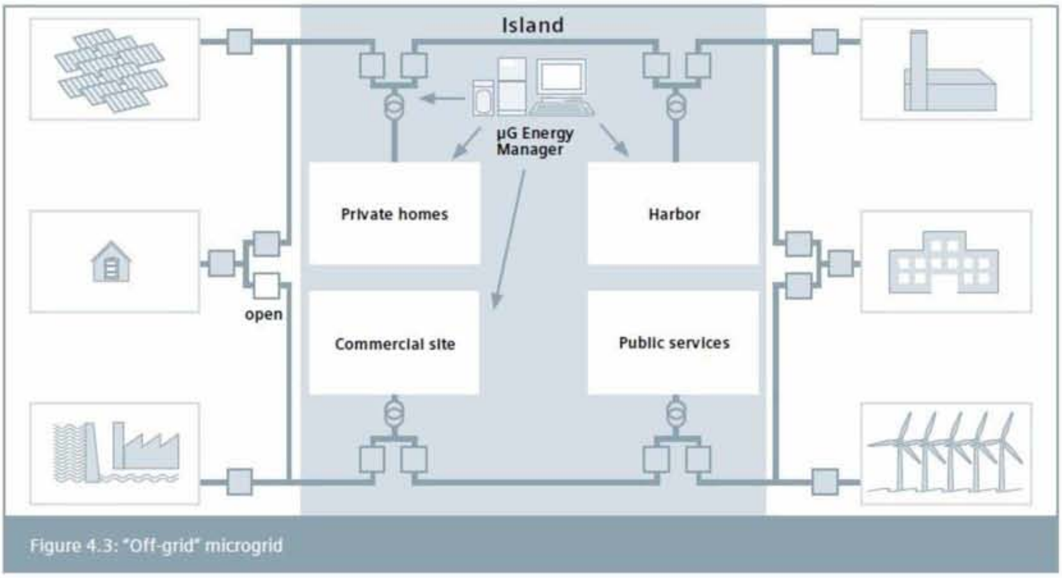


Figure 11. Off-grid Microgrid [6]

e. AC Microgrids

This kind of microgrid is designed to handle alternative current [27]. Inverters and power electronics play major role to theses grids as not only the majority of loads (especially home devices) are operating in DC mode, but also many of the generator plants either cannot generate power in AC, or if they do(e.g. wind turbines) the levels of voltage and frequency must reconfigured before the connection to the grid. So ac/ac or dc/ac inverters are used a lot and this is one of the main drawback of this type of microgrid.

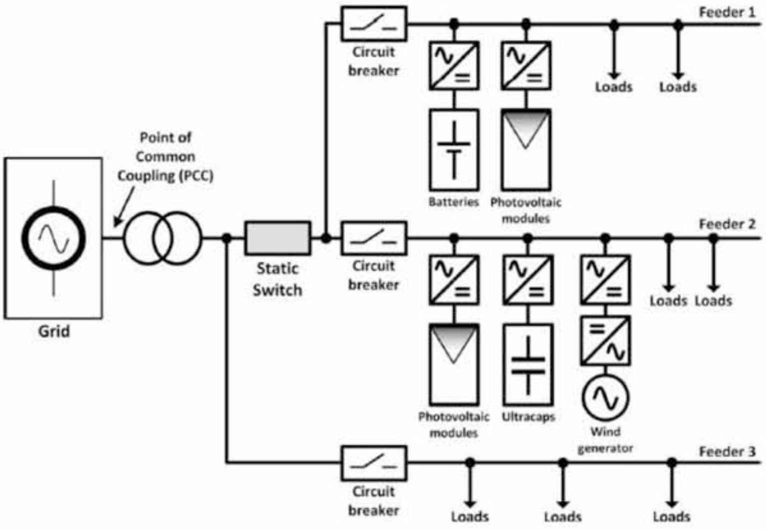


Figure 12. Schematic of an AC Microgrid [7]

f. DC Microgrids

In contrast with AC microgrid, a DC MG supports only direct currents and consists of a DC Bus where the loads and generators are being connected [27]. Again inverters are mandatory in every AC load and AC generator. In addition an ac/dc inverter is needed in the hub with the main utility grid giving much higher quality in the power.

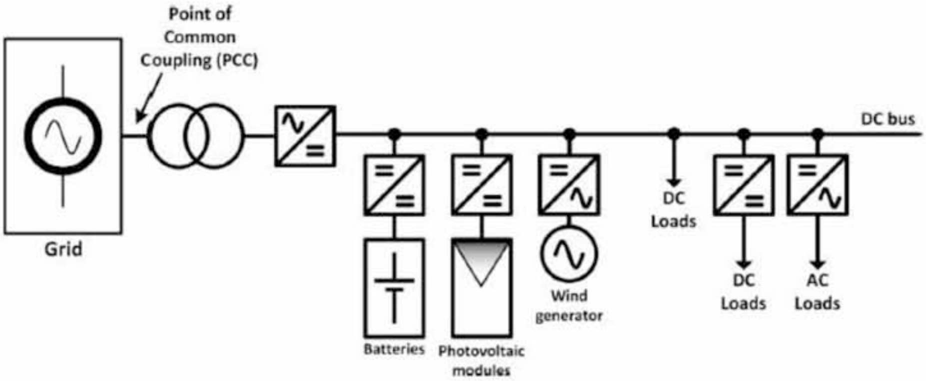


Figure 13. Schematic of a Microgrid with DC Bus [7]

g. Hidden Microgrids

Emergency grids for banks, hospitals, data centers places in cities for energy supply in emergency conditions. In most cases storage devices are primary included

Peer to Peer & Plug & Play

One of the most important benefits that offer the microgrid idea is the Peer to Peer characteristic [28]. Microgrids designed with ultimate goal, the ability of the system to operate functional, efficient and stable, independent of the number and type of the generator plants that was connected. The one generation unit is fully independent of the other and have peer involvement in the energy production process. Thus, there are not any generators that have leader role in the microgrid and their dispatch could affect the stability of the system. The duty of energy demand response is divided equally to the connected micro sources in this specific state.

Another key characteristic of microgrids which is complementary with peer to peer is Plug & Play [2]. The microgrid has the ability to continue its functional operation without any reconfiguration of parameters when a new generation plant or load connect or dispatch from the grid. This is a key issue for distributed generation technology with big fluctuations and for the growing consumer demands.

Microgrid in Energy Markets & End Node

At the same time with the technology progress in RES and DG, liberalization of energy markets attempt to change the face of electricity of 21th century. A conventional grid is unable to handle the growth of energy markets as intelligence is mandatory. Smart sensors, and central controllers are needed in every component of a grid to give this intelligence to the network. In Microgrids multi-agent system (MAS) is responsible to deal with that and solve a number of specific challenges. First of all, in contrast with centralized plants, DER units have different owners so several decisions should be taken locally. Next, Microgrids designed to operate in a liberated market so a degree of intelligence is mandatory. Furthermore, consumers of the past transformed to prosumers of the future, as they have the ability to sell energy generated by self-owned DERs. From the scope of reliability, MAS has to keep voltage and frequency levels at fixed values and also take care of the energy balance, and back up energy for sensitive loads.

Dimeas & Hatziargyriou [29] provides an operational cycle in the energy market to explain this procedure:

- The market period starts with an announcement of the Microgrid Central Controller (MGCC)
- After proper estimation of their energy capabilities, through local smart sensors and processors, power sellers announce their will to sell power by generating a specific number of virtual power-seller market agents.
- In the same sphere, loads of the microgrid estimate with the same way their energy demands and generate a proper number of virtual power-buyer market agents.
- In order to secure the energy balance, a central power system agent checks the market agents and do the proper actions in order to keep balance.
- At the end of this procedure the Central Controller announces the begging of the negotiation period.
- All the participants in energy market cycle (buyers and sellers agents) bid in the market. The agents have an inner predefined algorithm in order to take smart decisions.

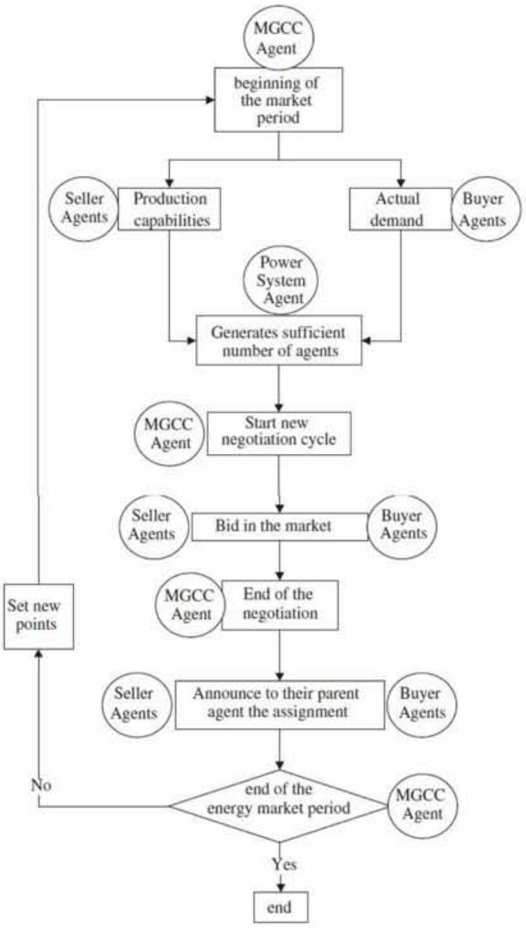


Figure 14. Negotiation cycle of energy market [8]

It can be concluded from the above that Microgrid and intelligent controls can ensure one more important benefit. The ability of the system itself to operate in Demand Response mode [17]. In power grids, operating margin is the condition where the balance between production and consumption is lost. In cases like microgrids where distributed generators are basically based on renewable energy sources this balance cannot be precisely predicted without the intelligent controllers. By Demand Response signals although, sent by supplier or the main MG operator to the loads, proper reduction or increase of energy production can be easily accomplished.

On the same direction, in Microgrids there are local entities called End-Nodes able to taking decisions and negotiate with suppliers and micro controllers in order to supply MG with proper power quality and power balance. In addition,

- Temporally shifting of energy demands of a local area for economic reasons (high price) can be succeeded.
- Smart decisions for energy storage in proper times in proper prices
- End nodes can detect emergency cases and take the decision to generate independently energy (in island mode).
- Peak-demand time shifting can be accomplished if detected, ensuring the reduction of prices and reliability of system.

Although there are a lot who object to End-Nodes, believing that loss of privacy is possibly, as these smart meters can become secret agents of government, or of hackers through cyber-attacks.

Taking into consideration the above study, there is no deny that Microgrids have major impacts on the whole electricity production and transmission chain. The majority of the benefits of renewable sources, distributed generation, energy markets and intelligent controllers are only obvious through a Microgrid concept. On the other hand, microgrid technology demands many changes and research before the fully integration in power production. Below a brief outline of the advantages and challenges of microgrids is provided:

- Local reliability through generation plants and storage devices near the customer
- Reduce feeder/transmission losses as energy distributed in restricted boundaries
- By separating DGs in traditional grid high cost and many risks (due to fatal faults) are arising. Clustering them in a microgrid is an effective way to overcome this.
- Environmentally friendly as MGs are based on RES.
- Peak demand time shifting can ensure low prices and efficiency
- Micro grid is the only way for off-grid regions power supply
- Take advantage of CHP. Everyone opposes to the construction of a polluting power plant near them. Microgrid based on RES can be close to residential areas.
- Autonomy through islanded mode
- Scalability through plug and play
- Black start operation
- Peer to peer characteristics improve flexibility.

SECTION 4

Smart Grid

All this survey and background research on power grid systems and new generation and distribution technologies was mandatory in order to understand all the challenges, potentials and implications of the new age in Electricity. In the following section a brief presentation of the innovative Smart Grid, the future of power grids is presented.

To begin the analysis an outline of the characteristics that a modern grid should have, according to the above survey in Microgrids, DERs and traditional grid is given [30]:

- A modern should accommodate all available generation and storage options of 21th century in order to provide the best power quality.
- Power generation should base in the majority to renewable energy sources in order to ensure low eco2 emissions and use conventional fuels only for emergencies or peak-demand times.
- Scalability of power system. The grid must have Peer to peer and Plug & Play characteristics in order to cover the growing energy demands of consumers.
- Security and safety against cyber-attacks or natural disasters and terrorism.
- A modern grid must motivate consumers and give them various choices, and low energy prices in the liberated energy market environment.
- Taking advantage of the technology progress in communications and data processing, a modern grid should be self-healing by detection and fast responding in faults and errors.

All these characteristics and features could not be expressed better rather than in the term Smart Grid. A Smart Grid (SG) can be regarded as an intelligent electric system that combines both the informational technology, data clouding and computational intelligence in order to optimize in the best way the electricity generation, transmission and distribution [31]. The ultimate strategy is to replace the whole traditional power grid with a bidirectional energy flow Smart Grid, even though at first the initial concept started with the idea of a grid with advanced metering infrastructure for demand side management optimization.

In other worlds, a smart grid is a self-healing intelligent power system, composed by a number of separate microgrids (with the characteristics of a modern microgrid) and an intelligent communication and monitoring network where all the units of the SG will communicate [31]. Each microgrid will replicate the architecture of the original one and all together they will create a big scale distribution network with no geographical limits (from a city to a country). Infrastructure is probably the same and consists of the clients, the markets, generation side, transmission, distribution and services.

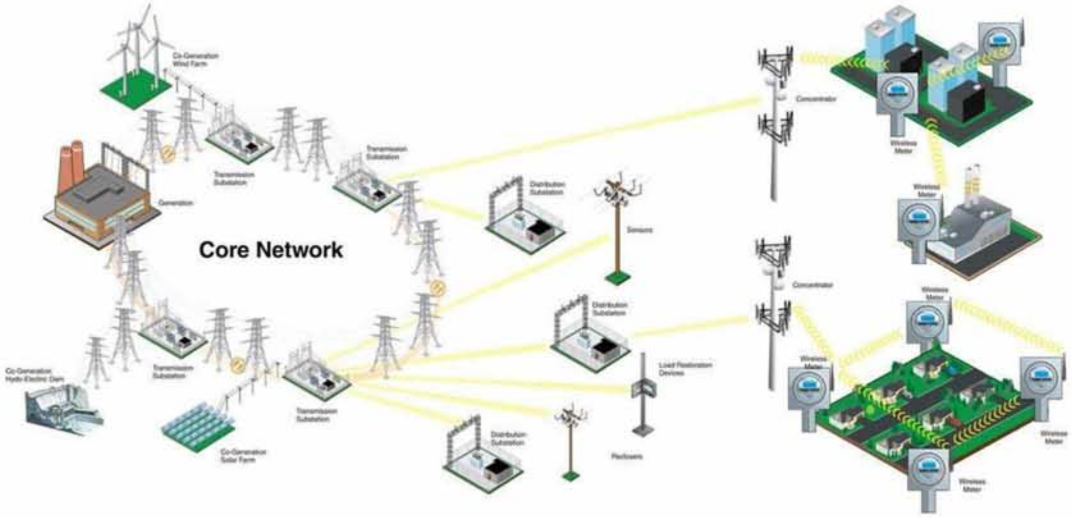


Figure 15. An ideal concept of Smart Grid

The concept of self-healing

In order to setup a self-healing smart grid, smart processors to each unit inside the microgrids and the whole smart grid. Each substation, generator, circuit breaker, transformer should have sensors and processors in order to communicate with each other and in the end to have the whole control of the grid. These processors will also store predefined data for the device for reconfigurations. In addition, smart materials, smart meters, sensors and nanotechnology can be used to give the ability to the smart grid to be self-recovered in live time with fast response. In a concept of failure, such a system has the ability to distribute in separate islanded microgrids. Taking into consideration the survey that have taken place before about MGs, there is no deny that these "islands" have the necessary intelligent infrastructure to recognize the present state and cover the local demands.

Improvements in Reliability

First of all, major reduction in outages duration and frequency disturbances can be accomplished taking advantage of the intelligent network of communication [32]. Real time acquisition and data transfer among all every unit's control system support fast error detection and accurate isolate of the fault with the minimal losses. Signals from system operators who gather all the data from local sensors will take the proper corrective actions to secure stable operation and of course continuous energy balance between production and consumption.

Furthermore, much more improvement of power quality can be succeeded with elimination of disturbances. Monitor system will detect power quality issues in supply and demand side in order to be corrected as fast as possible. Flexible AC transmission systems will provide support of voltage to reduce the sags at the transmission level [32]. Finally, using smart sensors and high speed transfer switches, disturbed sources will be detected, removed and replaced from other healthy busses. By increasing power quality it is obvious that customer satisfaction, productivity and cost will increase too.

Additionally, similar to microgrids, an emerging benefit of Smart Grids is the elimination of regional blackouts. Real time analytical tools, fast and accurate data transfer via smart grid network will prevent black outs and outages by predicting faults in weak busses. This has also economic impact as the annual costs due to grid outages are huge (Final report on the August 2013 black out cost 10$ billion per event in USA & Canada) [32].

Improvements in Security & Safety

Taking advantage of the characteristics of Distributed generation, Microgrid structure and intelligent network, Smart Grid has all the weapons to resist in any either natural or terrorist attacks. Live time data computational methods will identify the fault and make the proper moves to eliminate the impacts by avoiding cascaded failures [32]. Additionally the distribution generation makes the change to attack the whole system difficult, in contrast with the centralized one.

Considering now the various types of energy sources and energy plants in a Smart Grid two strong advantages are provided. Not only do the customers have more choices in response to a security emergence, but also countries and governments are not based in imported fuels or a specific energy source supplies and availability (e.g. fossil fuel or gas) [32].

Last but not least, the self-healing feature of Smart Grid gives the Grid operator the ability to detect failures and in an autonomous way protect consumers and the grid from fatal errors, or equipment disaster.

Improved Economics

Except from the already analyzed economic benefits like the cost reduction in transmission losses, Smart Grid emerges more economic improvements due to the liberation of energy markets. Both buyers and sellers of each microgrid will participate in the negotiation cycle of the energy markets. This fact, allow them to make smart decisions like local energy demand shifting, demand-response time shifting and selection among various owners and various prices. It is obvious that market efficiencies will reduce the price of energy and capacity.

More environmentally friendly

In a similar way with DERs and MGs, Smart Grid provided greener energy production, reduction to transmission power losses, live time energy balance and reduction of co2 emissions.

Implications in Smart Grid

- Peak-Demand times and prosumers. The fact that consumers become prosumers generates reverse energy flows. The consumer produce locally energy and transformed to prosumer so bidirectional current flow emerge. In spite of the challenges for new bidirectional grid that have already examined, in order to take advantage of the potentials the customers must be convinced to produce and share energy with the utility grid and the energy markets. It is not impossible for a number of customers to deny give energy at peak-demand times and so peak-demand shifting cannot be accomplished. The graph below shows this closed loop of consumption-generation.

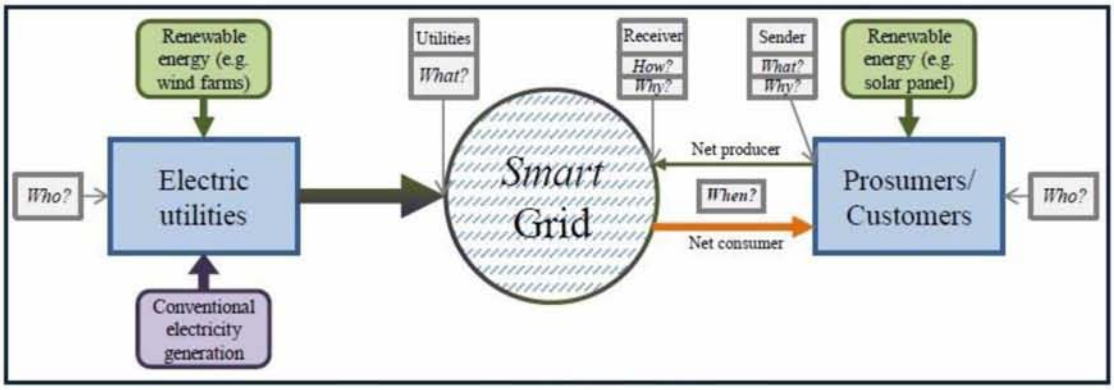
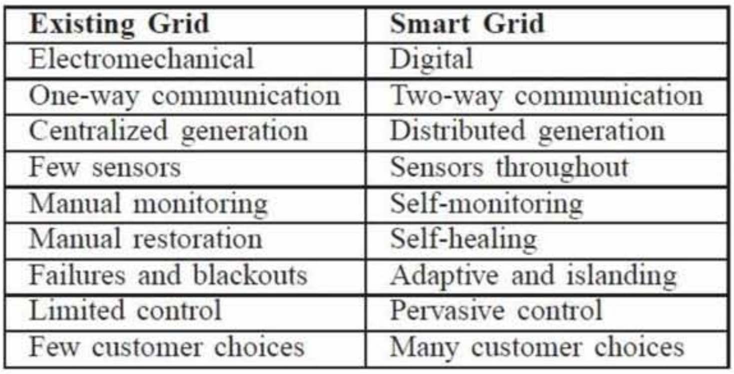


Figure 16. Smart Grid closed loop due to prosumer phenomenon [9]

- A worse on challenge is the big costs and the big investment funds needed. For example intelligent monitoring and metering systems are very expensive. In addition individual customers cannot detect direct benefits and the cost discourage the installations.



Existing Grid	**Smart Grid**
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

Figure 17. Main differences of conventional power grid and Smart Grid [10]

CHAPTER 3

THE CONCEPT OF WIND ENERGY

As widely acknowledged, the risk of human-induced climate change and the massive elimination of petroleum and other fossil fuel sources globally, are the most important and darkly challenges that the world of 21th century must deal with [33]. Conventional energy sources have proven to be effective drivers of economic and technological progress, especially after industrialization. Among with that, power systems and governments have to cover the continuously growing, power demands of an energy-intensive society. The risk of energy supply insecurity, the increasing high costs of conventional fuels and the restricted environmental policies led to a new revolution and a rising interest on renewable energy sources technology. In order to meet social and economic goals and improve quality of human's life several renewable energy sources are being exploited with many different benefits and costs. Wind, solar, biomass, hydro power, marine and geothermal energy are some of the most common energy sources used in this strategy. In Europe the primary production of renewable energy was 196 million tons of oil equivalent, which is translated in the 25.4% of total energy production [34]. Power generation from Wind Energy is a primary type of RES plants. Especially in countries with big energy wind capacity, wind energy can emerge many potentials. In this direction, 12.800MW of wind power capacity was installed in 2015 only in Europe nations [35]. Although, dealing with renewable energy sources requires sophisticated planning and government's strategies, as due to their nature operating schedule and long scale future predictions are unable, considering their randomness and big volatility. In the following section wind power energy and with power technologies are analyzed in order to point out the problem of volatility and the impact in power grid.

SECTION 1

Wind Energy

Wind energy is one of the most competitive Renewable energy sources topologies with many considerable potentials for humanity, environment and economy. For thousands of years humans exploit wind energy for pumping water, transport goods, milling grain through windmills or similar topologies. After the begging of industrialization although, wind power has totally eliminated and replaced by more efficient economic and reliable energy sources like fossil fuels, coal and petroleum. Even though it seems that these conventional type of sources would be the driver of electric power generation for years, their tremendous impacts on environment and human health stop their ascent. Parallel to that, Oil crisis in the end of 70's, petroleum crisis in 2009 and the Kyoto protocol greenhouse gas (GHG) reduction targets triggered the renewed interest in renewable energy sources and wind power technologies. Starting with small scale wind installations at the end of 20th century, for remote areas where the utility grid cannot reach, emergency grid connected wind turbines and water pumping systems, at the end of 2015 global cumulative installed wind capacity reach 450.000MW with the 5.000KW of them offshore[35].

Wind energy, is the energy that can be captured from wind and especially wind's speed, so it is a kinetic energy [36]. Wind can be considered as big moving masses of air created due to differences in temperature in the surface of earth. Sun heats up quicker the land than the water and so warmer masses of air with small density rising in the atmosphere, in contrast with cooler ones which falling. The movement of earth around the sun creates an infinite cycle between these masses of air leading to winds. Taking advantage of the infinite wind energy, systems installed in order to transform the kinetic energy of wind to mechanical power and finally to electricity.

Among the numerous benefits, it is obvious that wind energy has no fuel requirements, as do coal, gas or other conventional technologies of energy production. In addition, as a renewable energy source, not only the supplies are plentiful and widely distributed around the world, but it is also a clean and green technology as there is no greenhouse gas emissions during the whole operation of energy generation.

However, many implications and challenges are emerging under a brief examination. The primary drawback is the high cost investments for the equipment but also the costs of accommodating special characteristics for a stable and functional operation. Intermittence resource variability, competing demand for land use, power electronics and inverters, transmission and distribution cost must be added in the generation cost [37]. The benefits of Smart Grids and Microgrids are now obvious, considering wind plants as a part of DERs. Wind turbines are impossible to be installed and operate separately in the main grid, considering the high costs.

For this reason, in order to determine the economic success of a wind plant the above technical parameters must be examined:

- Annual energy output of the plant
- Average wind speed of the region
- Statistical wind speed distribution
- Turbulence intensities
- Roughness of the territory

Another major drawback of wind energy apparent from the high costs are the big fluctuations in power production [37]. The big volatility and randomness of renewable energy sources and wind specifically can be fatal not only from an economic approach but also for the stable operation of the grid itself. As it was mentioned before, the lack of large storage systems in traditional grid cannot solve the intermittent operation of wind turbines leading the power system to power unbalance. Even though, the concept of Microgrid can overcome that challenge, these volatility can lead to voltage fluctuations and even worse to system instability. In following chapter, best methods for ensuring grid stability will be examined.

Public resistance in addition, on the placement of wind turbines near residential areas or even at sited places can also become an obstacle to the emerging wind generation technology. Below an outline of the major drawbacks is provided [37]:

- Impact on the ecosystem of birds
- Visual impacts on landscape
- Acoustic noise emission
- Electromagnetic disturbances in radio, TV, radar signals (RF signals)
- High investment costs

Even though the drawbacks seem to be many, the majority of them are already solved taking advantage of the potentials of Smart Grid and Microgrid modern technologies. The others have minor importance, considering the numerous benefits. In order to summarize the main advantages of wind energy is given:

- Clean, green energy with no eco2 emissions (10% of energy production by wind energy lead to 1.4 Gton/year co2 reduction) [34]
- In a Microgrid but also in traditional grid wind turbines operate separately making the maintenance easier and the whole structure more secured in faults.
- Scalability of wind turbines give the ability to generating capacity to easily expand in contrast with conventional generating plants (e.g. nuclear)
- Wind plants help governments to comply with Kyoto protocol as there are GHG during the operation.

A country like Greece with numerous distributed islands and remote regions are suitable for wind energy production and Microgrids installations. In fact the compliance with Kyoto protocol among with the liberalization in energy markets force the Greece government to reduce co2 emissions and increase installed wind capacity the past 10 years [38]. The graph below presents the progress in the installed wind capacity in Greece.

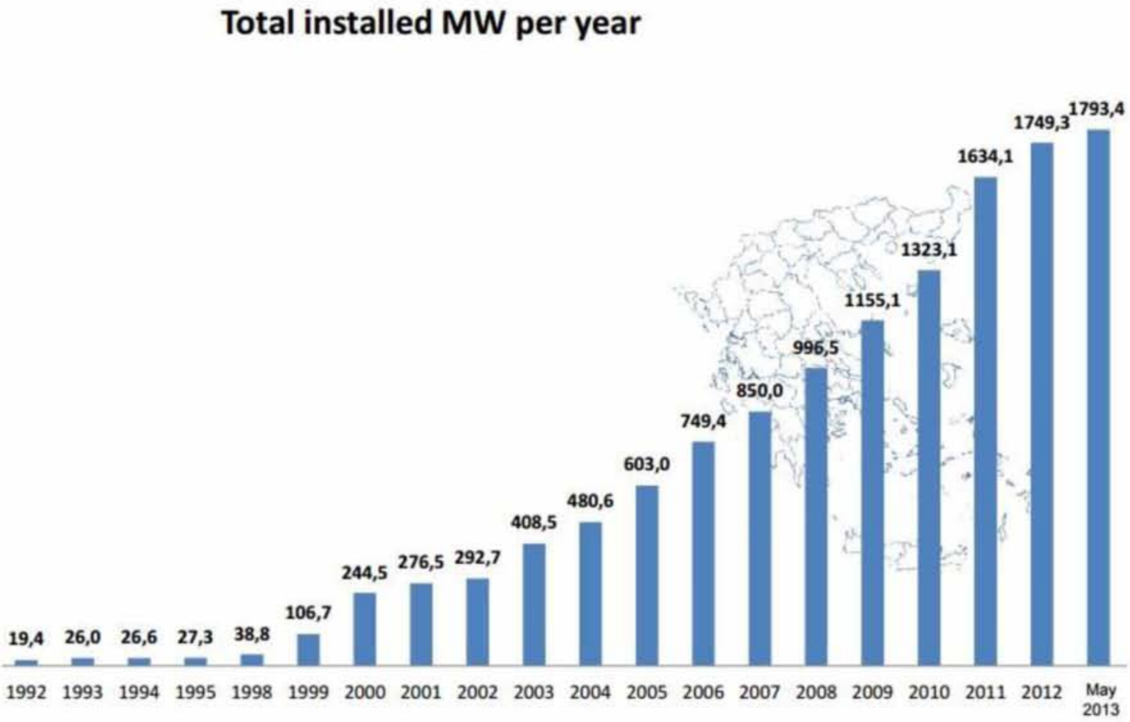


Figure 18. HWEA Wind Energy Statistics for installed MW per year in Greece [11]

The energy that can be captured from the wind is proportional to the cube of wind speed velocity [37] so brief examination on winds velocity characteristics (e.g. direction) is critical in order to plan a design strategy for the suitable installation place and economic prediction. The equation of the total power of a wind stream is given as:

$$PW= 0.5 \times \rho \times \pi \times R^3 \times V_w^3 \times CP(\lambda,\beta)$$

where ρ is air density, R blade radius, Vw wind velocity, CP power coefficient

This stochastic randomness of wind velocity is really challenging and is caused by many nature factors like climate conditions, weather conditions, ration of land and water and roughness of the territory around the wind turbine. It has been proved that higher level areas like a top of a mountain have much more wind energy capacity.

Although, even for those areas wind speed varies and continuously changing, so long term analysis and prediction is difficult. In addition during the day, variations on weather conditions can make difficult the prediction of wind speed power in very short time frames. Van der Hoven [39] found that there are two major peaks in power spectrum of horizontal wind speed. Migratory pressure systems caused wind fluctuations and a peak with 4 days period and the other sort term peak due to turbulence. Among the long term peak and the sort term peak there is a spectral gap (centralized at 1hour period) that was explained as the natural inability to create fluctuations at these frequencies.

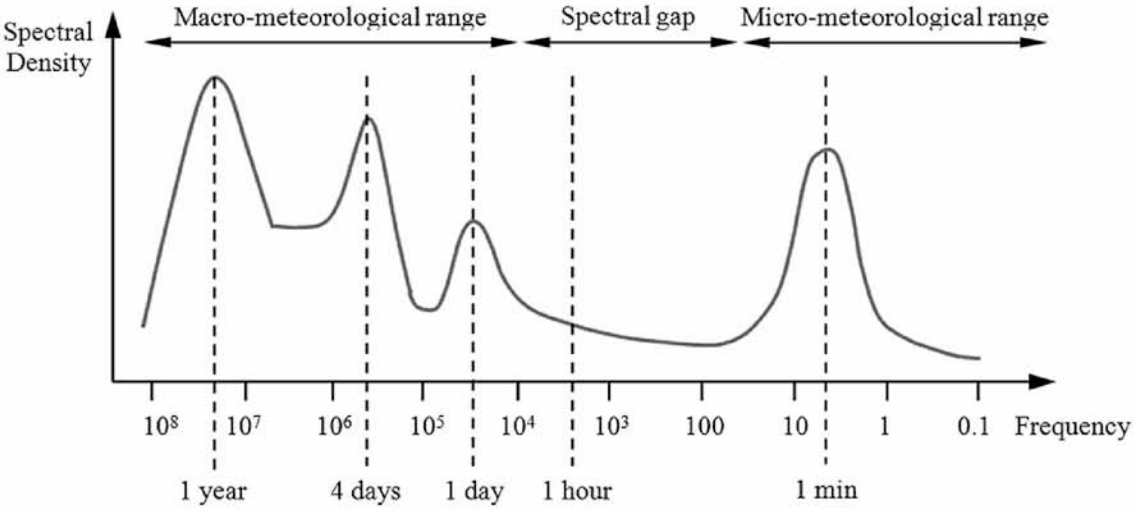


Figure 19. Van der Hoven Wind Spectrum curve [12]

SECTION 2

Wind Turbines

The conventional way of capturing wind energy is wind turbine. Wind Turbine is a rotating device which converts the kinetic energy of wind speed into mechanical energy. By driving a power generator, the generated mechanical energy can be converted to electricity. The operation is probably the same: wind rotates blades of the turbine, which blades drive an axis. A generator is connected on this rotating axis and generates electricity. The generating electricity can be direct transmitted and distributed to substations and the main grid or stored to batteries. There are two types of wind turbines: Horizontal Axis wind turbine (HAWT) which is mainly used, and the Vertical Axis wind turbine (VAWT) which is used in small scale plants [39].

A typical turbine subsystem includes:

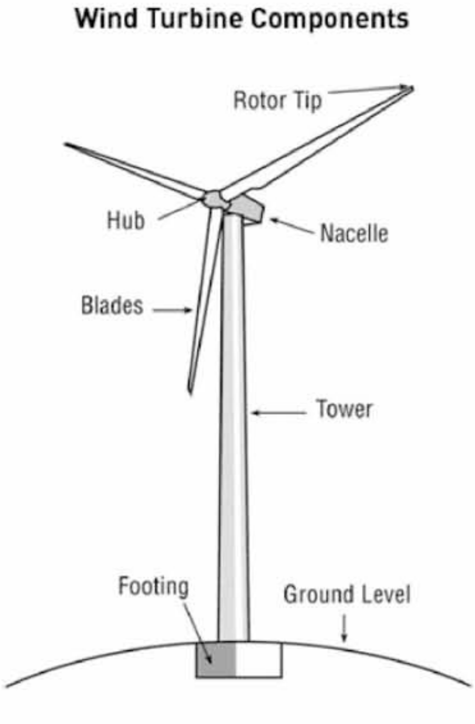


Figure20. Typical HAWT structure[13]

Rotor blades with main task the wind energy capturing and converting into mechanical energy

Nacelle which houses all the conversion structure (e.g. the generator, gearbox, axis)

Tower in order to give the proper height to the turbine to capture high speeds

Foundation of the whole system

Hub of turbine

Inside the nacelle now the conversion system can include [39]:

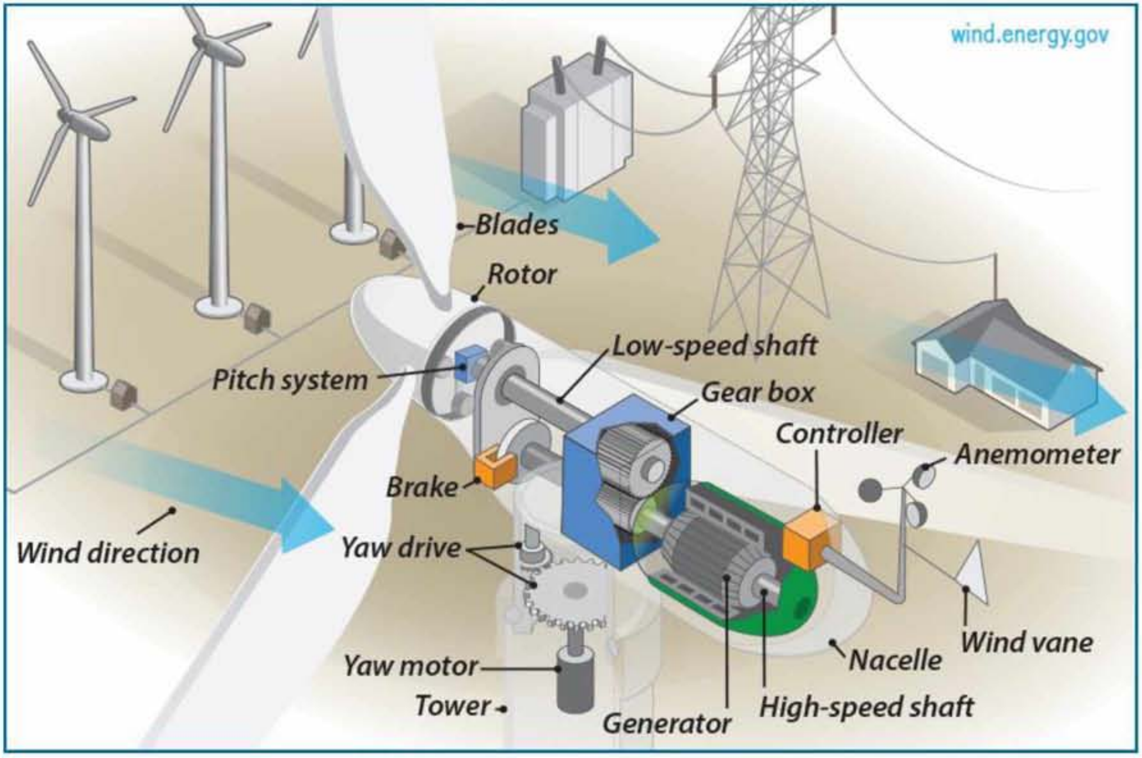


Figure 21. Infrastructure of a wind turbine [13]

- **Gearbox**: Transmits the mechanical energy from the rotating axe to a proper speed to the generator. Main job for this reason is to step down or up the turbines speed (e.g. from 60rpm to 2000rpm)
- **Brake**: In an extreme high wind speed conditions or in an emergency brake stops the rotation of axis and the whole process. It can be mechanical, hydraulic or electrical.
- **Controller**: All the data and measurements of sensors collected to the controller. This device controls all the procedure of generation, from the deliverable power to the pitch angle of the blade.
- **Generator**: A typical motor that produces electricity and it can be synchronous or asynchronous.
- **Anemometer**: A local sensor that measures the wind speed at live time in order for the controller to take the proper decisions.
- **Wind vane**: Sensor measures the wind flow.
- **High/Low speed shaft**: They drive the generator. They work complementary according to the speed of wind and turbine.
- **Yaw drive**: Main job is to rotate the turbine in order to capture in the most efficient way the energy from wind. For this reason is rotating proportional to the wind direction.
- **Yam motor**: Give the proper power to the yaw drive in order to rotate.

Horizontal Axis Wind Turbine [41]

In this type of wind turbine the axis of the roto's rotation is parallel to the wind stream and the ground, so the axis is horizontal. The majority of HAWTs have two or three blades and they divided in two sub categories: upwind turbines and downwind turbines according to if the turbine face the flow of wind or not. Even though a downwind system has the advantage that does not need a yam system of motor and drive, in order to keep up with the winds direction, it can cause regular turbulence so it has been declined. The differences in the pressure among the surface of the blades when the wind flows through the whole surface results in an aerodynamic lift. The gearbox converts the kinetic energy of the bladed to mechanical energy and then through the generator to electricity.

Vertical Axis Wind Turbine [41]

In contrast, a VAWT's turbine rotor rotates vertically around its axis instead of horizontal. In addition blades are vertical arranged to. Even though it tends to have fewer efficiency than the HAWTs, this type of turbines used in areas with very low wind capacity and wind speed, or in cases when the turbine must be place among buildings. Also a vertical axis turbine does not need for this high tower structure, as it can be placed near the ground.

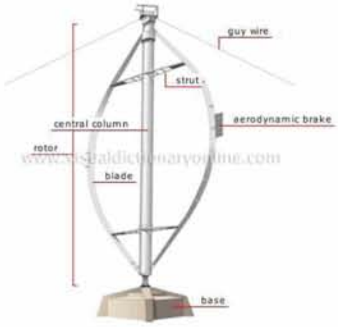


Figure 22. Typical Vertical axis Wind Turbine [13]

Advantages and disadvantages of both topologies conclude below:

HAWT	VAWT
Higher wind speed due to tower	**No Yaw mechanism**
Maximum efficiency through pitch angle	**Fewer noise emissions**
Additional Yam system	**No high tower structure**
Large costs due to tower	Easy maintenance
Electronic noise emissions	Low efficiency
High transportation cost	Unable to capture wind flows on high level

In order to achieve better efficiency wind turbines can be arranged in groups and clusters called Wind Farms. The selection of the topologies' installation depends on the wind capacity at this region. Common chosen places are regions with strong high speed winds like big mountains and high climbs. There are two types of wind farms: Offshore wind farms and onshore wind farms. The first ones are the typical ones placed on mountains and hills and in average almost three kilometers of the sea. Exact position of each wind turbine matters as a proper installation can give high quality output. On the other hand offshore wind farms are placed in the water, approximately twenty kilometers from the shore. Despite the high cost and the difficulties in maintenance, offshore turbines are much more efficiency and power quality, as the surface of the water is less roughness and the winds above region have bigger energy capacity. The already high costs of the installation are getting higher due to the challenge of the materials that have to be used in order to prevent corrosion due to the salt water. Although collisions like electronic noise and human resistance of typical wind turbines can be solved with this type of technology. In Europe now, according to annual statistics, there is 142GW of installed wind power capacity with 11GW of its offshore [34].

23. Offshore Wind farm example [13]

24. Onshore Wind farm example [14]

In order to summarize the examination on Wind Energy, some annual statistics are given below:

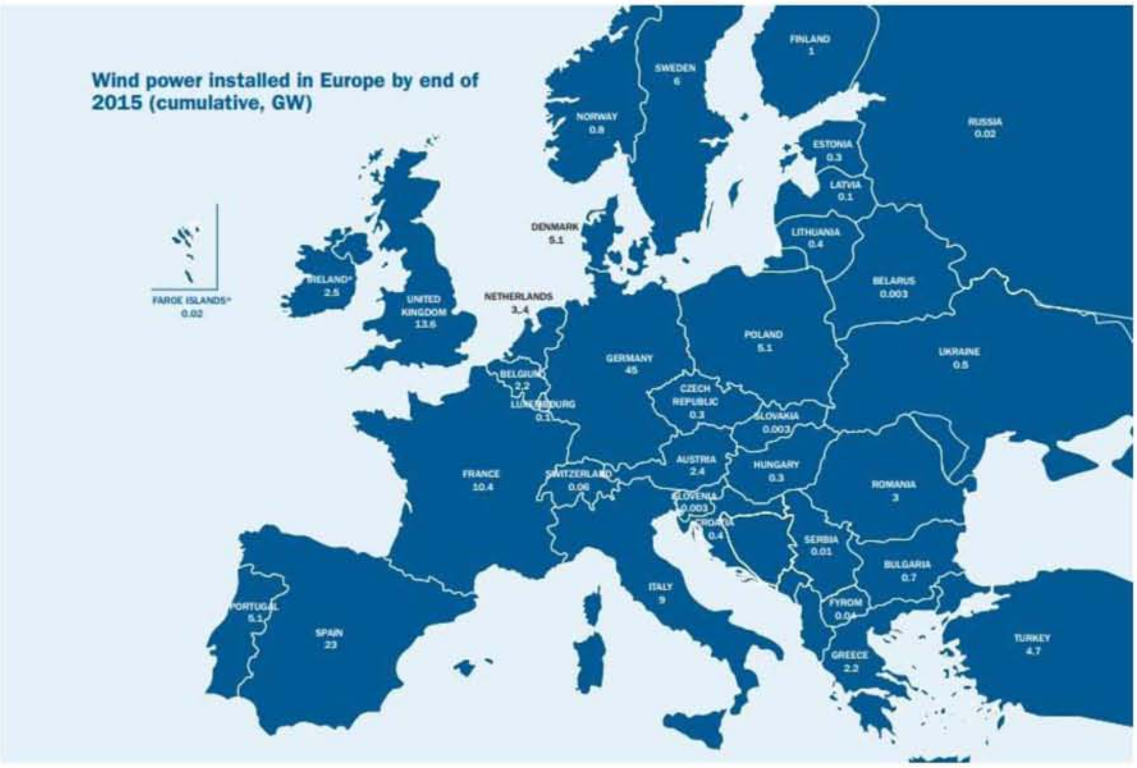
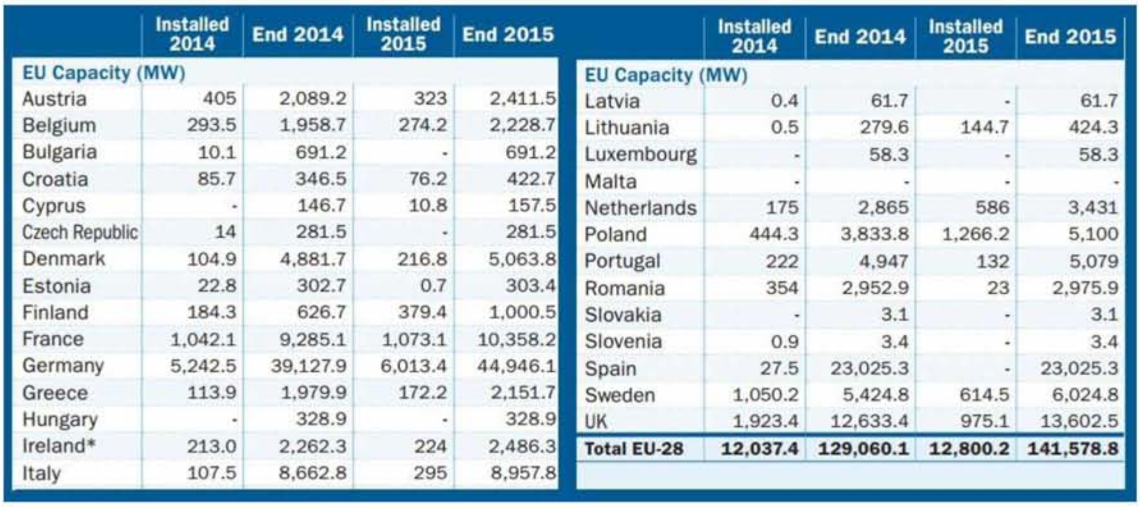


Figure 25, 26. Annual statistics in installed wind capacity in Europe [15]



	Installed 2014	End 2014	Installed 2015	End 2015
EU Capacity (MW)				
Austria	405	2,089.2	323	2,411.5
Belgium	293.5	1,958.7	274.2	2,228.7
Bulgaria	10.1	691.2	-	691.2
Croatia	85.7	346.5	76.2	422.7
Cyprus	-	146.7	10.8	157.5
Czech Republic	14	281.5	-	281.5
Denmark	104.9	4,881.7	216.8	5,063.8
Estonia	22.8	302.7	0.7	303.4
Finland	184.3	626.7	379.4	1,000.5
France	1,042.1	9,285.1	1,073.1	10,358.2
Germany	5,242.5	39,127.9	6,013.4	44,946.1
Greece	113.9	1,979.9	172.2	2,151.7
Hungary	-	328.9	-	328.9
Ireland*	213.0	2,262.3	224	2,486.3
Italy	107.5	8,662.8	295	8,957.8
Latvia	0.4	61.7	-	61.7
Lithuania	0.5	279.6	144.7	424.3
Luxembourg	-	58.3	-	58.3
Malta	-	-	-	-
Netherlands	175	2,865	586	3,431
Poland	444.3	3,833.8	1,266.2	5,100
Portugal	222	4,947	132	5,079
Romania	354	2,952.9	23	2,975.9
Slovakia	-	3.1	-	3.1
Slovenia	0.9	3.4	-	3.4
Spain	27.5	23,025.3	-	23,025.3
Sweden	1,050.2	5,424.8	614.5	6,024.8
UK	1,923.4	12,633.4	975.1	13,602.5
Total EU-28	**12,037.4**	**129,060.1**	**12,800.2**	**141,578.8**

CHAPTER 4

PLL FUNDAMENTALS

During previous study both in power grids and wind energy, it was mentioned that one of the most challenging implication of Distributed generators and modern Microgrids is the intermittent nature of renewable energy sources. It is very hard to predict the deliverable energy of a wind turbine, as the fluctuations and disturbances are numerous. Many research has be done, and many methods, algorithms and systems have been designed in order to secure the proper synchronization between the utility grid and the distributed generators. A quick survey on the literature [42][43][44] will show that in most cases, Phase Locked Loop (PLL) algorithms and methods are used on the internal control units of such systems. Thus, in order to analyze the controllability in Microgrids and Distributed Generators, a brief study on the PLL theory, and PLL structure is necessary.

SECTION 1

PLL Topology

A phase-locked loop (PLL) is a negative feedback system with a forward gain and a feedback term that compares and locks the phase and the frequency of a signal according to a reference predefined signal. The basic idea around the construction of PLL topology was the injection of a sinusoidal signal on the input of the building block, with long term goal the production of a filtered version of the reference input signal on the output [45].

Since 1970's, PLL topologies have fully established in RF industry, telecommunications generators and motors synchronization. Signal processing, frequency demodulation, signal conditioning, frequency detection, frequency synthesis, motor speed control, frequency-selective demodulation, tone decoding, frequency shifting-key are many of the main operations and uses of PLL structures. In addition, the growing desire of micro processing industry for high clock recoveries, has emerged the use of PLL devices as clock generators [46].

In other words, a basic PLL block, is an analog device that forces a signal to track another one, by keeping synchronized their phases and frequencies. All parts are connected to form a closed loop frequency system. Figure 27. presents a typical PLL topology:

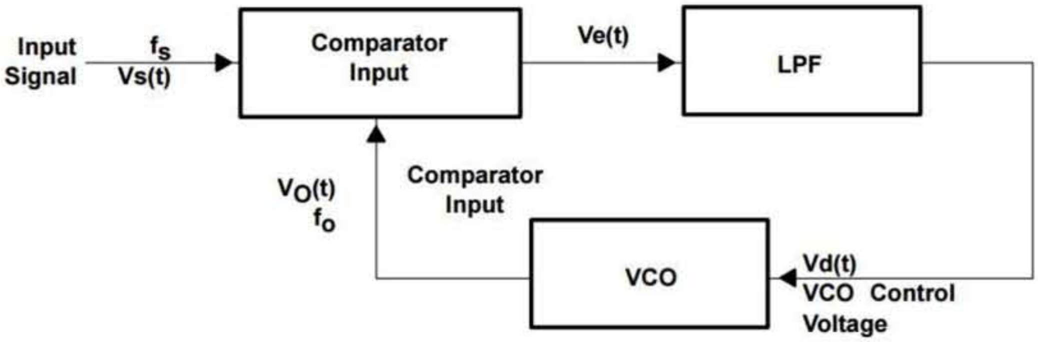


Figure 27. Block Diagram of PLL [16]

To be more specific, a PLL device consists of three fundamental elements. A Phase-Frequency Detector (PFD/PD), a Loop Filter (LF) and a Voltage Controlled Oscillator (VCO). Additional components of such a structure can be a frequency N-divider unit, prescaler, counter, charge pump according to the application of the topology. The process is typical the same. An input reference signal and the internal signal of the closed loop is compared by the Phase Detector. The phase difference produced by the PD is now fed to a charge pump circuit that generates a constant current at the output. Filter produces a filtered DC voltage according to the output current. Charge pump stage is compulsory, and PD can direct drive the Loop Filter. Typically the filter of the PLL is a first order low pass filter. This DC voltage from the filter drives a voltage controlled oscillator and forces him to generate a proper sinusoidal signal. Ultimate goal is the lock of the two signals in the reference frequency and phase. Order of the total PLL block is proportional to the filter's order. For an n-order loop filter the PLL's order is n+1. At least, a Phase-locked loop structure is first order due to the perfect integrator of the VCO. The PLL's performance depends on its order and the non-linearity, and the stability from the LF's order [47].

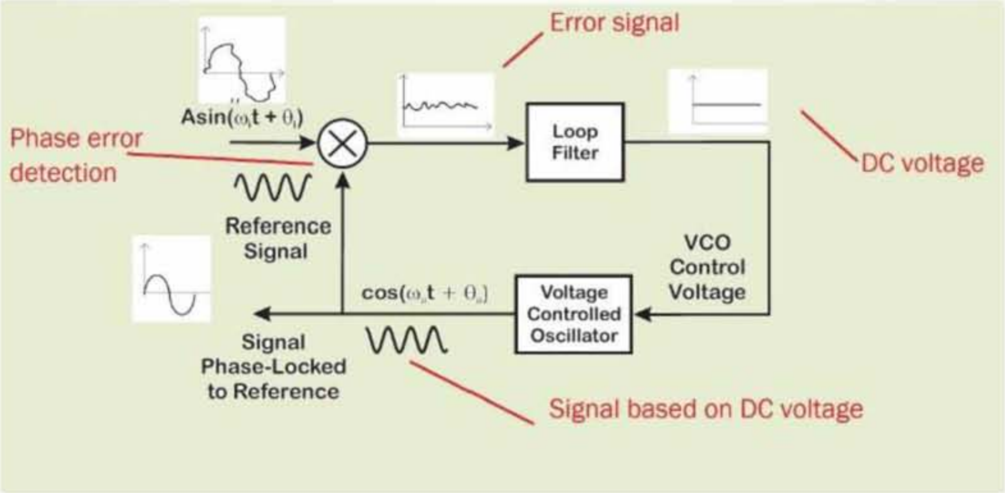


Figure 28. Signal processing in PLL [16]

With no signal input in the Phase Detector, there is no reference signal so the output of both phase detector (the error) and the loop filter (the filtered error) is zero. Voltage Controlled Oscillator with no signal from the filter just oscillates in a fixed, default frequency. The value of the frequency depends on the parasitic components of the structure (Capacitors and Resistances). For this reason default frequency of PLL can be modified by designer.

When an input reference signal is applied to the phase-locked loop, the topology performs in such a way that the signal of the VCO is locked to the reference. Phase detector compares the phase and frequency of the two signals and generates an error voltage proportional to this difference. The loop filter now, filters this voltage from harmonics and high frequencies and pass it to oscillator. The VCO now will generate a new signal (different from the default of the previous state), proportional to this DC voltage, in order to increase or decrease the frequency of the output signal.

This circular operation will stopped when the difference of the two signals on the phase detector minimized in a threshold value (close to zero).

According to that procedure, there are three operation modes/regions [47]:

- *Free running region.* In this region there is no input on the input of the PD so no reference signal and the VCO produces a default-frequency signal. This frequency is also called center frequency.
- *Capture region.* In capture region the PLL tries to lock the oscillator output signal to the reference signal. Capture region depends on manufactures parameters, especially loop filter design.
- *Lock region.* When the difference of the two signals minimized in a fixed threshold value the frequency of the VCO locks. The PLL stays in this specific locked mode for a range of frequencies on the input. This lock region is typical bigger than the capture region and if an input signal has as frequency out of this region the PLL unlocks.

SECTION 2

Voltage Controlled Oscillator

An oscillator, and especially a voltage controlled oscillator (VCO) is on the most important and common used subsystems in digital and analog circuits [48]. Especially in RF field and telecommunication transmissions is a mandatory block in every application. It is an electronic circuit which generates signals in the form of sinusoidal or square pulse. In fact an oscillator converts a DC voltage in a periodic signal. There is no need for extra input, as the oscillator can start the local oscillation by the environment noise. The challenge in the VCO design is the stable frequencies with minimal fluctuations and the big tolerance to electric noise (inner or envimeromental).

There are various types of voltage control oscillators. The LC oscillators (e.g. Armstrong, Hartley, Colpitss, Dynatron etc.) based on charging and discharging of capacitors in a feedback network. Another type of oscillators, is crystal oscillator which takes advantage of the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a precise frequency. Finally there are the Ring Voltage Controlled Oscillators (which are being examined on this thesis). They are the most common used oscillators in digital and analog circuits due to their easy integration. The lack of discrete components like capacitors or inductors give them this benefit. They are probably based on the complementary nature of inverter gate.

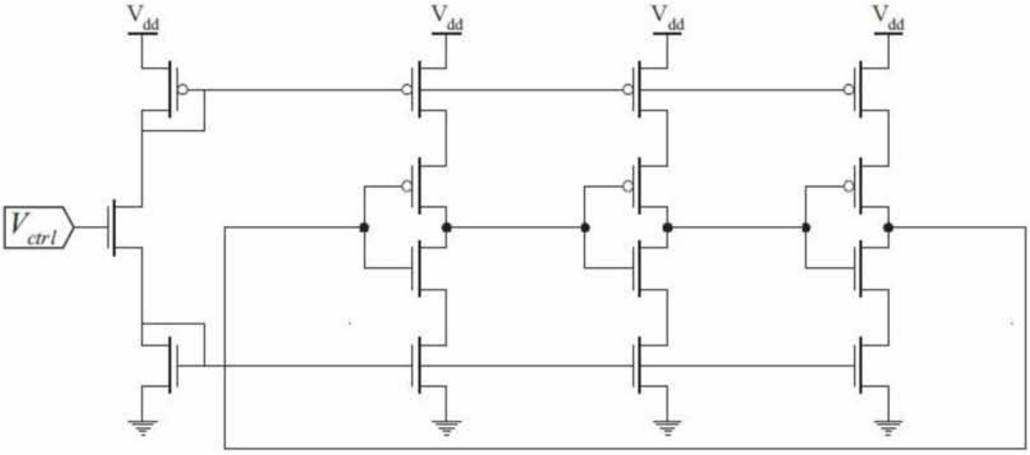


Figure 29. Typical 3 stage Ring Voltage Controlled Oscillator [17]

A Ring VCO consists of cascaded NOT-gates (inverters) in a closed loop. In order to have the desired oscillation, even number of inverters is mandatory. The oscillator characterized and takes his name by the number of these gate (e.g. 3 stage Ring VCO). Just a number of cascaded NOT-gates in a closed loop is not enough to have a fully functional oscillator. A voltage control drives the oscillator, and the generated frequency is proportional to it. In fact, this voltage modifies the current of the NMOS and PMOS mirrors, so it modifies the biasing of the inverters. Later it will be proved that the oscillation frequency depends on this voltage (Without this, the oscillator will generate a signal with a fixed frequency proportional to the permanent manufacturing characteristics) [48].

The phenomenon of oscillation based on complementary theory of inverters and on their delay. This delay is actually the period of the produced signal and completely depends on the parasitic of the transistors. In order to have a functional Ring VCO two conditions must be satisfied. First the gain of the loop must be greater than one, unless in every operation cycle the losses will force the oscillation to stop in a certain sort time. The second one refers to the phase shifting which must be 2π in every cycle (so zero). These conditions are always known as the Barkhausen conditions.

Taking into consideration the second Barkhausen condition and the fact that frequency depend on inverter's delay the period given by [48]:

$$T=tdelay \quad \& \quad f=1/2Ntd$$

where N is the number of stages and td or tdealy is the delay time in every stage.

As it is difficult to predict and calculate this delay due to parasitic, an equivalent RLC circuit is used instead. The inverter replaced by transconductance with unit gain and the parasitic as a combination of a resistance parallel to a capacitor that drives the inverter.

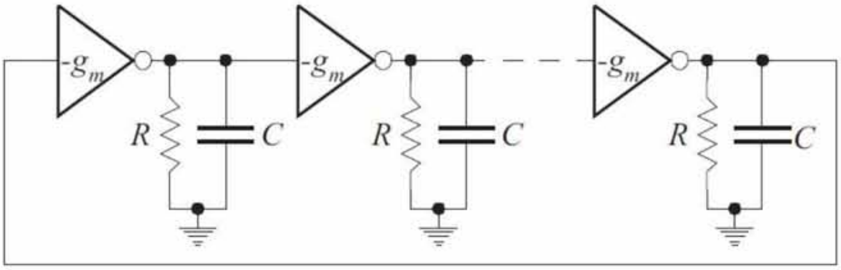


Figure 30. RC equivalent of Ring Oscillator [17]

Now by the known equations for parasitic on MOS transistors and the equivalent circuit:

$$Rn=VDD/IDS=VDD/(Kn'(W/L)(VDD-VTHN)^2)$$

$$Cin=3/2(Cox'(WnLn+WpLp)$$
$$Cox'=Cox.W.L$$

and

$$t=RCin=1/f$$

It is obvious from the equations that the frequency is proportional to the width of the transistors and the voltage supply. In addition it is reverse proportional to the resistance and the capacitor.

In order to explain and briefly understand its operation, a Ring Voltage Controlled Oscillator designed and simulated in the ADS design tool of Agilent in 65nm MOSFET technology. In the following figure the schematic is provided:

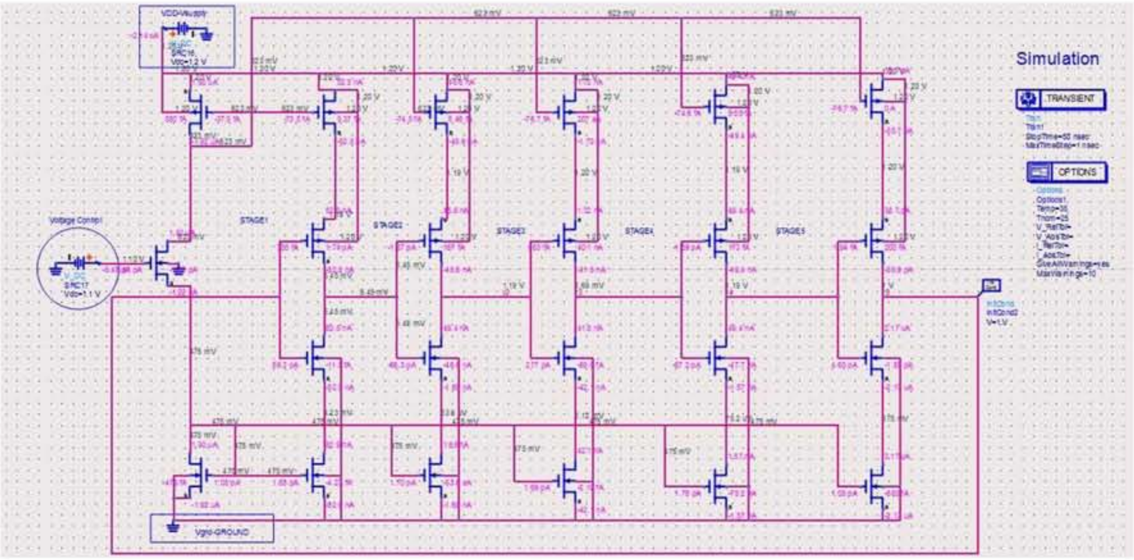


Figure 31. Schematic on the designed VCO on ADS

Five transistor are biasing the nmos transistors with certain current from the nmos current mirror and other five the pmos transistors of the five inverters. Firstly the single transistor on the left give a proper current according to the DC input voltage to its gate to the two current mirrors. By giving an initial condition to the loop (as there is no necessary external noise) the inverters start to operate complementary. When the first's pulldown is activated the next is deactivated. The output of the last inverter is locked to the input of the first in order to construct the feedback necessary loop. A transient simulation gave the above results:

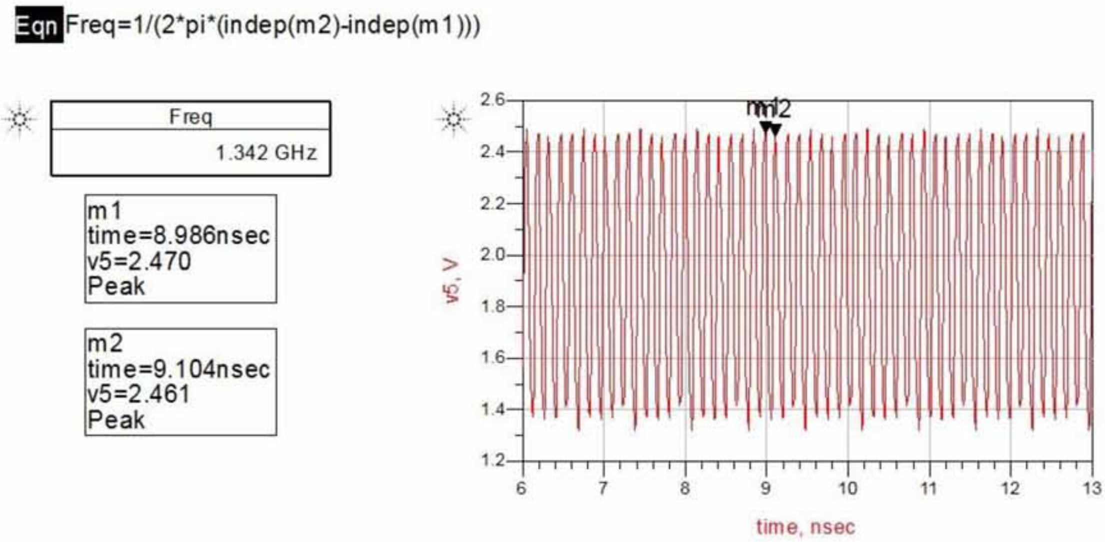


Figure 32. Transient response of Ring VCO

Width (nm)	Frequency(Hz)
VDD=3V	Vctrl=1.65V T=35o C
65nm	725Mhz
130nm	294Mhz
260nm	132Mhz
500nm	66.5Mhz
1000nm	29.91Mhz
2000nm	12Mhz

Voltage Supply	Frequency(Hz)
Wn=65nm	VDD=3V T=35oC
0.5V	397.2Mhz
1V	415Mhz
1.5V	725Mhz
2V	1.26Ghz
2.5V	1.59Ghz

Voltage Supply	Frequency(Hz)
W=65nm	Vctrl=0.8V T=35oC
2V	191Mhz
3V	354Mhz
3.5V	542Mhz
4V	1.04Ghz
5V	1.94Ghz

Temperature	Frequency(Hz)
Wn=65nm	VDD=3.5V Vctr=0.8V
45o	611Mhz
55o	650Mhz
70o	500Mhz
85o	455Ghz
120o	390Ghz

Table 1. Results of VCO simulation (Freq vs Temperature, voltage supply, control voltage, width)

Finally the equivalent RC circuit is simulated by adding resistances and capacitors as drivers of each inverter. The simulation showed that bigger the capacitor or the resistance lower the frequency was. In addition the addition of extra resistances give "pulse" form to the sinusoidal signal.

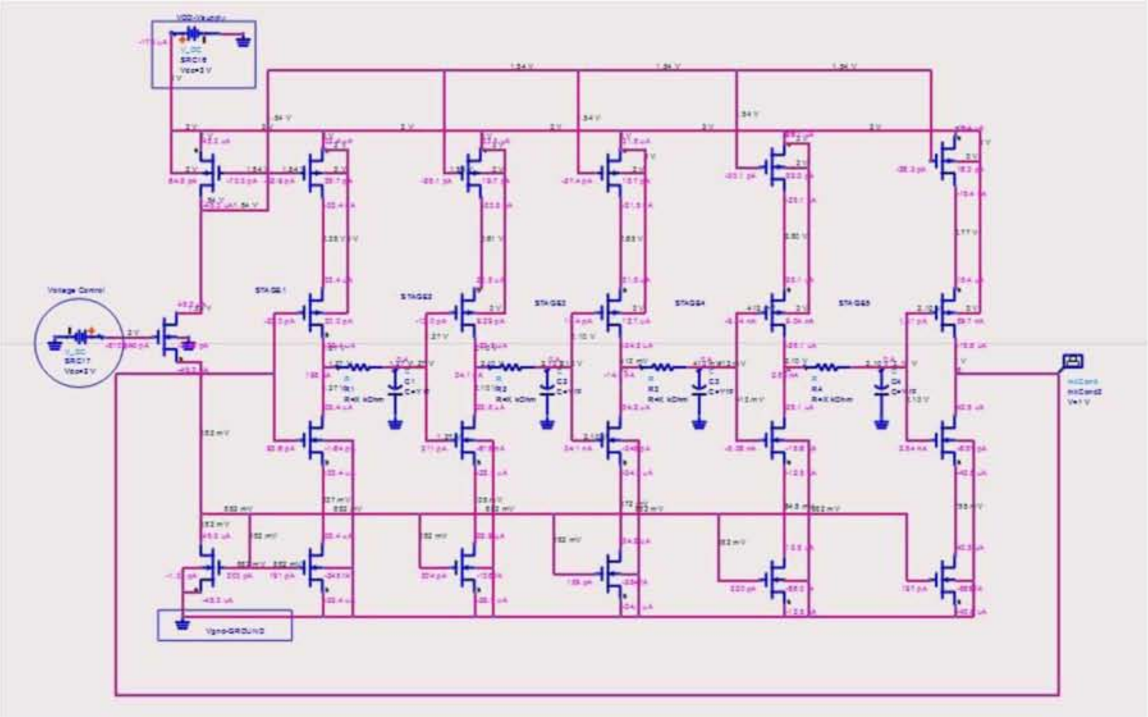


Figure 33. Schematic on ADS of the Ring VCO with additional R, C

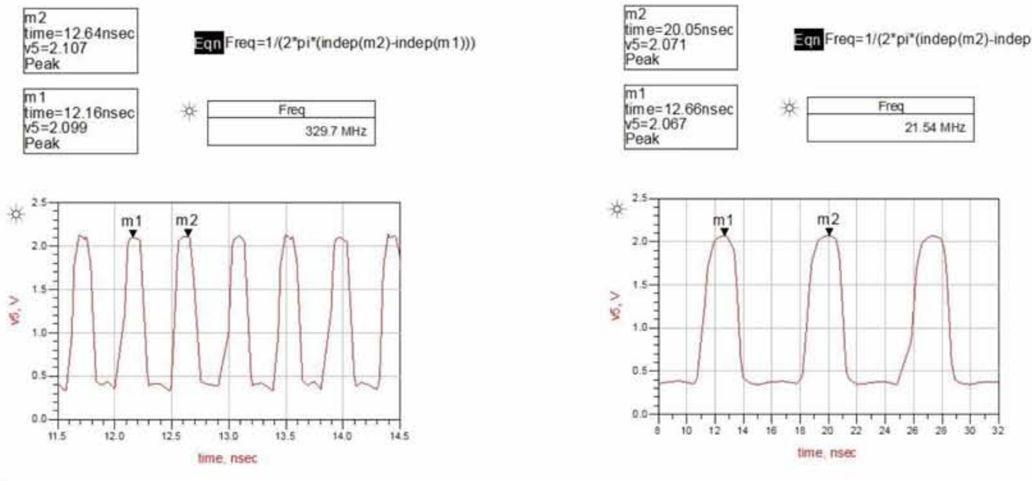


Figure 34. a) transient response with 1kΩ, 1fF, b) transient response with 10kΩ, 2fF

SECTION 3

Phase Frequency Detector

The second more important part of a Phase-locked loop is the Phase Detector. Phase Detector or Phase Comparator is an analog or digital circuit with the ability to detect phase difference between two signals and generate an error voltage [45]. Also a different version of comparators are Phase Frequency Detectors with the advantage of capturing differences not only on the phase but also on the frequency. In power grids, the idea is the same but instead a PI controller is used to minimize this error difference.

A simple PD is a mixing detector. The Phase Detector operates like a frequency mixer with two inputs. Assuming that inputs are two sinusoidal signals with a and b phases, and the phase difference is mall by using a simple trigonometric function and small signal approximation the multiply is [46]:

$$a\text{-}b = \sin(a - b)$$

$$\sin(a) \times \cos(b) = \sin(a\text{-}b)/2 + \sin(a+b)/2 = (a\text{-}b)/2 + \sin(a+b)$$

Where the first term is the desired phase difference and the second a high frequency term able to be filtered out by the loop filter.

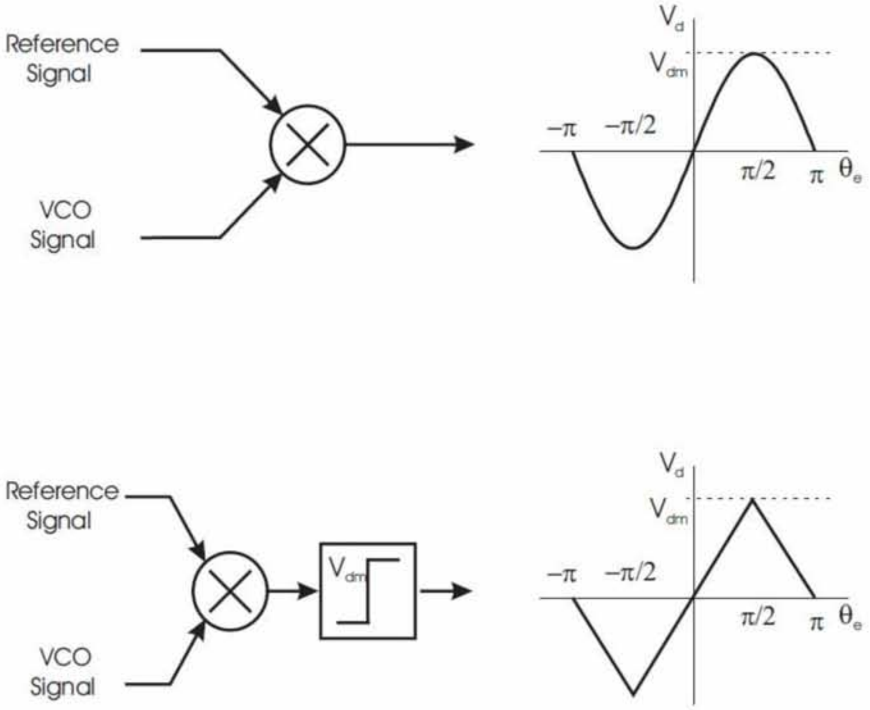
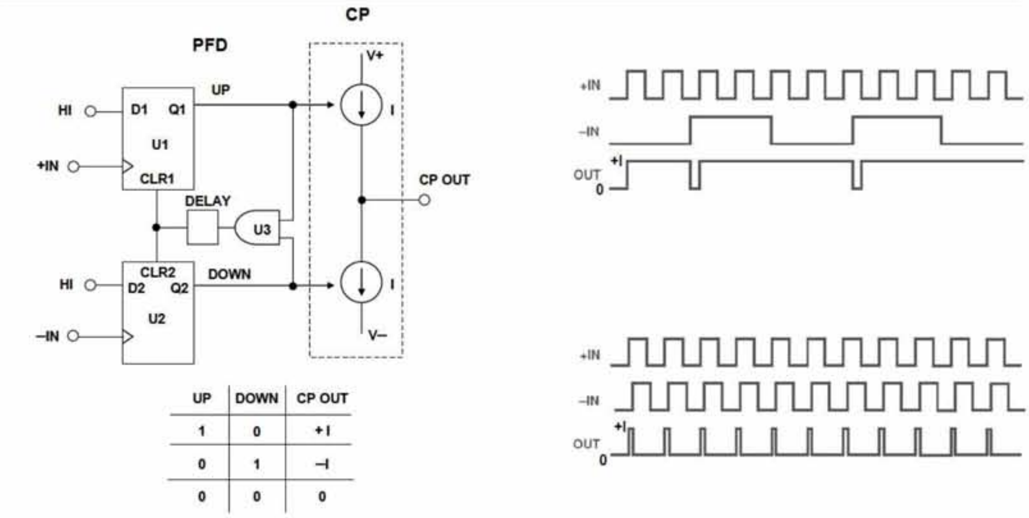


Figure 35. Analog and digital mixing PD [18]

From the output graphs on Figure 35. it is obvious that in both cases when two signals with same phase are applied in the mixing detector the output is zero. Unless a signal with Vd amplitude is produced, where Vd is the phase difference. In the same direction but with digital circuitry, an XOR gate can be used for the mixing

Another common used type of phase comparator is and edged digital memory network and basically consists of two D-flip flop elements.



UP	DOWN	CP OUT
1	0	+I
0	1	–I
0	0	0

Figure 36. a) D-flip flop based PD, b) output out of lock, c) output in lock[19]

There are two outputs (Q1, Q2) from the D-flip flops: Q1 enables a positive current source while the Q2 output drives a negative current source [47]. If the frequency on the input of the upper flip flop is bigger than the input on the other, up output is on high state (+I) so the positive current source is enabled and the detector output is on high state. When the first positive edge comes on the –IN the output falls. If the –IN was the one with the higher frequency, then a reverse operation will occur (-I in the output until a rising edge on +IN). The waveform on Figure 36.b. present exactly the first condition that was explained. Figure 36.c. shows that even though the two signal on +IN –IN are on frequency they have slightly different phase, so the procedure continuous until complete elimination of error.

CHAPTER 5

MICROGRID CONTROL & STABILITY

On electric power systems, traditional or modern, one of the most important and crucial parameters is the ability of the system itself, to remain in a steady-state secure point due to the whole operation cycle. Disturbances, fluctuations or even worse, faults and errors can lead the system to non-desired conditions. Except with that, unsolved instability issues for a long time of period can lead to cascaded faults and serious damage on the system's equipment or even worse on generators (In fact, power system has been designed in such a way, that in a case of fault near generator, transformers in the common bus ground all the fault current and the damage).

Thus, the ability of the Power System to recover to a new steady-state secure point after such a fault called *Stability*. Previous study shows, that the high penetration of DERs and RES, can lead to numerous disturbances and volatilities on voltage frequency and power. To be more specific, for the Wind Turbines that are examined in this thesis, the intermittent nature of the wind energy can arise serious instability issues for the Microgrid or the Smart Grid. In addition, as a non-conventional big power centralized plant, wind turbines and wind farms have low inertia causing additional frequency instability and power flow oscillations. In order to ensure a secure power system, constant live-time synchronization between micro sources and grid must be accomplished. In a Smart Grid, microgrids ensure stability with an intelligent way through power electronics, circuit breakers, intelligent controllers and PLL synchronization algorithms. In the following section control management and main of the control units in Microgrid are examined in addition with the most common PLL synchronization methods.

SECTION 1

Stability Factor

There are three main types of stability that must be ensured in an electric power system. Stability of Angle, Stability of Frequency and Stability of Voltage.

Voltage Stability

The ability of an electric power system to keep the voltages of all busses on the grid, on accepted fixed values, when a disturbance happens called Voltage Stability [49]. Main reason that lead to voltage instability is the condition, where a group of loads try to increase their power demands above the production levels. It is obvious now, that a well-designed power system that can keeps the energy balance between production and consumption is voltage stable. Big disturbances arise after a sudden dispatching of a big generator, while small fluctuations on voltage levels on bus can happen after small fluctuation in energy demands.

In a conventional system with big centralized plants, during a disturbance the fluctuation on demands can be covered by the kinetic energy stored in the rotating mass of synchronous generators. Instead a Microgrid has a low voltage stability profile due to lower power sharing support. A microgrid based on Wind Farms, during a fault or disturbance will go on isolated islanded mode due to the current control mode on turbine's power electronics, and the system will be leaded to deep imbalance [50].

Frequency Stability

Frequency stability called the ability of a power electric system to keep frequency of the system in accepted levels (50~60Hz) [49]. In fact this parameter depends on the ability of the power system to restore errors in the energy balance between production and consumption, with the minimum load rejection. This kind of instability appears in a form of oscillations in the systems frequency. Unless a proper methodology for fast frequency recovery takes place, cascaded rejection of loads and generators can occur. In a microgrid such instabilities arise due to surplus of generation, after islanding or equipment miss.

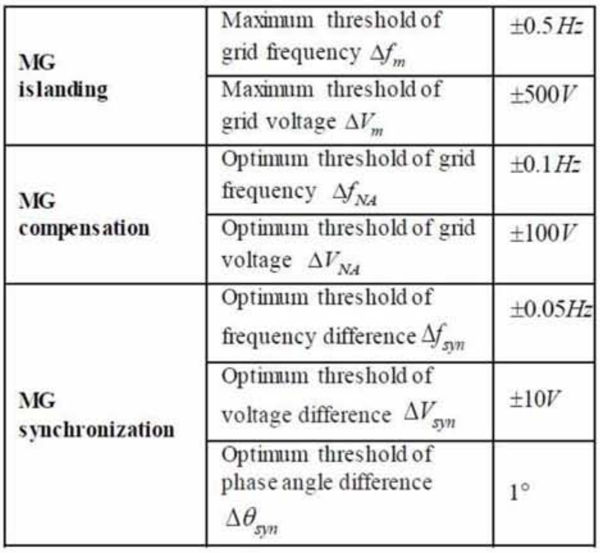
It will be explain in following study, that inverters on turbines and micro sources are those who define the amount of the output power of the turbine and it depend on the frequency of the grid on the common bus at that time. Little variations on frequency of the grid on that bus will lead to little variations on output power [50]. These fluctuations on the turbines output power can transformed into oscillations in total power generation which translated in rotor oscillations on synchronous generators. These electromechanical oscillations produce low frequency power oscillation on the Micro Grid. The impact of such oscillations is of major concern, as the intelligent controllers on such a grid are very sensitive on those disturbances. Oscillations can be translated as big disturbances and the control manager of the Micro Grid will set it to an undesirable islanded mode. Considering that those oscillations are numerous on a power system, the whole Micro Grid is declined for long time of period.

Angle Stability

Angle Stability refers to the ability of grid's generators to keep in synchronization with the grid [49]. Such a kind of instability depends on the ability of the synchronous generator to keep balance between electromagnetic torque and mechanical torque of the motor, in order to have a steady speed on the rotor. During a disturbance state, variations between rotors' speeds among the generators can arise. This condition creates differences on rotor's angles leading to physical oscillations on rotors.

A microgrid based on wind turbines has lower angular stability due to lower system inertia. In conventional grids inertia supports by the rotating mass of the synchronous generators on big plants. Again, in transient states due to disturbances the microgrid is isolated and the inertia falls dramatically. *The lower the inertia of a power system the higher the vulnerability to voltage and frequency instabilities* [50].

In addition, island mode on Microgrids can produce sudden changes to power demands of synchronous generators and as a result power imbalance. This can either accelerate or decelerate motors leading to frequency and angle instabilities.



MG islanding	Maximum threshold of grid frequency Δf_m	$\pm 0.5 Hz$
	Maximum threshold of grid voltage ΔV_m	$\pm 500 V$
MG compensation	Optimum threshold of grid frequency Δf_{NA}	$\pm 0.1 Hz$
	Optimum threshold of grid voltage ΔV_{NA}	$\pm 100 V$
MG synchronization	Optimum threshold of frequency difference Δf_{syn}	$\pm 0.05 Hz$
	Optimum threshold of voltage difference ΔV_{syn}	$\pm 10 V$
	Optimum threshold of phase angle difference $\Delta \theta_{syn}$	1°

Figure 37. Standards for IVSI control [20]

SECTION 2

Microgrid Control Structure

A typical power grid controlled and managed by a central operator. SCADA systems, PLCs and sensors send signals in the System Operator through a human interface. The system operator decides about critical operation parameters of the grid. Even though a conventional power system consists of few centralized power plants the grid's analysis complexity is big, and in addition the final decisions are from humans. For a Smart Grid consisting of a number of small Microgrids consisting of a number of DERs, the typical control management is unable. It is obvious that with so many fluctuations and disturbances on the grid all the period, human decisions must be replaced by automated methods.

For the Micro Grid's control a typical hierarchical three level control model is applied [51].

- *Third Level Control.* Optimization and balance between main grid and micro grid power flow.
- *Second Level Control.* Restore of any errors have occurred on the primary control on the frequency and voltage levels.
- *Primary Level Control.* Voltage and frequency synchronization parallel to optimized energy demand distribution.

In this sphere, a Micro Grid Central Controller has been designed in order to centrally control the whole operation in the grid. The MGCC is the head of hierarchical control system and is unusually installed at the medium voltage/ low voltage substation after the point of common coupling with the main grid (PCC) [52]. Several tasks like economic managing functions, communication with markets controllability configurations can be included on the MGCC system. The next control unit on the hierarchical control system is the Load intelligent Controller in each load and the Micro Source controller in each generator or storage device. Information like power consumption, power demands, reactive power, setting points for controllers, and signals for smart switches can be included on the communication between local controllers and the MGCC [52].

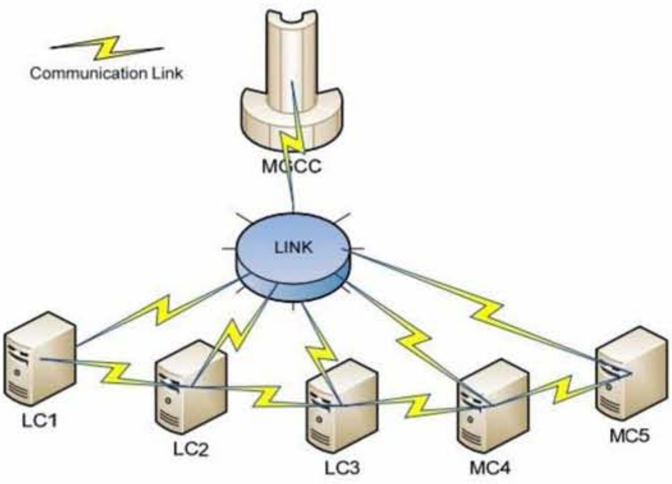


Figure 38. MGCC, MC, LC communication network

It is unable to directly connect distributed generators like wind turbines on the grid due to the intermittent nature of the plants. Synchronization limitations forbid the direct connection of the WT to the DC bus. In order to prevent that limitation and synchronize the wind turbine, power electronic inverters placed between the microgrid and the generator. Each inverter has an intelligent controller which control the system in two ways: Current source inverter control (CSI) where the controller gives a setting point for reactive and active power, and Voltage Source inverter (VSI) control where the controller gives setting points for voltage and frequency [50]. In the first state, the micro sources are interconnected with the microgrid so references for voltage and frequency are taken by the common bus. In an islanded mode where there is no connection with the bus a VSI control strategy is unable, so VCI control can be used in order to provide the reference voltage frequency parameters.

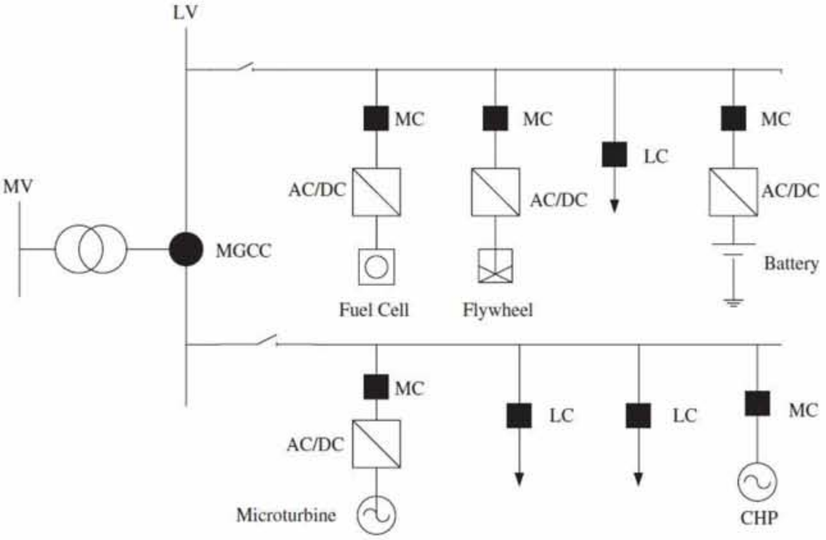


Figure 39. Microgrid topology with MGCC, LC, MC and Power electronics [21]

This intelligent control unit on the inverter is also called Micro-controller-based grid synchronizing controller (GSC) [50]. In the interconnected mode the preset values of the output power are given in real time by a maximum power point tracking algorithm (MPPT) in order to ensure maximum deliverable power from the wind turbine [50].

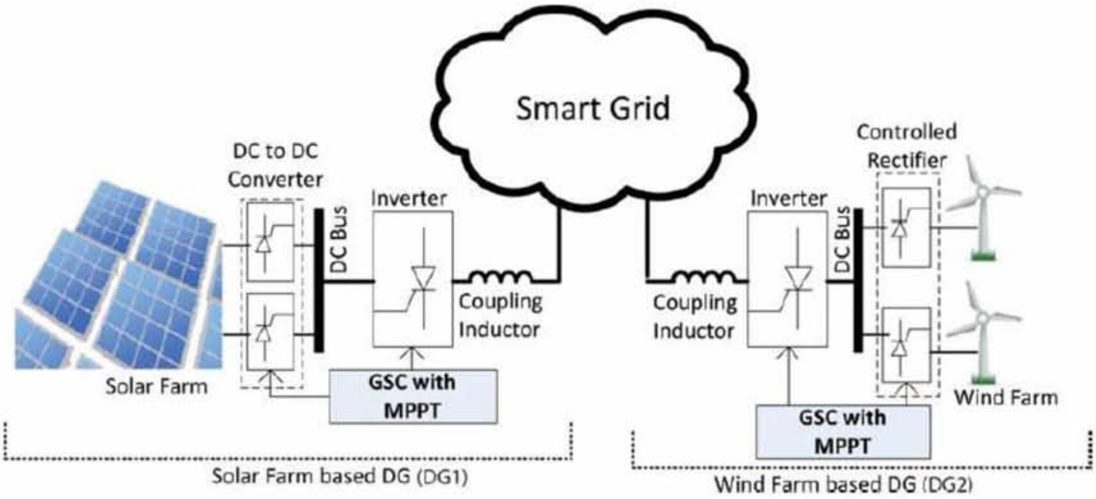


Figure 40. Connection of DERs with the Smart Grid [22]

Something that does not present in Figure 39. is the PCC controller. In the common coupling point there is an intelligent controller which communicate with the MGCC and monitors if there are any disturbances or imbalances on the grid. In problematic case, PCC controller sends signals to PCC circuit breakers in order to return to isolated islanded mode.

In addition, there is one extra control unit in a Micro Grid the Microgrid Energy Manager (MEM), which is a control management and monitoring software running on the grid. Typically include functions like energy management (demand responses, balances both for active and reactive power), generator and load management, SCADA and system reconfiguration after faults [53]. From analytical processing of such data in addition with weather forecasts and manufacturing characteristics of wind turbines a MEM can predict in a satisfactory way the available amount of generated energy in the near future.

SECTION 3

Microgrid Control Methods

The challenge in the Microgrid and in Wind Turbines synchronization is the extraction of the phase angle and frequency of the grid in live time. A quick review on literature, proves that methods and algorithms based on Phase-locked loop have become a state of the art for detecting this parameters [54], [55], [56]. Before starting the literature review on the main synchronization techniques, an explanation on some parameters is needed as at the majority of the techniques are being used.

Clark Transformation

By theory, Clark transformation takes as input three rotating vectors, the three voltage vectors (Va, Vb, Vc) which have the same amplitude and 120o angle difference (if the system is symmetric, unless proper analyze in sequential components is mandatory) and produces two vertical rotating vectors with the same frequency with the initial ones. The below equation gives the Clark transformation [57]:

$$\begin{bmatrix} Ua \\ U\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \end{bmatrix}$$

where Uan, Ubn, Ucn are the voltages of the three grid voltages. The Clark transformation will produce two alternative signals with 90o phase difference and magnitude equal to those of the grid, in a non-rotating reference frame.

Park Transformation

In common Park and Clark transformations come together on an analysis. Taking as input the two produced alternative signals of Clark transformation, the Park transformation gives two DC values in a rotating reference frame. If the rotating reference frame has different frequency from the previous f of the grid (the 50Hz) then Park transformation will give two signals with frequency the difference of the initial two. The below equation of Park transformation gives the two DC components Ud, Uq [57]:

$$\begin{bmatrix} Udg \\ Uqg \end{bmatrix} = \begin{bmatrix} cos\,\hat{\theta} & \sin\hat{\theta} \\ -sin\,\hat{\theta} & cos\,\hat{\theta} \end{bmatrix} * \begin{bmatrix} U\alpha g \\ U\beta g \end{bmatrix}$$

Mouna Rekik et al [53] proposed a new synchronization technique for Microgrids based on an intelligent voltage source inverter (IVSI). Taking into consideration the constant fluctuations on frequency and voltage in PCC bus, the method tries to synchronize the microgrid with common coupling point. By analyzing the grid state, the IVSI controls automatic switches in order to ensure reconnection of a Microgrid after islanding in the proper time. As shown in figure 41. the synchronization algorithm consists of six separate but with, complete communication, and control blocks. First the conditions both of microgrid and utility grid on the Common point coupling (PCC) are detected (voltage, frequency, phase, and angle). In order to achieve that, two DQ-PLL topologies are being used. Inside the phase-locked loop there is a set of Clark and Park transformation in order to analyze the voltage three-phase vectors on steady dc values on a reference system. From DQ equations and assuming that the angle (θj – θj') is very small

$$\begin{bmatrix} V_{dj}(\theta) \\ V_{qj}(\theta) \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta}_j & \sin\hat{\theta}_j \\ -\sin\hat{\theta}_j & \cos\hat{\theta}_j \end{bmatrix} \begin{bmatrix} V_{\alpha j} \\ V_{\beta j} \end{bmatrix} = \left\| V_j \right\| \begin{bmatrix} \cos(\theta_j - \hat{\theta}_j) \\ \sin(\theta_j - \hat{\theta}_j) \end{bmatrix}$$

$$V_{qj}(\theta) = \left\| V_j \right\| (\theta_j - \hat{\theta}_j)$$

where θj is the estimation on voltage's vector phase angle and Vj is the source voltage module of the network. The PLL lock is succeeded by minimize the error (θj – θj') to zero. For this reason a PI controller drives the transformations. The output of PI regulator (the angle frequency variation – the error) is added with the nominal angle frequency and the angle estimation θj' produced by final integration component.

Having both the estimation of angle of Microgrid and Utility grid in PCC, network analysis block checks at each instant if there is any instability issue. By comparing the measured values of voltage and frequency with fixed thresholds of figure , and by sending proper signals on next blocks, controls the static switch SS in order to go off-grid or interconnected mode.

If Δf>Δfm or ΔV>ΔVm , the network analysis sends a signal (NA=0), SS switch opens and Microgrid goes to islanded mode. As long as the values are above thresholds the SW12 switch is on 0 position and the microgrid synthesizes its own frequency and voltage. On the first positive measurement an NA =1 signal is being sent and the procedure for optimal reconnection begins.

If voltage and frequency of grid on the bus are into the threshold margins the MG reconnects. In a different condition, the synchronization algorithm block compares the threshold values with the PLL outputs in order to analyze the state of MG. A signal S sets to "1" only if the two voltages of MG and Grid are synchronized. If NA=0 the microgrid is standalone so no addition action is needed of this block. If NA=1 the algorithm understands that the grid has stabilized after a disturbance or fault, but the voltages are out of synchronization. In this state only, SW12 switcher is "1" showing that there is a reference for Vpcc-grid and the MG can use it as reference. IVSI control block, reconfigure Vpcc-MG through a PI regulator until Vpcc-mg Vpcc-grid be synchronized. After the end of synchronization a signal S=1 send to SS switcher to close and connect the Microgrid with the stable Grid.

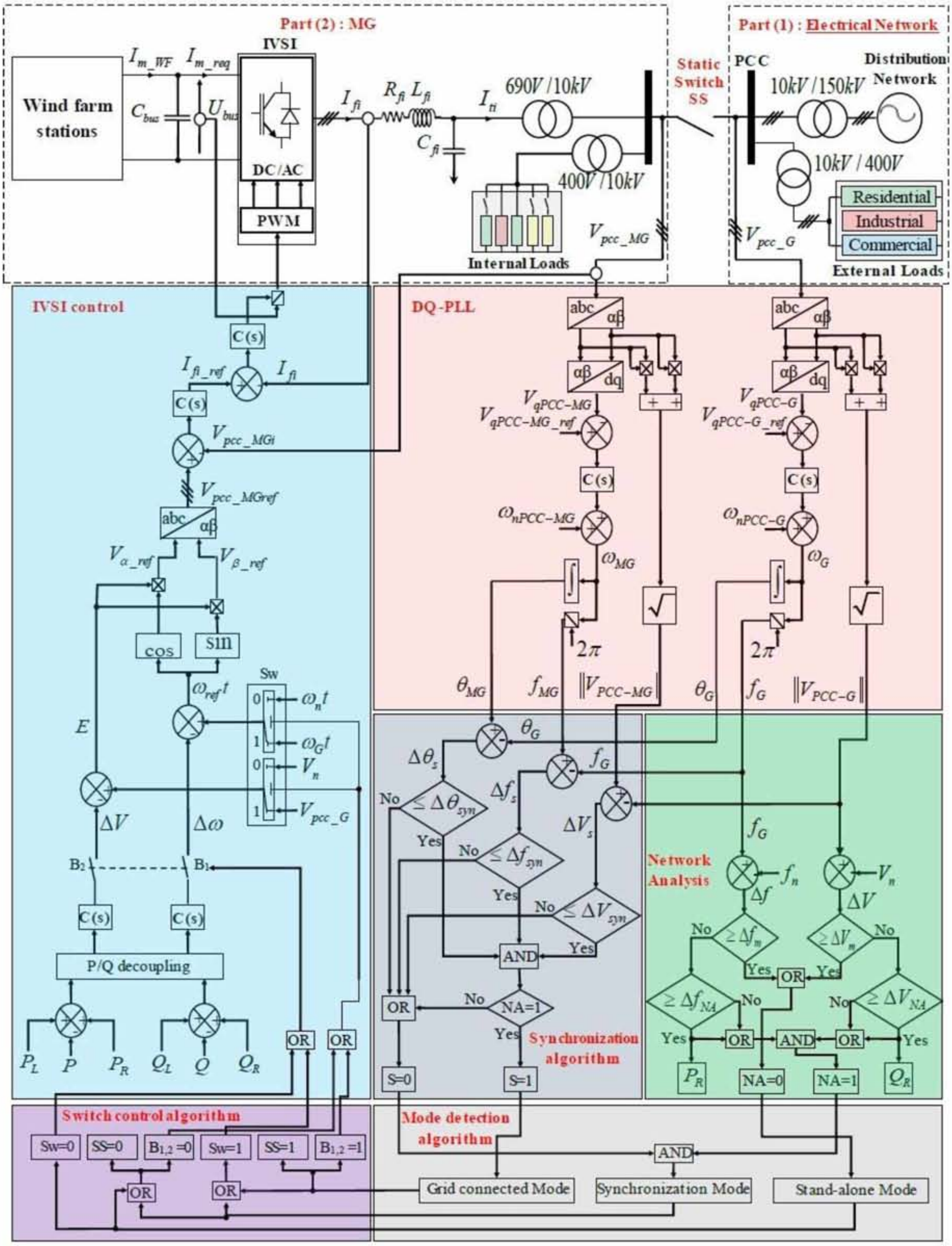


Figure 41. Block Diagram of the proposed synchronization method [20]

In a different sphere, S. Tripathi et al [58] propose a wind energy conversion system consisting of a wind turbine with a permanent magnet synchronous generator, a frequency converter topology with two inverters, one on the side of turbine and the other on the side of microgrid, two PWM systems and a dc link capacitor. The main task of a dc link capacitor is to filter out the dc voltage ripples. In addition, the converters should be configured in such a way, that the maximum possible power can be generated to the output with the best power quality.

As a first step in the procedure, a PLL block tracks the phase angle of the three wired grid. The produced tracked angle, drives two d-q transformation blocks (with the previous examined Park/Clark transformations) in order to provide a set of reference frame (idg-iqg, edg-eqj) that rotates synchronously with the grid voltage and another one with the current grid.

Continuing on the grid-side, the authors propose a control structure with two loops, one inner current loop and one (the outer) dc-link voltage control loop, as the main task of the control structure is the configuration of DC-link voltage among the converters. First a comparison between the actual dc-link voltage and the reference dc-link voltage occurs through a PI controller who generates the reference current id. Then the estimated reference currents id, iq and the actual are compared and after a PI controller the converters reference voltages vd, vq are produced. Using a modulation technique pulses encoded to signal for the grid-side converter.

On the other side of examination, in order to set the control parameters for the turbine-side converter, the generator must be modeled. The stator voltages of the generator of the wind turbine transformed in d-q system given by the following equation:

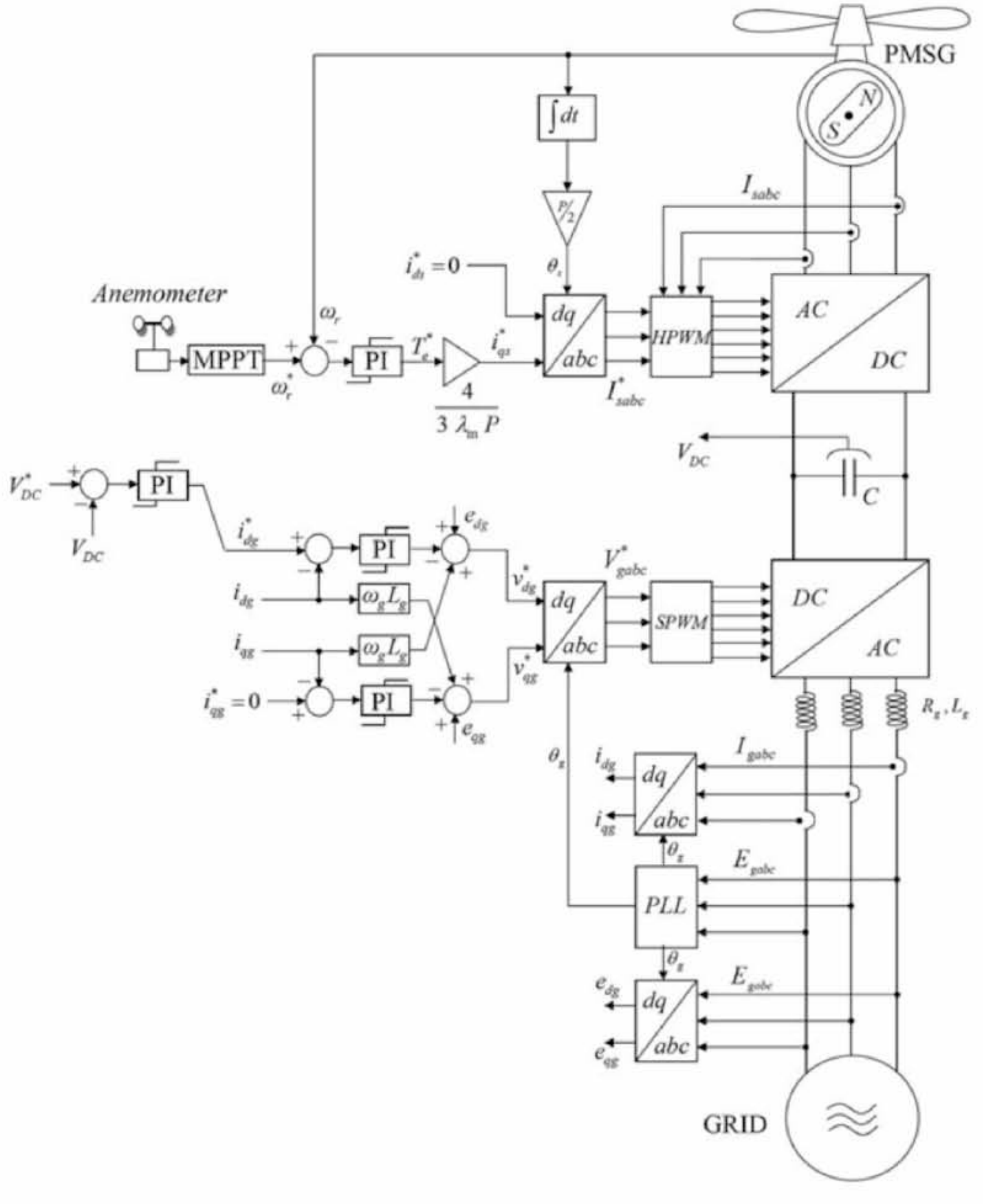
$$v_{ds} = R_s i_{ds} + L_d \frac{d}{dt} i_{ds} - \omega_s L_q i_{qs}$$

$$v_{qs} = R_s i_{qs} + L_q \frac{d}{dt} i_{qs} + \omega_s L_d i_{ds} + \omega_s \lambda_m$$

where ωs is the electrical speed, Rs stator resistance, Ld and Lq stator inductance transformed in d-q system and λm the rotor flux. Generators torque also is given by the above equation (Due to low speeds Ld can be considered as equal to Lq.):

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[\lambda_m \cdot i_{qs} + \left(L_d - L_q \right) \cdot i_{ds} \cdot i_{qs} \right]$$

It is obvious that, the control structure must take under consideration the above equations to ensure the proper results. The turbine-side converter control topology consists again of two loops: an inner current control loop and an outer speed control loop. In the outer loop, the actual rotor speed from the wind turbine is compared with the estimated rotor speed given by measurements of anemometer and an MPPT algorithm. Through a classic PI controller topology, estimation of the electromagnetic torque (Te) is achieved by minimizing the error of rotor's speeds. Considering the above equation for electromagnetic torque, and the estimated value of torque, a prediction for q-reference current of the stator is given. For the known angle of the wind turbine, the produced estimated currents for the three phases produced by a reverse Park transformation, drive a PWM in order to be compared with the actual ones in the inner current loop.

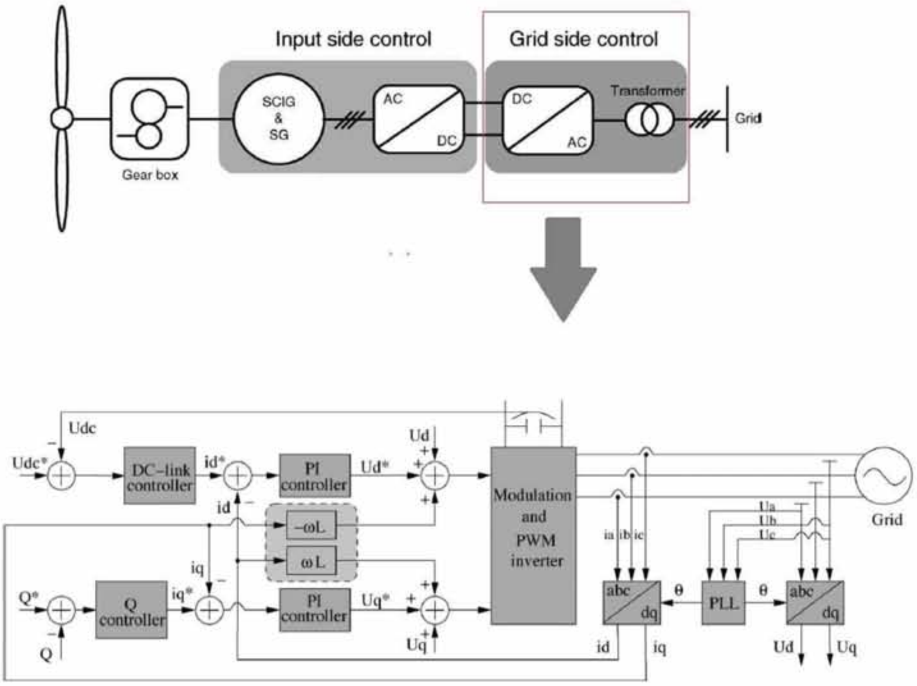


42. Schematic of the S. Tripathi's et al suggested control structure. [23]

Another microgrid control strategy based on PLL, examined by Frede Blaabjerg et al [59] in their effort to give an overview of the main control structures. They propose a division among the control strategies with respect to the reference frame control. One of the studied methods dq control also called synchronous reference frame control transforms the grid voltage and current using Park and Clark transformation into a reference frame which rotates synchronously with the grid voltage. This method is targeting in grid-side inverter synchronization and control.

In a similar way with the above methods, a PLL is used in order to track the grid's phase angle. This angle is used by Clark & Track transformations in order to produce new references in the form of DC values. The control strategy of the converter now consists of two loops. The first one (the outer) is responsible for regulating the dc link voltage. The inner, the current loop controls the power quality.

Taking the difference of the actual dc-link voltage and the estimation, DC link controller generates the estimation for d-reference current and again with the actual one (by the initial transformation of the grid's current) a PI controller generates the estimation for Ud. In order to improve PLL's performance decoupling technique is used. In a similar way, Q controller produces the q-reference Uq*. Using a PWM before the inverter the proper tones-pulses for the electronics biasing are generated. Figure 43. presents this dq-control method.



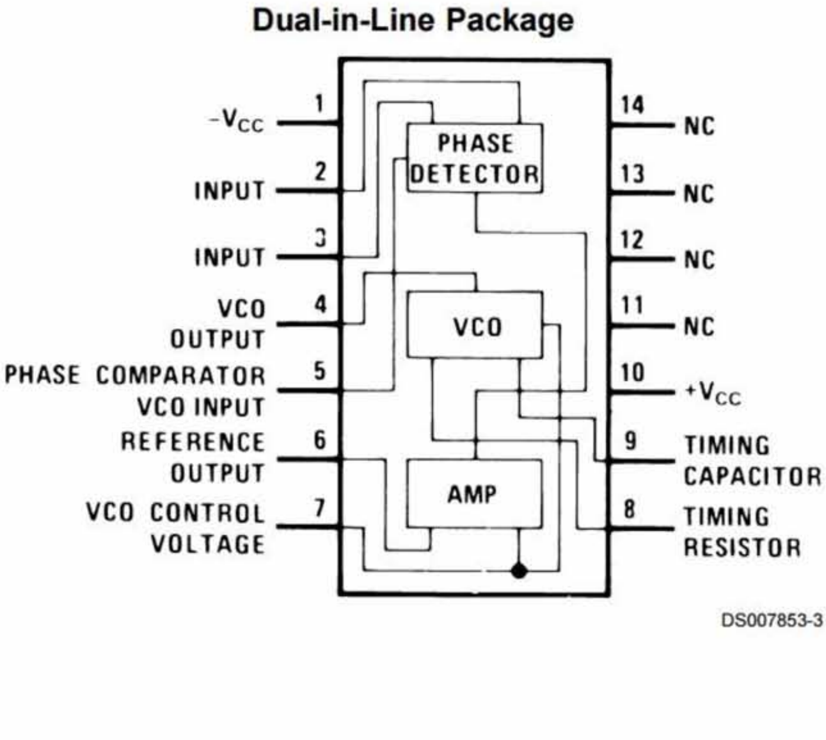
43. Schematic of the dq control structure. [24]

CHAPTER 6

SIMULATIONS & RESULTS

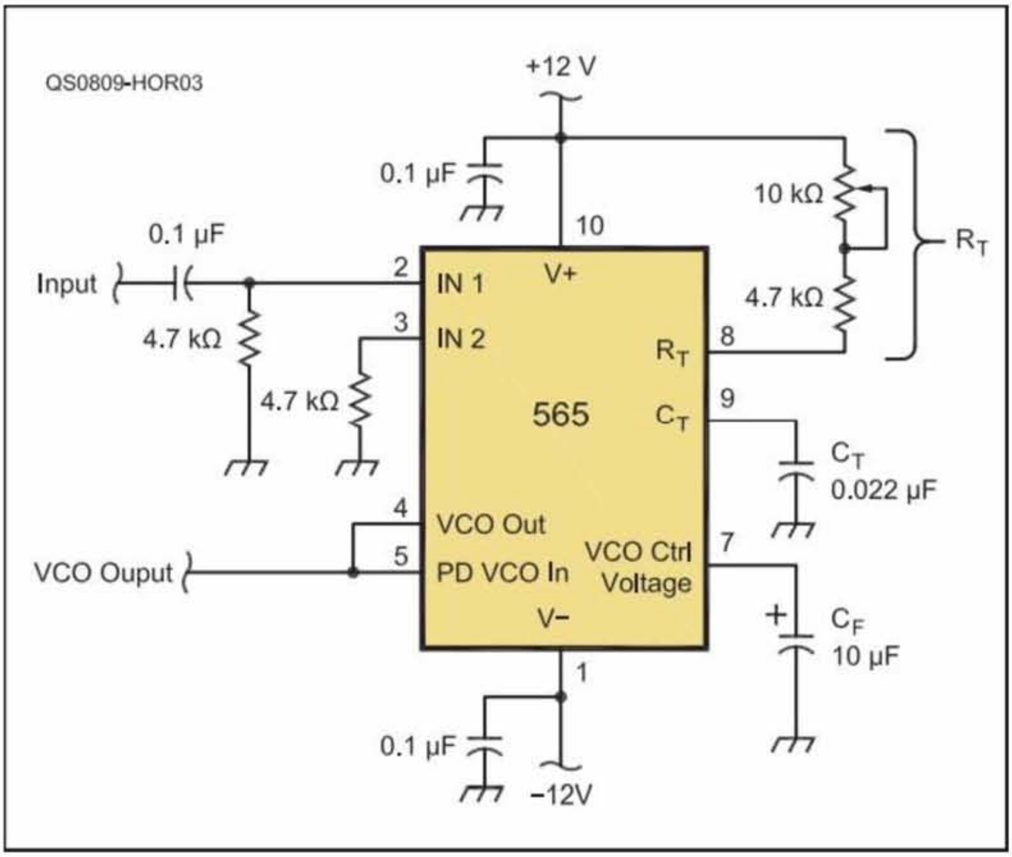
The previous literature review showed that one of the basic blocks on the microgrid-wind turbine control management is Phase-Locked Loop. Even though PLLs used in many applications with various operations and functions, in the control management its main task is to track the phase (the angle specifically) of a current.

In order to be fully understood, a Phase-Locked Loop using NE565 IC, has been designed and simulated and the results will be provided and examined in the following section. In figure 44, pin diagram of NE565 PLL is given.



44. NE565 PLL Pin Diagram [25]

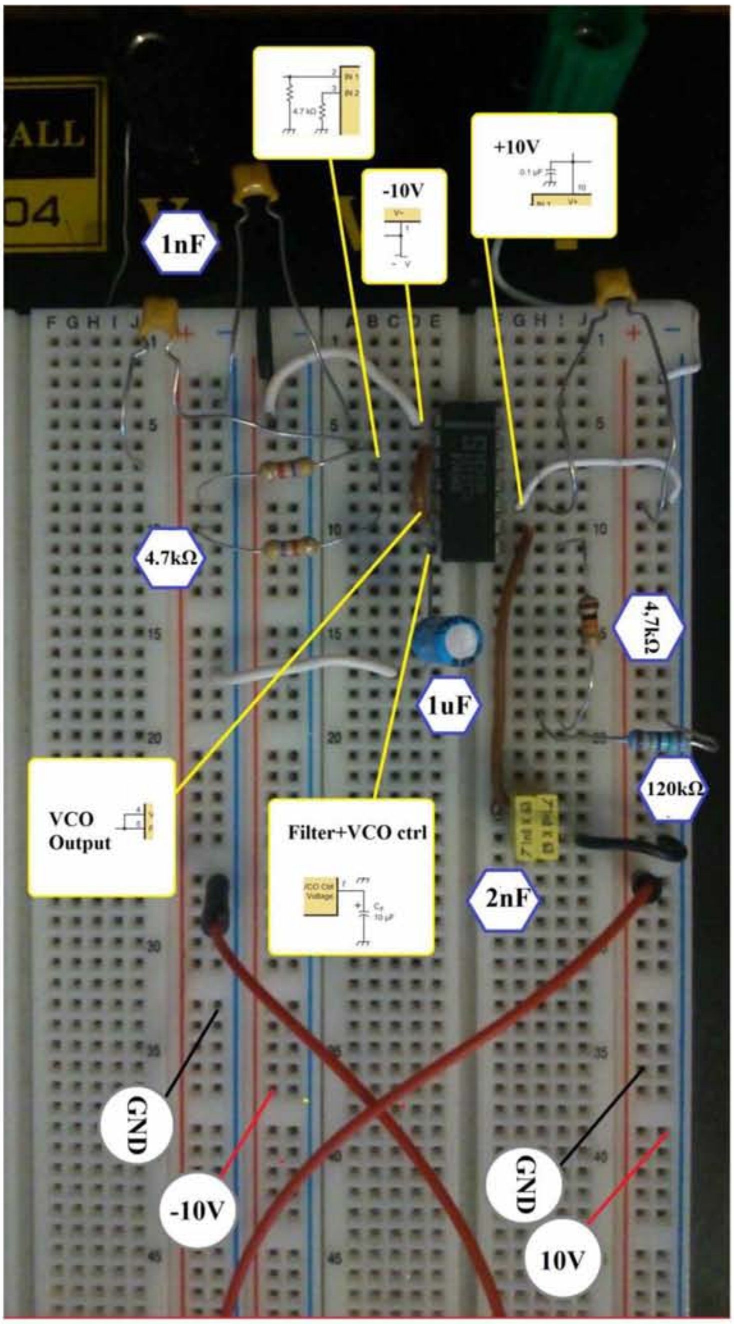
For a typical operation as an FM demodulator, only a few resistors and capacitors are mandatory. Specifically one capacitor in order to form the low pass filter, a timing resistor and a timing capacitor to configure the oscillator, capacitors for coupling and resistors for biasing. Figure 45 shows the designed schematic.



45. LM 565 schematic as an FM demodulator [26]

By reading the datasheet and with selected values for resistors and capacitors [60]:

- Free running frequency of VCO: **fo= 1.2/4R1C1 = 1.121kHz**
  Where R1= 124.6kΩ and C1=2nF
- Lock frequency range of PLL : **fL= 8fo/VCC= 448Hz**
  Where VCC=20V
- Capture frequency range of PLL: **fc=1/2π(2πfL/τ)^0.5=60Hz**
  Where τ=(3600 x CF) and CF=1uF



COMPONENTS

1. **0.001uF Capacitor**
2. **4.7kΩ Resistor**
3. **120kΩ Resistor**
4. **1+1nF (2nF Capacitor)**
5. **1uF Capacitor**
6. **4.7kΩ Resistor**

Figure 46. Connection diagram of the designed PLL in breadboard

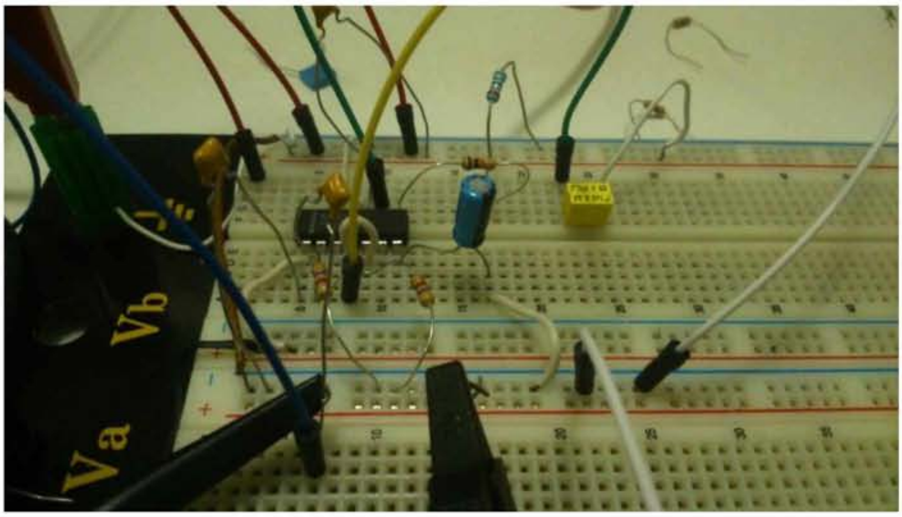


Figure 47. Designed PLL in a different simulation

In order to find the three operation regions, the free running frequency of VCO is firstly configured. A timing resistor 124,6kΩ is being selected in order to achieve a frequency close to 1 kHz. Specifically, the free running frequency of VCO for this value and for 10V supply is 1.121 kHz. Next, a reference signal with 1.120 kHz is connected to the input (pin1). As figure 49 shows, the PLL is closed and the two signals are stable and have the same frequency. In this point of analysis, we have to mention that there are certain frequencies, where the PLL seems to be locked, due to the fact that they are stable, but they don't have the same frequency. These kind of frequencies are pseudo-lock PLL frequencies. For instance in 2.3 kHz the input and output signal are stable, but VCO generates 1.15 kHz signal instead of the 2.3 kHz reference signal.

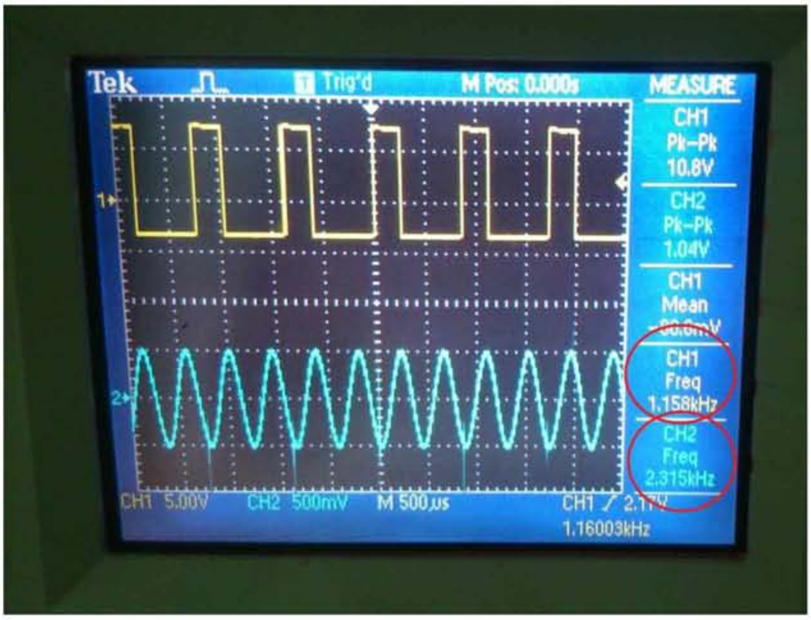


Figure 48. Pseudo-lock at 2.3 kHz reference signal.

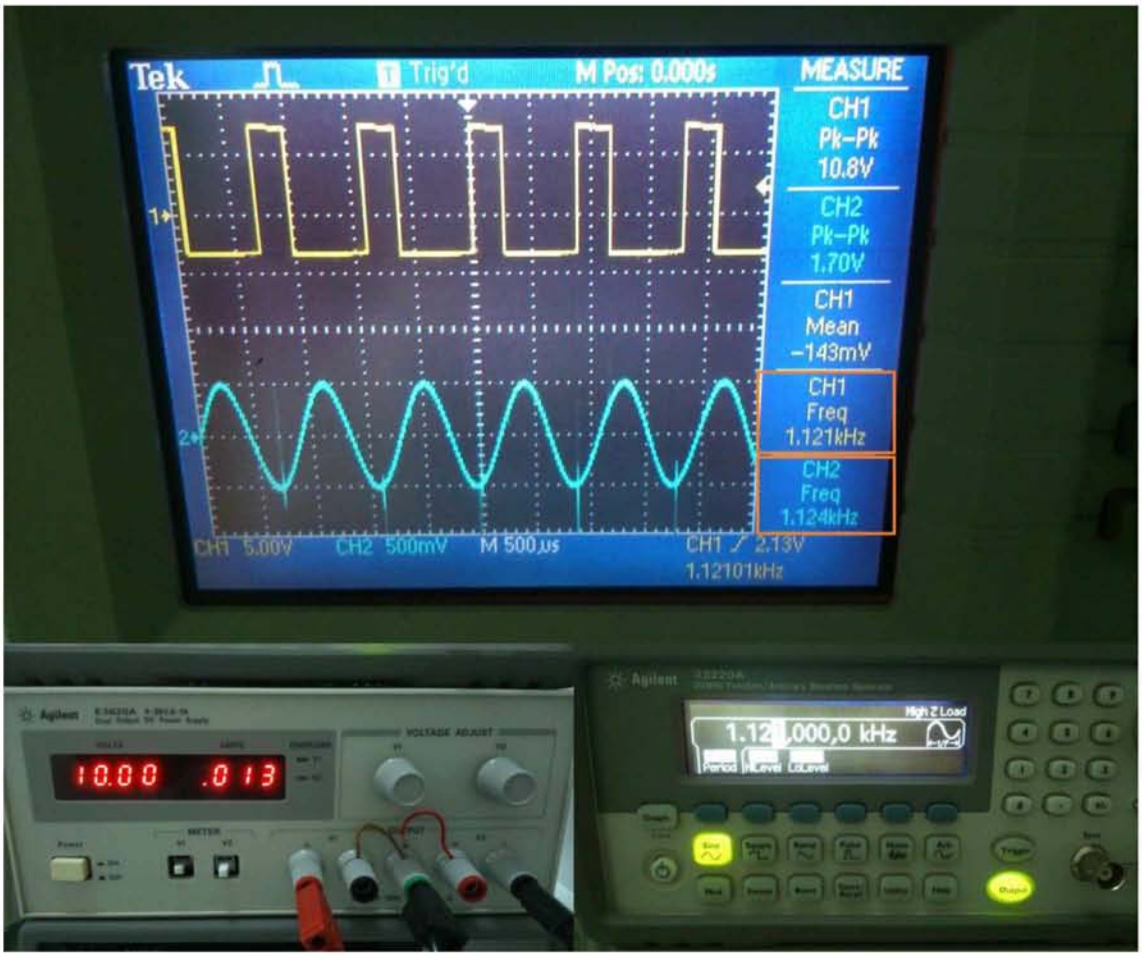


Figure 49. Locked PLL at 1.121 kHz center frequency

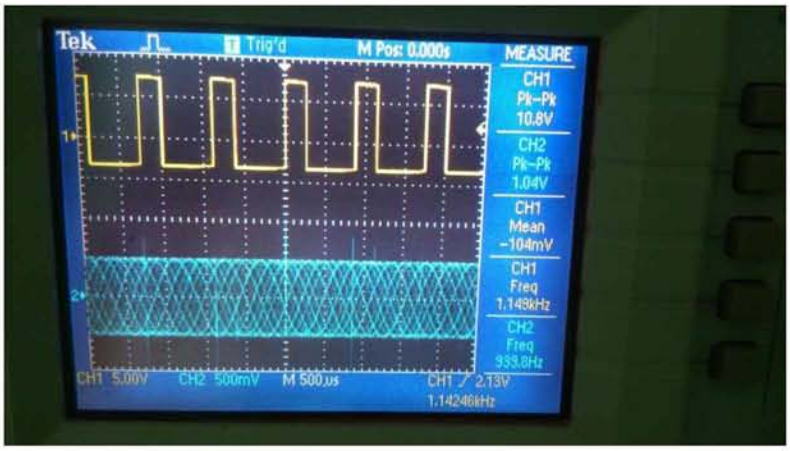


Figure 50. Lower Capture Frequency at 940 Hz

Next, with small reductions in reference's signal frequency (10Hz) to avoid the PLL's unlocking, the lower capture frequency found at 940 Hz. In this frequency the PLL goes to unlock state and the VCO signal is unstable. In experiment the opposite effect seems to happen (reference signal runs) as CH1 is triggered.

In addition, by increasing the frequency with small increments, similar to the above simulation, the higher frequency that the PLL can be locked found at 1.4 kHz. This frequency is the higher lock frequency of PLL. By PLL's theory, the higher lock frequency is much higher than higher capture frequency, so in order to find the second one, the PLL goes in intentional unlock at 1.5 kHz and then with small frequency reductions the loop locks again at 1.19 kHz, where the f_{CH} is. Finally, continuous reductions can lead to the low lock frequency of PLL at 830 Hz.

From simulations it can be summarized that:

Free running frequency	Lock frequency range	Capture frequency range
1.121 kHz	580 Hz	89 Hz

The results seem to be very close to these ones of theory, so they can be accepted. It is obvious that in lock region the PLL's output has a pulse waveform, and the gain of close-locked loop is 11Vpp.

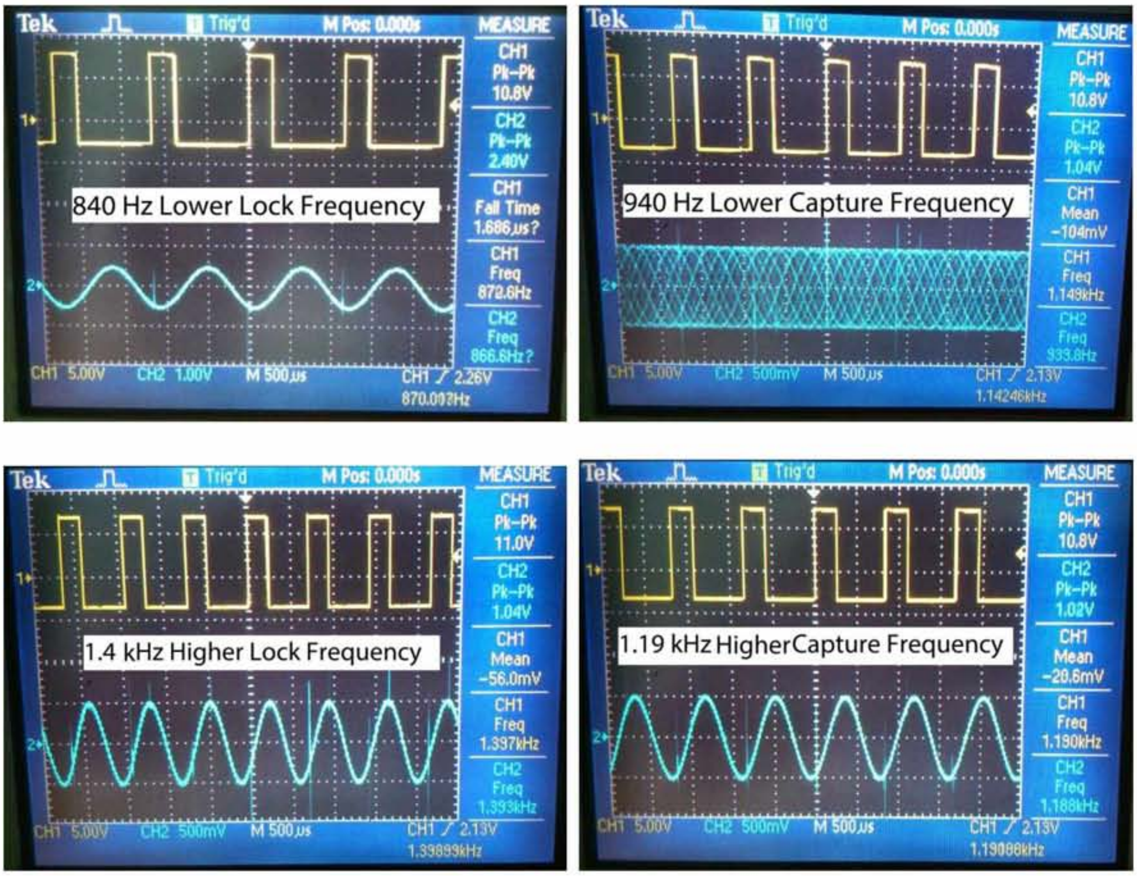


Figure 51. a) Lower Lock, b) lower capture, c) Higher Lock, d) Higher Capture frequency

Taking into consideration the design equations of capture and lock frequency range, different capacitors on low pass filter structure (C5 in the block diagram) simulated in order to prove that the smaller the capacitor the bigger the capture range (reverse proportional). Lock range remain the same as it only depends on free running frequency and voltage supply.

Finally, to close the low pass filter analysis, changes of reference's signal frequency will lead to changes on the produced DC value of filter in order to control the VCO. In fact, the output of filter in lock range is an AC signal with very small magnitude due to noise and not a DC one. For instance, CH1 of olliscope in figure 52 presents the signal in pin7 (in low pass filter output) in 1.121 kHz lock frequency.

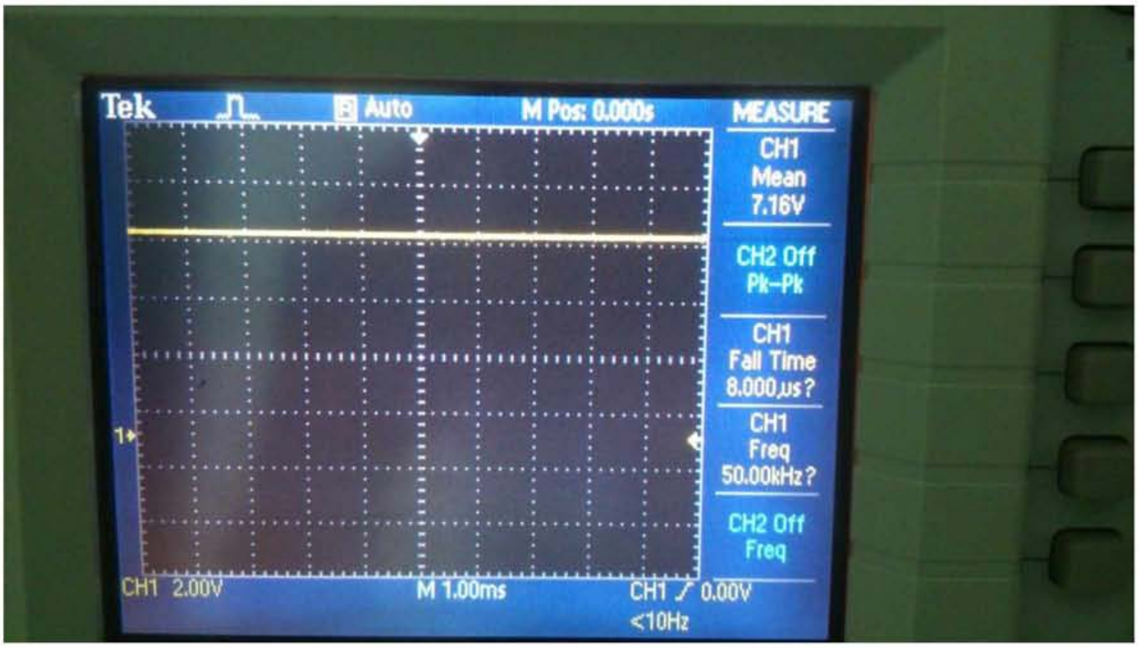


Figure 52. Pin 7 wave in 1.121 kHz

CHAPTER 7

CONCLUSION

To deal with energy crisis and environmental problem systems based on renewable energy sources gaining ground. By replacing centralized big plants with distributed generation, power systems are going through a paradigm change. From traditional long scale transmission and distribution networks to Smart Grids and Microgrids able to cover energy demands of a whole country. Although, the most crucial challenge of such systems is the intermittent nature and randomness of renewable energy sources. To avoid fluctuations and fatal errors power electronics with specific synchronization algorithms are being used on the connection between the utility grid and the generator.

In this thesis, an outline of the common synchronization and control methods of wind turbines in a Microgrid was provided among with a brief study on electric power systems and wind energy systems. Studies and experiments have shown that PLL systems could provide accurate and live-time phase detection and as a consequence satisfactory synchronization. However PLLs suffer from nonlinear structure and slow performance, which can bring many problems in front of a growing customer's desire for better power quality. It is worth mentioning that with new systems, the Virtual Synchronous Machines and inverters with embedded synchronization units it is possible to remove this dedicated synchronization and improve performance, but as it is an emerging technology ,further experiment and research are mandatory [61].

CHAPTER 8

REFERENCES

[1] R. Lawrence and S. Middlekauff, "The new guy on the block," IEEE Industry Applications Magazine, vol. 11, no.1, pp. 54–59, 2005. doi: 10.1109/MIA.2005.1380328

[2] R.Lasseter, P. Piagi," Microgrid: A Conceptual Solution", IEEE 35th Annual Power Electronics Specialists Conference, Germany, 2004 doi: 10.1.1.153.8831&rep=rep1&type=pdf

[3] B. O'Neill, "CLIMATE CHANGE: Dangerous Climate Impacts and the Kyoto Protocol", Science, vol. 296, no. 5575, pp. 1971-1972, 2002. doi: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-RPT-kyotoprot.pdf

[4] I. Dincer, "Renewable energy and sustainable development: a crucial review", Renewable and Sustainable Energy Reviews, vol. 4, no. 2, pp. 157-175, 2000. doi: http://www.sciencedirect.com/ science/ article/pii/S1364032199000118

[5] T. Johansson, H. Kelly, A. Reddy and R. Williams, "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential", *Energy Studies Review*, vol. 4, no. 3, 1993.

[6] N. Panwar, S. Kaushik and S. Kothari, "Role of renewable energy sources in environmental protection: A review", *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513-1524, 2011

[7] A. Herzog, T. Lipman, J. Edwards and D. Kammen, "Renewable Energy: A Viable Choice", *Environment: Science and Policy for Sustainable Development*, vol. 43, no. 10, pp. 8-20, 2001. doi: http://rael.berkeley.edu/old_drupal/sites/default/files/old-site-files/2001/Herzog-Lipman-Edwards-Kammen-RenewableEnergy-2001.pdf

[8] The European Wind Energy Association (EWEA), "Wind in power: 2015 European statistics", *EWEA's Technology Workshop,* Leuven, 2015. doi: http://

www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2015.pdf

[9] J. Guerrero, F. Blaabjerg, Y. Li, Y. Mohamed and M. Salama, "Introduction to the Special Section on Distributed Generation and Microgrids", *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1251-1253, 2013. doi: http://sci-hub.cc/10.1109 /tie.2012.2224195

[10] A. Abo-Khalil, "Synchronization of DFIG output voltage to utility grid in wind power system", *Renewable Energy*, vol. 44, pp. 193-198, 2012. doi: http://sci-hub.cc/10.1109/tie.2012.2224195

[11] S. Mishra, D. Das, R. Kumar, and P. Sumathi, "A power-line interference canceler based on sliding DFT phase locking scheme for ECG signals", *IEEE Trans. Instrum.* Meas., vol. 64, no. 1, pp. 132–142, 2015. doi: http://sci-hub.cc/10.1109/tim.2014.2335920

[12] L. Wang, Q. Jiang, L. Hong, C. Zhang, and Y. Wei, "A novel phase-locked loop based on frequency detector and initial phase angle detector", *IEEE Trans. Power Electron*, vol. 28, no. 10, pp.4538–4549, 2013. doi: http://sci-hub.cc/10.1109/tpel.2012.2236848

[13] U. B.Mujumdar, "PLL for Grid Synchronization of Single Phase Distributed Generation System", *IOSR Journal of Electrical and Electronics Engineering*, vol. 11, no. 05, pp. 28-33, 2016.,doi: http://iosrjournals.org/iosr-jeee/Papers/Vol11%20Issue%205/Version-3/D1105032833.pdf

[14] Regulatory Authority For Energy (RAE), "General Information on the Greek Electricity Sector for the period 2000-2003 : Installed capacity, production & consumption levels, Renewable Energy Sources and Long Term Energy Planning.", Athens, 2003.

[16] A. Richter, E. Laan, W. Ketter and K. Valogianni, "Transitioning from the traditional to the smart grid: Lessons learned from closed-loop supply chains", *Smart Grid Technology, Economics and Policies (SG-TEP)*, 2012.

[17] M. Amin and J. Stringer, "The Electric Power Grid: Today and Tomorrow", *MRS Bulletin*, vol. 33, no. 04, pp. 399-407, 2008.

[18] G. Giannakopoulos and N. Vovos, "Introduction to Electric Power Systems ", Zhth Publications, 2008

[19] R. Miceli, "Energy Management and Smart Grids", *Energies*, vol. 6, no. 4, pp. 2262-2290, 2013.

[20] H. Jiayi, J. Chuanwen and X. Rong, "A review on distributed energy resources and MicroGrid", *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, pp. 2472-2483, 2008.

[21] T. Ackermann, G. Andersson and L. Soder, "Distributed generation: a definition", *Fuel and Energy Abstracts*, vol. 43, no. 3, p. 191, 2002.

[22] V. Gowrishankar, C. Angelides and H. Druckenmiller, "Combined Heat and Power Systems: Improving the Energy Efficiency of Our Manufacturing Plants, Buildings, and Other Facilities", *NRDC Issue paper*, 2013.

[23] C. Hudson, B. Kirby, D. Kueck and R. Staunton, "Industrial use of distributed generation in real-time energy and ancillary service markets", *Oak Ridge National Laboratory*, 2001.

[24] ABB Inc., "Microgrids: a primer for policymakers", *ABB Inc.*, 2015.

[25] E. Hayden, "Introduction to Microgrids", *Securicon*, Virginia USA, 2013.

[26] Siemens, "White paper: Microgrids", *Siemens AG*, 2011.

[27] Iván Patrao, Emilio Figueres, Gabriel Garcerá, Raúl González-Medina, "Microgrid architectures for low voltage distributed generation", *Renewable and Sustainable Energy Reviews 43,415-424*, 2015.

[28] A. Beyene, "Energy efficiency and industrial classification", Energy *Engineering*, 2005

[29] A. Dimeas, N. Hatziargyriou, "Operation of a multi-agent system for MicroGrid control". *IEEE Trans Power Syst*, 20(3):1447–55, 2005.

[30] T. Considine, W. Cox and E. Cazalet, "Understanding Microgrids as the Essential Architecture of Smart Energy", *Grid-Interop Forum 2012*, 2012.

[31] X. Fang, S. Misra, G. Xue and D. Yang, "Smart Grid – The New and Improved Power Grid: A Survey", *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4,p 944-980, 2011.

[32] National Energy Technology Laboratory, "Modern grid benefits", *National Energy Technology Laboratory*, 2007.

[33] B. de Vries, D. van Vuuren and M. Hoogwijk, "Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach", *Energy Policy*, vol. 35, no. 4, pp. 2590-2610, 2007.

[34] Eurostat, "Renewable Energy Statistics", 2016, http: //ec.europa.eu/ Eurostat/statistics-explained/index.php/Reneable_energy_statistics.

[35] European Wind Energy Association EWEA, "Wind in power 2015 European Statistics", *EWEA*, 2016.

[36] National Energy Education Development Project, "Exploring Wind Energy-Student Guide", 2016, www.need.org

[37] T. Burton, N. Jenkins, D. Sharpe, E. Bossanyi, "Wind Energy Handbook-Second Edition", *Wiley Publications*, 2011.

[38] P. Papastamatiou, "RES and wind energy development in Greece", *HWEA Wind Energy Statistics May 2013*, 2013.

[39] I. Van der Hoven, "POWER SPECTRUM OF HORIZONTAL WIND SPEED IN THE FREQUENCY RANGE FROM 0.0007 TO 900 CYCLES PER HOUR", *Journal of Meteorology*, vol. 14, no. 2, pp. 160-164, 1957.

[40] G. Johnson, "Wind Energy Systems – Electronic Edition", Manhattan KS, 2006.

[41] M. M. Saad, "Comparison of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines", *IOSR Journal of Engineering*, vol. 4, no. 8, pp. 27-30, 2014.

[42] F. Freijedo, A. Yepes, O. Lopez, P. Fernandez-Comesana and J. Doval-Gandoy, "An Optimized Implementation of Phase Locked Loops for Grid Applications", IEEE Transactions on Instrumentation and Measurement, vol. 60, no. 9, pp. 3110-3119, 2011. doi: 10.1109/tim.2011.2122550

[43] M. Ciobotaru, R. Teodorescu and F. Blaabjerg," A New Single-Phase PLL Structure Based on Second Order
Generalized Integrator", PESC Record - IEEE Annual Power Electronics Specialists Conference, Denmark, 2006 doi: 10.1109/PESC.2006.1711988

[44] X. Guo and W. Wu, "Simple synchronization technique for three-phase grid-connected distributed generation systems", IET Renewable Power Generation, vol. 7, no. 1, pp. 55-62, 2013. doi: 10.1049/iet-rpg.2011.0243

[45] Analog Devices, "Fundamentals of Phase Locked Loops (PLLs)", *Analog Devices Inc.*, 2009.

[46] D. Abramovitch, "Phase-Locked Loops: A Control Centric Tutorial", *2002 ACC*, 2002

[47] D. Morgan, "CD4046B Phase-Locked Loop: A Versatile Building Block for Micropower Digital and Analog Applications", Texas Instruments, 2003.

[48] G. Jovanovi´c, M. Stojˇcev, Z. Stamenkovic, "A CMOS Voltage Controlled Ring Oscillator with Improved Frequency Stability", Scientific Publications of the state University of novi Pazar, vol2, 2010.

[49] M. Glavic, "Power System Voltage Stability: Short Tutorial", University of Liege, http://www.montefiore.ulg.ac.be/~glavic/REE-Seminar.pdf

[50] P. Gopakumar, M. Reddy and D. Mohanta, "Letter to the Editor: Stability Concerns in Smart Grid with Emerging Renewable Energy Technologies", Electric Power Components and Systems, vol. 42, no. 3-4, pp. 418-425, 2014.

[51] X. Lu, J. Guerrero, K. Sun, J. Vasquez, R. Teodorescu and L. Huang, "Hierarchical Control of Parallel AC-DC Converter Interfaces for Hybrid Microgrids", IEEE Transactions on Smart Grid, vol. 5, no. 2, pp. 683-692, 2014.

[52] H. Jiayi, J. Chuanwen and X. Rong, "A review on distributed energy resources and MicroGrid", Renewable and Sustainable Energy Reviews, vol. 12, no. 9, pp. 2472-2483, 2008.

[53] M. Rekik, A. Abdelkafi, L. Krichen, "Synchronization of Wind Farm Power System to Utility Grid under Voltage and Frequency Variations", International Journal of Renewable Energy Research, vol5, 2015.

[54] G. C. Hsieh and J. C. Hung, "Phase-locked loop techniques—A survey," IEEE Trans. Ind. Electron., vol. 43, no. 6, pp. 609–615, Dec. 1996.

[55] S.-K. Chung, "A phase tracking system for three phase utility interface Inverters," IEEE Trans. Power Electron., vol. 15, no. 3, pp. 431–438,May 2000.

[56] L. N. Arruda, S. M. Silva, and B. Filho, "PLL structures for utility connected systems," *in Proc. IEEE-IAS Annu. Meeting*, vol. 4, pp. 2655–2660, 2001.

[57] K. Jash, P. Saha, G. Panda, "Vector Control of Permanent Magnet Synchronous Motor Based On Sinusoidal Pulse Width Modulated Inverter with Proportional Integral Controller", *Kaushik Jash et al. Int. Journal of Engineering Research and Applications*, vol3, 5, pp. 913-317, 2013.

[58] S. Tripathi, A. Tiwari and D. Singh, "Optimum design of proportional-integral controllers in grid-integrated PMSG-based wind energy conversion system", International Transactions on Electrical Energy Systems, vol. 26, no. 5, pp. 1006-1031, 2015.

[59] F. Blaabjerg, R. Teodorescu, M. Liserre, A. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", *IEEE Transaction on industrial electronics*, vol53, 2006.

[60] National Semiconductor, "LM565/LM565C Phase Locked Loop", National Semiconductor Corporation, May 1999.

[61] Q. Zhong, "Virtual Synchronous Machines", *IEEE Power Electronics Magazine*, vol.3 no.4, pp. 19, 2017

Reference for Figures

[1] U.S. Energy Information Administration, "What is the electric power grid and what are some challenges it faces?", Energy in brief, 2015
[2] "Innovative Industrial Automation Software", http://scada-system.net/
[3] T. William and S. Madden "Greening the Grid, an Overview of the Greening of the U.S. Generation Fleet", ScottMadden Inc. , 2016
[4] "German Experiences to obtain Energy Efficiency Gains in Cities through Application of Renewable Energies in Urban Areas", http://low-carbon-urban-development-germany-china.org/wp-content/uploads/2016/05/M4-Textbook_Renewable-Energies_EN_final.pdf
[5] M. Froese, "The emerging microgrid market", Wind power engineering development, 2015
[6] Siemens, "White paper: Microgrids", Siemens AG, 2011.
[7] I. Patrao, E. Figueres, Garcerá, R. Medina, "Microgrid architectures for low voltage distributed generation", Renewable and Sustainable Energy Reviews 43, 415-424, 2015
[8] A. Dimeas, N. Hatziargyriou, "Operation of a multi-agent system for MicroGrid control". IEEE Trans Power Syst, 20(3):1447–55, 2005.
[9] A. Richter, E. Laan, W. Ketter and K. Valogianni, "Transitioning from the traditional to the smart grid: Lessons learned from closed-loop supply chains", Smart Grid Technology, Economics and Policies (SG-TEP), 2012.
[10] X. Fang, S. Misra, G. Xue and D. Yang, "Smart Grid – The New and Improved Power Grid: A Survey", IEEE Communications Surveys & Tutorials, vol. 14, no. 4,p 944-980, 2011.
[11] P. Papastamatiou, "RES and wind energy development in Greece", *HWEA Wind Energy Statistics May 2013*, 2013,
[12] I. Van der Hoven, "POWER SPECTRUM OF HORIZONTAL WIND SPEED IN THE FREQUENCY RANGE FROM 0.0007 TO 900 CYCLES PER HOUR", *Journal of Meteorology*, vol. 14, no. 2, pp. 160-164, 1957.
[13] Life Free Energy, http://lifefreeenergy.com/h/how-do-wind-turbines-generate-power.html
[14] B. Valpy, P. English, "Future renewable energy costs: onshore wind", BVG Associates, 2014
[15] The European Wind Energy Association (EWEA), "Wind in power: 2015 European statistics", *EWEA's Technology Workshop*, Leuven, 2015. doi: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2015.pdf
[16] D. Morgan, "CD4046B Phase-Locked Loop: A Versatile Building Block for Micropower Digital and Analog Applications", *Texas Instruments*, 2003.
[17] G. Jovanovi´c, M. Stojˇcev, Z. Stamenkovic, "A CMOS Voltage Controlled Ring Oscillator with Improved Frequency Stability", *Scientific Publications of the state University of novi Pazar*, vol2, 2010.
[18] D. Abramovitch, "Phase-Locked Loops: A Control Centric Tutorial", 2002 ACC, 2002
[19] Analog Devices, "Fundamentals of Phase Locked Loops (PLLs)", *Analog Devices Inc.*, 2009.
[20] M. Rekik, A. Abdelkafi, L. Krichen, "Synchronization of Wind Farm Power System to

Utility Grid under Voltage and Frequency Variations", *International Journal of Renewable Energy Research*, vol5, 2015.

[21] H. Jiayi, J. Chuanwen and X. Rong, "A review on distributed energy resources and MicroGrid", Renewable and Sustainable Energy Reviews, vol. 12, no. 9, pp. 2472-2483, 2008.

[22] P. Gopakumar, M. Reddy and D. Mohanta, "Letter to the Editor: Stability Concerns in Smart Grid with Emerging Renewable Energy Technologies", Electric Power Components and Systems, vol. 42, no. 3-4, pp. 418-425, 2014.

[23] S. Tripathi, A. Tiwari and D. Singh, "Optimum design of proportional-integral controllers in grid-integrated PMSG-based wind energy conversion system", International Transactions on Electrical Energy Systems, vol. 26, no. 5, pp. 1006-1031, 2015.

[24]F. Blaabjerg, R. Teodorescu, M. Liserre, A. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", IEEE Transaction on industrial electronics, vol53, 2006.

[25] National Semiconductor, "LM565/LM565C Phase Locked Loop", *National Semiconductor Corporation,* May 1999.

[26] H. Ward Silver, "Hands-on Radio Experiments", *ARPL*, 2008.