INVESTIGATION OF MULTI-FREQUENCY POWER TRANSMISSION AND SYSTEM

A Dissertation

by

RONALD YOEL BARAZARTE CONTE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2011

Major Subject: Electrical Engineering

Investigation of Multi-Frequency Power Transmission and System

INVESTIGATION OF MULTI-FREQUENCY POWER TRANSMISSION AND SYSTEM

A Dissertation

by

RONALD YOEL BARAZARTE CONTE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Mehrdad Ehsani
Committee Members,	Karen Butler-Purry
	Shankar Bhattacharyya
	Peter McIntyre
Head of Department,	Costas Georghiades

August 2011

Major Subject: Electrical Engineering

ABSTRACT

Investigation of Multi-Frequency Power Transmission and System. (August 2011)

Ronald Yoel Barazarte Conte, B.S., Technological University of Panama

Chair of Advisory Committee: Dr. Mehrdad Ehsani

This dissertation presents a new power system transmission concept based on frequency selectivity named Multi-Frequency Power System (MFPS). This system allows for selective power transmission among terminals in an interconnected system, and is enabled by power electronic technology.

The dissertation starts with a presentation of some of the challenges faced by modern power systems, and includes a description of various power system technologies developed in an attempt to solve them. Then, our proposed solution is presented as an alternative to electric power transmission, and the fundamental concepts are explained.

A version of the MFPS is developed, which has relevance to the problem of renewable sources integration. This AC + DC Power System is further explored, and the topology of the system and the converters is presented, as well as the control techniques used in its operation. The dissertation also presents a performance study of the AC + DC system, which was done in Simulink, and it demonstrates the robustness of the system under various dynamic and fault conditions.

Finally, a summary of the work is given in the last section of the dissertation. The contributions of our research to the state of technology are discussed. These contributions include, the demonstration of power selectivity based on frequency identification, the development of a novel transmission system and a AC + DC integrated implementation of it, and the development of a control and converter that enables selective power transmission. Also, some of the most relevant future research initiatives related to this topic are presented.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. M. Ehsani for his guidance and support during my research at Texas A&M University and for offering his friendly advice well beyond academic matters.

Thanks are also due to my professors and colleagues at Texas A&M University as well as the Electrical Engineering Department staff for their support over these years, and for sharing these years with me. I thank my friends and colleagues at the Power Electronics Laboratory with whom I shared long hours of work and consulted in many occasions. Especially, I appreciate Mr. H. Mena, Mr. R. Doolittle, Mr. S. Ehmani and Mr. B. Yancey.

I must recognize the support of the Panamanian Government through the "Professional Excellence Scholarship Program" administered by SENACyT and IFARHU. Without their support, my graduate studies would not have been possible. Also, want to acknowledge the Technological University of Panama for supporting my candidature to such a renowned scholarship program.

I want to give special thanks to my most respected colleague and best friend Miss Guadalupe González for encouraging me every time I needed it and being there for me in both good and bad times. Finally, I want to thank my parents, who have always supported me in everything I do. Without you, I wouldn't have reached this goal.

TABLE OF CONTENTS

Page

ABSTRACT iii

ACKNOWLEDGEMENTS v

TABLE OF CONTENTS vi

LIST OF FIGURES viii

LIST OF TABLES xi

CHAPTER

I INTRODUCTION 1

II BACKGROUND 6

  A. High Voltage Direct Current Transmission (HVDC) 6
  B. Flexible AC Transmission System (FACTS) 12
  C. Smart Grid 16

III PROPOSED SYSTEM 22

  A. Frequency Selective Power Transmission 23
  B. Multi-Frequency Power System 26

IV THE AC+DC POWER SYSTEM 36

  A. The Single Phase AC + DC System 37
  B. The Three Phase AC + DC System 49

V SIMULATION STUDIES 57

  A. Description of the Model 57
  B. Simulation Results 61

CHAPTER Page

V SUMMARY AND FUTURE RESEARCH 73

A. Summary of the Work 73
B. Description of the Contributions 75
C. Future Research Initiatives 76

REFERENCES 78

VITA 80

LIST OF FIGURES

FIGURE Page

1 Schematic of a HVDC Transmission Line 7

2 Monopolar HVDC Transmission Line 8

3 Bipolar HVDC Transmission Line... 9

4 Cost of HVAC and HVDC vs Distance 10

5 Tripole HVDC Transmission System 12

6 FACTS Controllers Categories 14

7 Goals of Smart Grid 19

8 Multi-Frequency Power-Selective Transmission 22

9 Simplified Example Circuit.. 23

10 Instantaneous and Average Power for Single and Multi-Frequency Case. 26

11 Typical Distribution System... 29

12 Equivalent Model of a Typical Distribution System................................. 30

13 Multi-Frequency Model of a Distribution System 30

14 Single-Phase AC + DC Power System... 37

15 Ratio of Rac to Rdc vs Conductor Size... 40

16 Single-Phase Normalized Total VA vs. Voltage and Current................... 42

17 Single-Phase Normalized Total Power, DC Current and AC Current vs AC Voltage 45

18 Single-Phase Load Terminal Converter 47

19 Load Converter PWM Controller... 47

FIGURE Page

20 Input Converter Controller 48

21 Current Distribution for Three Phase Three Wire AC + DC System.......... 50

22 Current Distribution for the Three Phase Four Wire AC + DC System 52

23 Three Phase Load Terminal Converter 53

24 Three-Phase Normalized Total VA vs. Voltage and Current.......... 54

25 Alternate Three-Phase Normalized Total VA vs. Voltage and Current..... 55

26 AC + DC Power System Simulation Model.......... 57

27 Simulation Model for the Load 58

28 Load Terminal Converter Simulation Model 59

29 Single-Phase Switching Module 60

30 DC Terminal Controller 60

31 AC Terminal Controller 61

32 Load Change AC and DC Terminal Current and Voltages.......... 63

33 Load Drop and Load Rise AC and DC Terminal Currents 64

34 Load Side Voltages and Currents Under Load Change 65

35 DC Link Voltage and Demanded Power for AC and DC Terminals 66

36 0 to 100% Rise in AC Load 67

37 100% to 0 Drop in DC Load 68

38 DC Terminal Brownout.......... 69

39 AC Terminal Brownout 70

40 DC Channel Blackout.......... 71

FIGURE Page

41 AC Channel Blackout.. 72

LIST OF TABLES

TABLE Page

1 Simulation Parameters.. 62

CHAPTER I

INTRODUCTION

The last 20 years have posed a paradigm shift for power systems. Localized load has kept growing in the major cities, but still new areas have to be fed, which always seem to be farther away from the main grid. The liberalization of energy markets has caused a high level of regional interconnection in order to provide the customer with better prices and with it a power system increasingly dependent on the quality and speed of the communications through which this interconnection is coordinated.

Even the nature of the load and generation has changed dramatically. On one hand there are an increasing number of non-linear loads that introduce power quality problems to the power system [1-3]. But there is also an increase in sensitive loads that require very high quality, highly reliable power supply. This situation, in general causes clients with non-critical loads, to have to pay for high quality power without them needing it.

Finally, rising environmental concerns have pushed the penetration of renewable energy sources and storage into the power system [4, 5]. This poses a dispatch difficulty because of the unpredictable nature of the sources, but also a transmission problem because their location tends to be far from the existing transmission lines [6]. Another issue with renewable energy integration is synchronization to the power grid, which

---

This dissertation follows the style of *IEEE Transactions on Power Electronics*.

might be difficult because of the nature of the sources, and the equipment necessary for it becomes an important cost of renewable installations and rises the cost of the energy produced with them and hence, has caused integration of renewable power into the grid to slow down.

All of these changes clearly demand a different power system, and a number of solutions have been developed over the years to respond to these new needs, for example:

- High Voltage DC transmission (HVDC)
- Flexible AC transmission (FACTS)
- HVDC light (Voltage Source HVDC)
- Smart Grid

Although all of these alternatives are improvements to the power system, and all of them have found application in today's transmission grid, none of them provides complete freedom to the user as to when, how and what type of energy to use. HVDC and FACTS are centralized transmission system architectures that rely on an energy mix and the only way in which Smart Grid is different is that it allows the user to decide what to use the energy for and at what time, based on real time energy pricing information [7, 8].

Even the National Renewable Energy Laboratory (NREL) has identified that changes to the power system tending to optimize wind and other renewable integration to the electric grid will enable renewable hydrogen production. They suggest that a way to make this economically feasible is to find a method to integrate wind cheaply in the transmission system, and selectively use it at the hydrogen production facility located near the users [9].

The alternative that we propose in this dissertation creates the possibility of adding channels to the power system. Each one of these channels is isolated, so we can, for example, have discernible low and high quality power channels. In this system, renewable power could be transmitted on the low quality channel at low cost to feed intermittent, non-critical loads, for example: energy storage or hydrogen generation, and the high quality channel could be used to feed sensitive loads from conventional energy sources which are more reliable. That is, power is integrated at various frequencies at the source end of the line, and selectively picked up by the loads.

The general objective of this dissertation is to investigate a new multichannel power system architecture concept capable of selective power transmission named Multi-Frequency Power Systems (MFPS), as it applies to electric power distribution systems.

While accomplishing this, the following specific objectives will be achieved:

- Explain the of concept multi-frequency power transmission and demonstrate how a MFPS achieves power selectivity
- Evaluate different alternatives on how to implement the system and select the one that better fits the needs of a distribution system
- Determine the conditions that limit the power transmission capability of such a system and compare it to a conventional power system

- Develop a control method for the power electronic converters needed to operate the system
- Do a conceptual design of a specific power system and study it's performance via simulation

The dissertation starts with an introduction chapter. Here, some issues challenging modern power systems are presented briefly. Then different technologies developed to overcome some of these problems are presented as is our alternative. Finally the objectives of our dissertation are exposed.

Chapter II is a review of other relevant power transmission technologies. Each one of them is described and their operating principles are presented. A qualitative analysis regarding the advantages and disadvantages of each technology is also presented.

Chapter III describes the concept of Multi-Frequency Power Transmission Systems (MFPS). On it a demonstration of frequency selectivity is presented. A discussion on the selection of the topology for a MFPS is also included and the detailed description of the selected topology is presented. Finally, some arguments as to what frequencies are more suitable for distribution systems are presented.

Chapter IV deals with AC+DC transmission systems. First, the topology for the AC + DC system is presented and explained. The operating constraints of the system are developed and with them, the possible operating space of the system is defined. Then the converters for the loads are selected and a control method is developed for them. Finally, a method to size the system is presented, and with it a conceptual system is designed.

Chapter V presents the simulation studies of our designed system performed in MATLAB$^{®}$ Simulink$^{®}$. The model used for the simulation is described first, as will be the issues encountered during the development of it. Then, results will be presented for a number of static and dynamic studies performed to the system with their respective analysis.

Finally Chapter VI summarizes the dissertation and points out our contributions, as well as future research work to be developed in this subject.

CHAPTER II

BACKGROUND

As mentioned in the introduction, modern power systems face a number of challenges related to growth of the load, power quality and integration of alternative sources, which is unprecedented. In response to these needs, engineers have developed a number of technical solutions involving the use of solid state switching technologies and communication technologies, which have helped us, overcome each of these difficulties. Although none of these technologies solves by itself all the challenges of modern power systems, they are the basis for our study, in terms of use of technology and functionality. The purpose of this chapter is to present a qualitative description of the technology and operation of each of these power system solutions.

A. High Voltage Direct Current Transmission (HVDC)

High Voltage Direct Current Transmission (HVDC) [10 - 12] uses direct current (DC) to transmit power instead of conventional alternate current (AC). The general scheme of an HVDC transmission line is shown in Figure 1, it consists of a rectifying station, an inverting station, AC and DC filters and the transmission line itself which, depending on the scheme, can consist of either one (Monopolar) or two conductors (Bipolar).

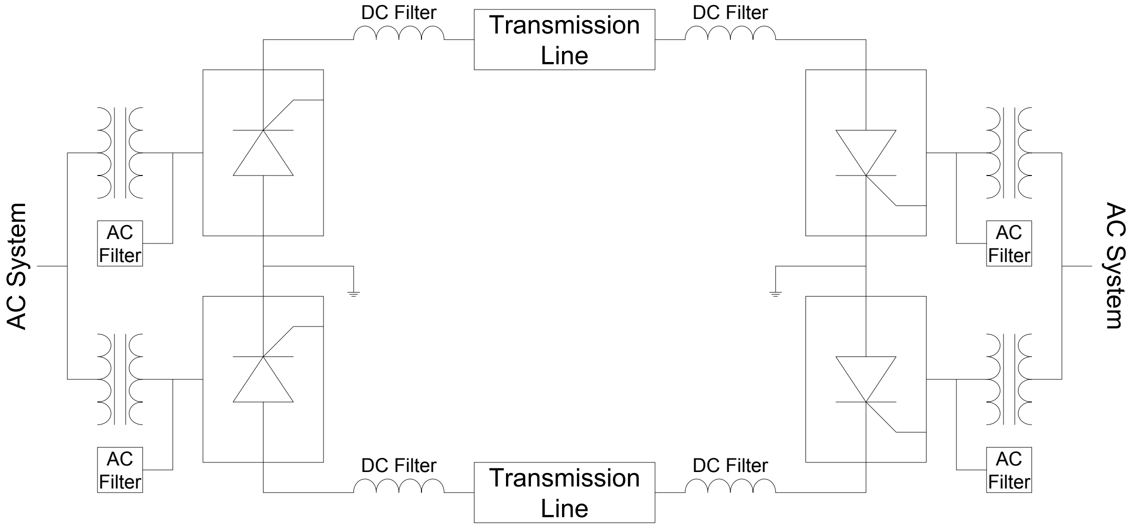

Fig. 1 Schematic of a HVDC Transmission Line

Already in the late 1800's, engineers worked on the implementation of a DC transmission system. These early systems consisted on DC generating stations connected to DC loads. However, the advent of high speed prime movers deemed DC generators not appropriate for the task, and the rising popularity of transformers and induction motors caused the idea of DC transmission to be abandoned.

On the early part of the 20th century, work on the mercury arc valve, and an increasing need of underground and undersea power transmission brought back research on HVDC technology. Dr. Uno Lamm from ASEA developed a mercury arc valve suitable for high voltage applications in the late part of the 1930's, thus enabling HVDC transmission technology.

The first applications of HVDC used mercury arc valves, but the appearance of the silicon controlled rectifier (SCR) in the 50's prompted a shift in HVDC implementation toward solid state-based systems. These systems gained the favor of engineers because of increased reliability and reduced maintenance costs.

Recent advances in self-commutating power electronic devices have opened the door to voltage sourced HVDC transmission schemes. Such a scheme is named differently by the two companies that have developed it, ABB calls it HVDC-Light (which is based in PWM converters) and Siemens names it HVDC+ (which is based in multilevel converters). Where the focus of HVDC is on long distance transmission, the focus of voltage-source HVDC is on increased power distribution capacity on underground systems.

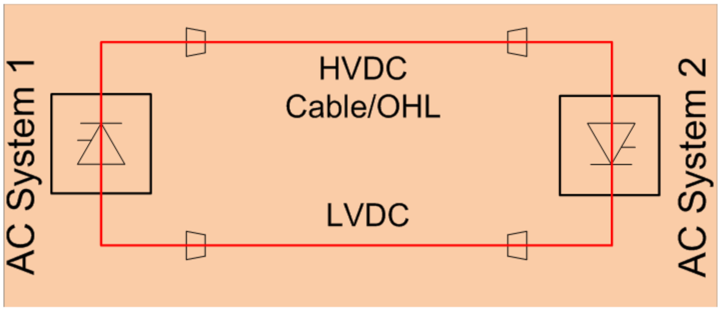

Fig. 2 Monopolar HVDC Transmission Line

Various different configurations for HVDC are possible, and their implementation depends on the needs of the project and the complexity level deemed acceptable. From these, two terminal configurations are the most popular. Two terminal configurations of HVDC can be either monopolar (Figure 2), in which a single conductor is used for the power transmission set at a negative polarity while the earth, the sea or a ground conductor is used as a return, or bipolar (Figure 3), in which two conductors (one of positive and one of negative polarity) are used. Out of these, bipolar configuration is preferred because ground and sea return provokes corrosion of buried metallic structures, boats and may produce harmful radiations and interference with telephone and radio systems.

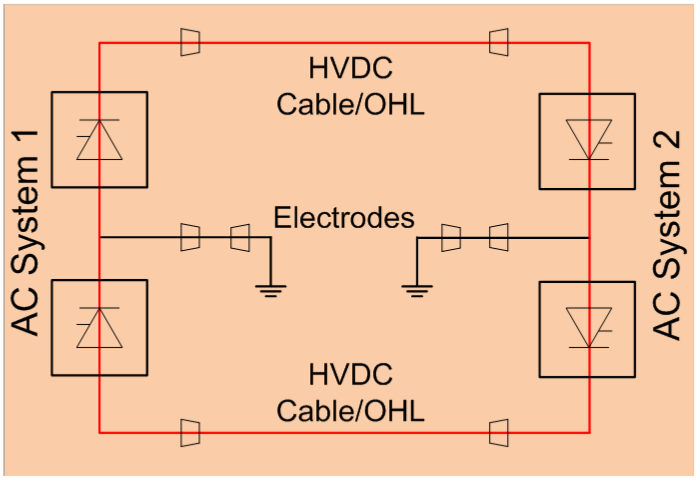

Fig. 3 Bipolar HVDC Transmission Line

Use of HVDC transmission systems has several advantages, for example, increased power system stability in the connected AC power systems is reported. Besides, it provides dynamic damping for the power unbalances among the power systems it connects. However, the most notorious advantage of using a HVDC transmission system over a conventional AC transmission system is the increased usage of the conductors due to the DC nature of the currents.

As mentioned before, there exist however, some limitations to the HVDC application when compared to conventional AC transmission systems. For example, HVDC has increased substation (terminal) costs in both equipment and maintenance due to the power electronics required for its operations. Also, multiterminal operation of HVDC is complex (at least in the case of conventional HVDC), and it is, in most cases, only suitable as a means to connect two power systems without any “taps”.

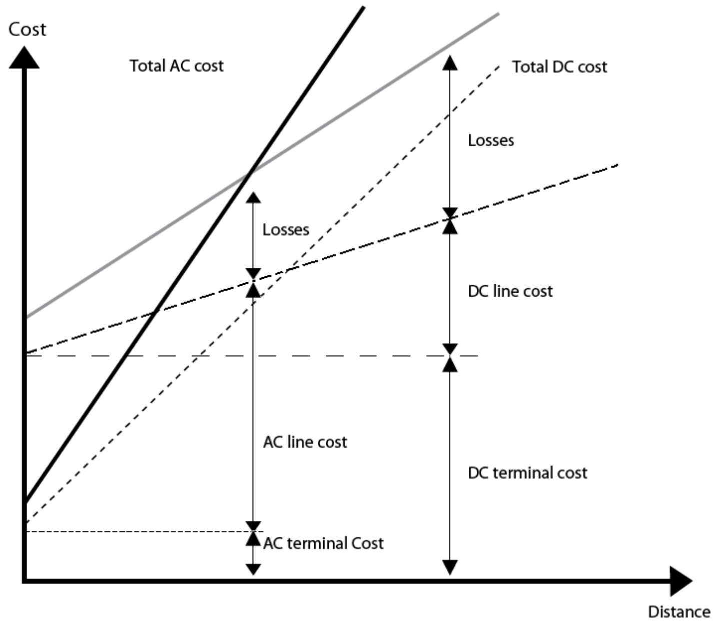

Fig. 4 Cost of HVAC and HVDC vs Distance [10]

Conventional HVDC is especially well suited to bulk power transmission over long distances. This is due to the fact that conductor losses are reduced in a DC transmission system when compared to an AC transmission system. However the cost of the terminal stations and their associated losses place the breakeven distance of a HVDC system at around 300 – 400 miles (Figure 4). In the case of underwater transmission this distance is shortened by the negative effect of the proximity of the cables in an AC transmission system.

A HVDC link can also be used for back to back connection of unsynchronized power systems. That is systems that are out of phase or even operating at different frequencies. This is possible because the waveform at each transmission line end is controlled independently, and the DC link serves as an instantaneous power buffer between the connected power systems.

Because of all the advantages that HVDC provides, there exists interest in not only using it for new transmission lines, but to replace some existing lines as well. And, although it is done, there are many complexities in doing so. For one, when converting a transmission line from three phase AC to bipolar DC, one of the conductor positions is unused, or at best, is used for emergency return conductor. Also, when doing this conversion, there is not a notorious advantage in terms of transmitted power, unless the conductors are upgraded and their size is increased (which is sometimes not viable because of space or clearance limitations).

An invention has emerged recently, which relates to this problem and solves it by making possible a tripolar HVDC system. The invention consists of a technique called "Current Modulation of Direct Current Transmission lines" [13-15]. It consists of controlling the currents and voltages in an HVDC system, so that it can be implemented using the three conductor positions available in three-phase AC transmission.

In this technique power is transmitted by overloading at least one conductor at a time over a period of time, and alternating which conductor (or conductors) is overloaded periodically, so as to maintain an average thermal usage of each conductor equal to their thermal rating. This way, power transmission can be increased by a factor as large as two when compared to a set of similarly sized AC conductors.

In general it can be said that two schemes related to this method of HVDC operation exist. One in which all of the three conductors are overloaded at some point during the system operation, in which case each conductor is fed by a bi-directional HVDC converter, and the other in which two of the conductors are periodically overloaded and the third conductor is alternated between the positive and negative pole, which requires only one bi-directional converter.

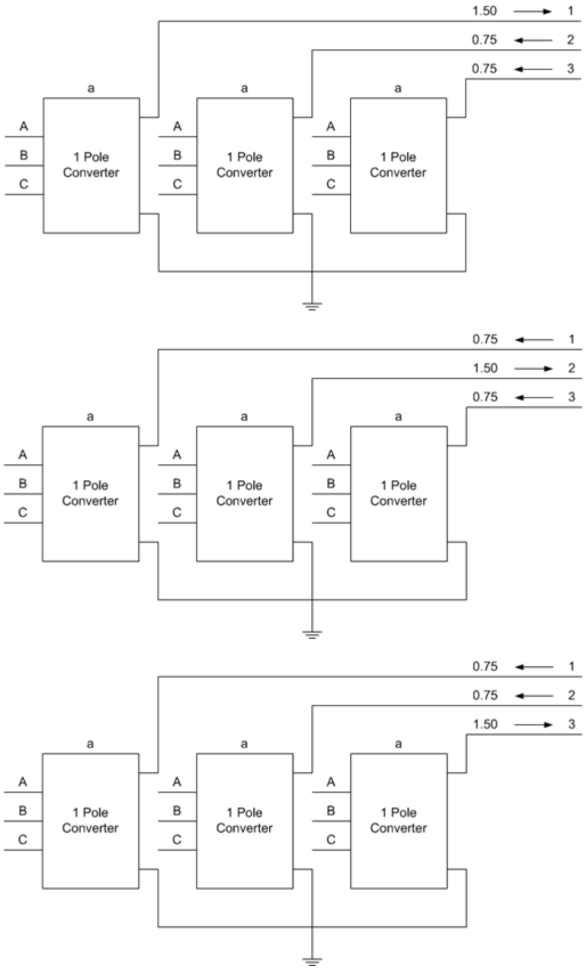

Fig. 5 Tripole HVDC Transmission System

B. Flexible AC Transmission System (FACTS)

Flexible AC transmission systems (FACTS) [10, 16] attempt to increase grid reliability and improve transmission line utilization. This is possible by manipulation of the series and shunt impedance, the current, voltage and phase angle of the transmission line. FACTS controllers are passive or active components that achieve this function by injecting voltage and / or current into the system. By adding this flexibility, FACTS allow operating a transmission line closer to its thermal rating, thus effectively increasing its capacity.

IEEE defines FACTS as: “Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability”. As expected, most of the FACTS controllers are power electronic enhanced devices, which allow for controlled (magnitude, phase) voltage and current injection, but as this statement implies, even a passive line device (as a capacitor or reactor) can be considered a FACTS controller.

In general FACTS has a number of economic advantages over other technologies. For example, all FACTS Controllers represent applications of the same basic technology (that is in the case of power electronic enhanced devices), so their production can take advantage of technologies of scale. Also, FACTS will take advantage of recent and future advances on power electronic devices capacity and efficiency. On the other hand, they can also be implemented progressively in a transmission line on a staged investment scenario, because of the localized nature of the device. This last thing makes it a strong competitor against HVDC in retrofitting existing bulk power transmission lines.

FACTS is not a single thing, but a concept encompassing a number of passive and power electronic applications for HVAC transmission capacity and flexibility improvement. As it is not a single component, some of the FACTS converters pre-date the introduction of the concept, for example, the static VAR compensator was introduced as a commercial product first by GE in 1974 and then by Westinghouse in 1975.

FACTS Controllers can be divided into 4 categories (Shown in Figure 6):

- Series
- Shunt
- Combined Series-Series
- Combined Series-Shunt

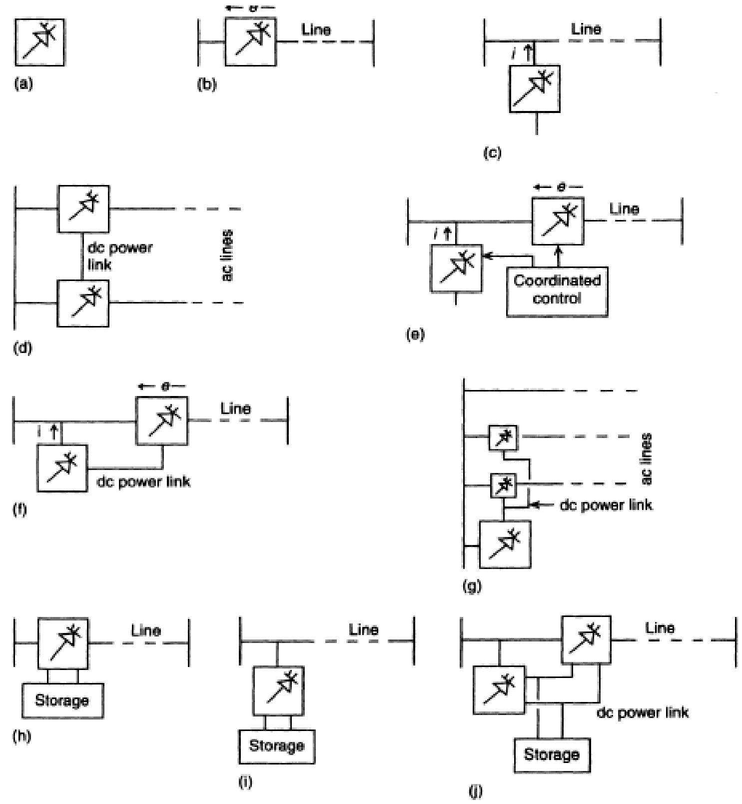

Fig. 6 FACTS Controllers Categories [16]

Series Controllers are used for voltage injection in series with the line so that voltage drop of the line is controlled. Shunt Controllers are used for current injection in shunt with the line (at the connection point) they can control both phase of the current and / or voltage drop in the line. Both devices can be either variable impedances or power electronics based variable sources.

Simple FACTS controllers (series and shunt) are operated to affect the reactive power flow in the line so that current flow can be limited or voltage drop can be reduced. This is done without affecting real power flow by injecting voltage in quadrature with line current (as in the case of series Controllers) or by injecting current in quadrature with the line voltage (in the case of shunt controllers).

In general, combined controllers are those in which more than one simple FACTS controller is involved. They can be operated in a coordinated manner, where the only connection between the converters is at the control level, or as a unified converter, in which case the DC electrical terminals of each converter are connected together and real power flow among them is possible. Combined Series-Series Controllers are used to control reactive power flow in various lines, and if unified, can balance both real and reactive power among the lines. Combined Series-Shunt Controllers can inject both current and voltage to a transmission line, to regulate reactive power flow. If unified, real power flow is possible among the series and shunt controllers.

Power electronic based FACTS controllers topologies require a certain amount of energy storage, necessary just to ensure the correct switching of the components, and if used for reactive power flow control that is the only DC side energy storage they need to be provided with. However, to best accommodate the fast dynamics of the system operation (sags, swells, demand or generation steps, load disconnections and others), a larger storage needs to be added, so that the injected current or voltage can be controlled so that the deviation from the quadrature is possible with respect to the line voltage and currents.

Because of the frequency isolating capabilities power electronic converters present (output magnitudes and frequencies are generally synthetized from a DC bus) FACTS controllers can be designed to act as active filters, and even used to balance line currents or voltages making use of the power transfer capabilities among phases.

C. Smart Grid

The concept of smart grid [7, 8] refers to the modernization of the current electrical grid. This modernization consists of integrating a number of information technologies to the system, so that the system operators, the clients and the system element themselves, have up to date information on the system status which will allow them to make informed decisions on what actions to take in the system.

Many of the power system actors agree that smart grid it is a technology well within reach, especially because it is based on a fast and ever growing technology as information and communication systems. In the context of the technology implementation time frame, specialists make a division among two stages of the grid: a smarter grid which encompasses technologies that are already deployed or can be deployed in the near future, and a smart grid which is a longer term goal. Some people place it ten years or more into the future

In comparison to other technologies (for example communications), electric energy transmission hasn’t experienced any major fundamental technological change.

However, the power system is the largest and more complex machine and it interconnects everybody and interacts with most of the modern activities. The lack of fundamental technological advances has resulted in a lack of interest for investment in transmission infrastructure. In the US, since 1982, the growth in electricity demand has exceeded the growth in transmission by 25%. Also, as a share of revenue, research in power transmission has one of the lowest percentages across industries with less than two percent.

The conventional grid is centrally planned and controlled and responds slowly to system events. Also, the system as it is in place was not designed thinking of current concerns such as energy efficiency, environmental impacts or customer choice. And because transport of remote information to a central control location isn't fast enough, system operators lack of situational awareness to make decisions.

Because of the massive size of the power system, any efficiency improvements achieved could have a significant impact in energy consumption. This is one of the major drivers of smart grid technologies, in which system operators can take better informed decisions leading to efficiency improvements on the line, or the "smart" devices can optimize the power flow based on situational data.

Another major driver of advancement in power transmission technologies is the increasing of power electronic load. Load from sensitive electronic equipment has increased in the last years from 10% in the late 90's to 40% today and an expected 60% by 2015. This impose a challenge because some of these loads require a tightly regulated service, but may also represent an opportunity, because they can be cheaply equipped with “smarts” that can receive and send information to and from the system [7].

Finally, the main reason driving advances in power system technology and in smart grid, is that there is a need for enabling technologies that allow for renewable resources to be connected to the grid in a financially sound manner. The purpose is to change the business model that rules the current power system. These changes are possible by bringing the same technologies that enabled the internet to the grid.

Some of the necessary tools and technologies for smart grid are already in place, but the major actor missing is the two way communication systems among the devices. One example of these already available technologies is Advanced Metering Infrastructure (AMI). With real or near real time information on energy prices, these meters send signals to enabled household items which interpret the prices according to a set of rules established by the users or users’ choices and routine.

Another component which will be prominent in a smart grid is the phasor measurement units (PSU’s). Their importance lies in their capacity to sample voltage and current at a high frequency. In a smart grid, these measurements will provide us with dynamic situational data of the area and that information could help to ease line congestion and even prevent failures from happening.

Smart grid will enable distributed generation and thus improve the distribution system efficiency. Different from the current distribution systems, a smart grid will be characterized by a two-way flow of power and information. And although wind turbines, plug in hybrids and solar panels aren’t part of the smart grid, smart grid technologies allow us to connect those resources to the grid and take the most advantage of them. These and other important elements of the smart grid concept are presented in Figure 7.

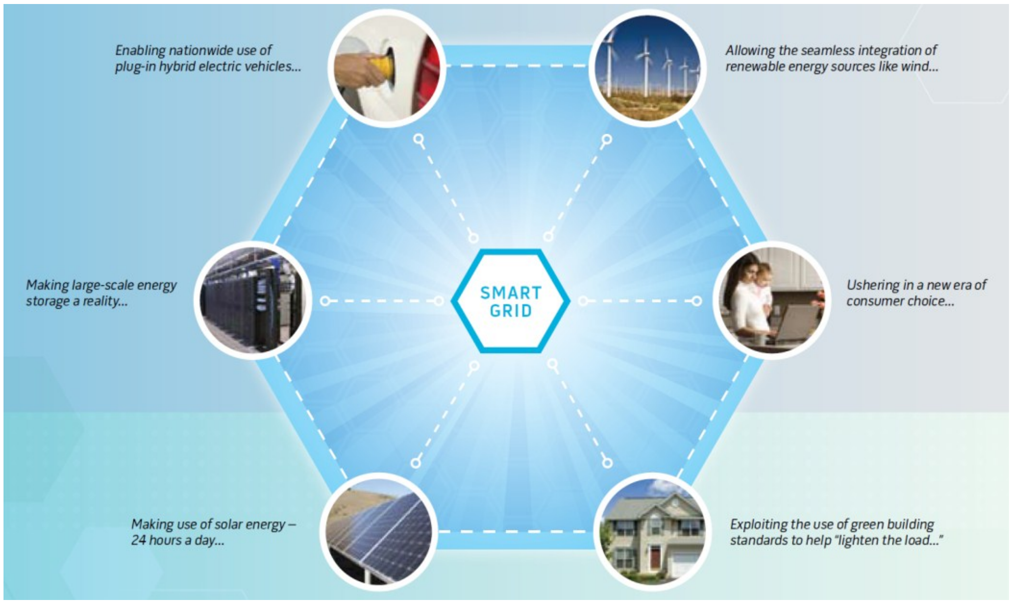

Fig. 7 Goals of Smart Grid. [7]

In summary the benefits provided by smart grid are:

- It can sense overloads and act before the failure to prevent it or minimize its impact
- It accommodates conventional energies, renewables and distributed storage resources
- Provides real time communication between the consumer and the utility
- Improves the power quality
- It is resistant to attacks and natural disasters

From the utility point of view smart grid is seen as a technology that will enable the selling of more energy through the existing power distribution infrastructure, thus reducing the need for them to invest in order to satisfy the increasing load. Although initial costs are high, in the long term they are expected to outgain the comparative costs of upgrading the grid by conventional means, which means that costs for infrastructure upgrading won’t be passed to the clients.

Another strong point of Smart grid is that it enables user choice; at least it allows the user to decide when to use the power and for what tasks. This is possible because the system provides the user with near real time information on the energy cost. Also, real time information of the prices on the hands of consumers will drive the peak demand closer to the average, which will reduce the stress on the existing infrastructure, allowing the increasing load to be allocated without new equipment.

DOE lists five technologies that will drive the Smart Grid:

- Integrated communications
- Sensing and measurement technologies
- Advanced components (superconductors, storage, power electronics and diagnostics)
- Advanced control methods
- Improved human machine interfaces

Smart Grid devices integration, standardization and interoperability will be one of the most difficult issued to deal with, because of the commercial interests involved in proprietary component communication schemes. Some international entities like EPRI and IEC have been working for years on this issue as it is closely related with advanced protection and monitoring of the power system and a clear solution is not yet developed, although some open communication protocols have been developed to which manufacturers can adhere to.

CHAPTER III

PROPOSED SYSTEM

As it was mentioned earlier in the introduction, today's power system is facing new challenges in terms of transmission and generation capacity, power quality, integration of non-conventional sources and controllability. In light of these changes, various power transmission technologies have appeared which have successfully solved some of these many issues. However, none of these technologies provides the user with full control on what type of energy he consumes.

The system we propose allows the users to identify and select the energy providers in an interconnected power network. It is enabled by power electronics and results from the combination of the superposition theorem and the principle of frequency selectivity. This Multi-Frequency Power-Selective Transmission System allows for multiple independent source load interactions to happen simultaneously over the same transmission media. Fig. 8 illustrates the concept.

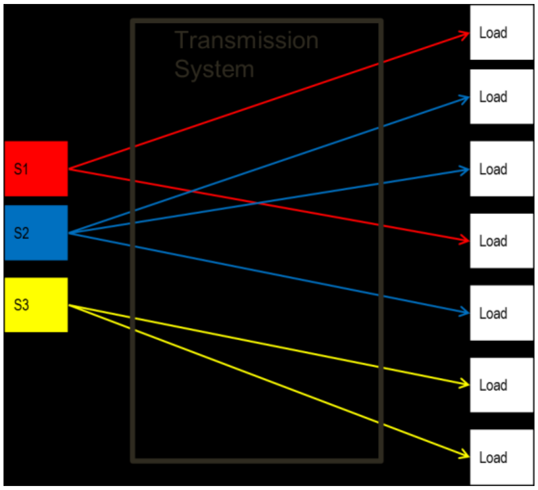

Fig. 8 Multi-Frequency Power-Selective Transmission

This chapter starts with the presentation of the frequency selectivity concept as it applies to our system. Then, a discussion on the proposed system topology is included and a brief description of the operation of the system is given. Also, some considerations on which frequencies we will use for our design example are included. Finally, some of the possibilities for Multi-Frequency Power Systems are presented as well as its expected advantages.

A. Frequency Selective Power Transmission

The concept of frequency selectivity explains why two circuit elements tuned at different frequencies will have a null average interaction in time. As a way of an example we will use a very simple electric circuit which is depicted in Fig. 9.

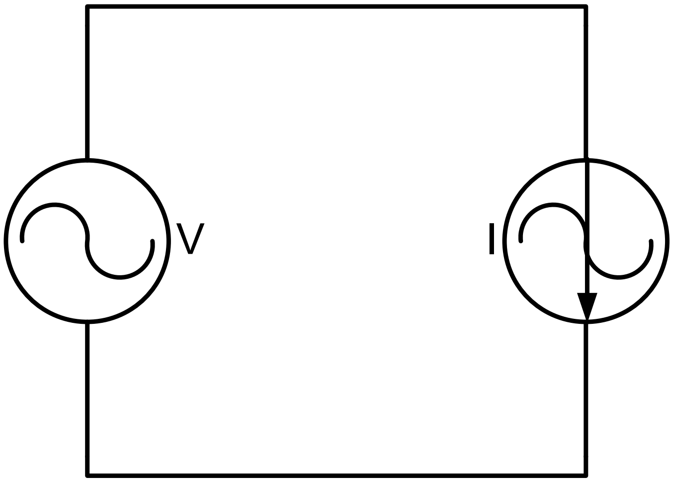

Fig. 9 Simplified Example Circuit

This electric circuit is one of the simplest possible, and it will help us explain the concept of frequency selectivity as it applies to energy transfer in electric circuits and therefore, in power systems. In it, an ideal current source and an ideal voltage source are connected together, which makes this a completely determinate circuit. The ideal voltage source determines the voltage of the circuit and can provide any current demanded from it, while the ideal current source determines the current of the circuit at any voltage level. However, as the two of them are sources, we must note that the frequencies of both sources could be independently controlled.

Now, if the voltage and current sources of the circuit presented in Fig. 9 are controlled to have the same frequency, it is possible to demonstrate that a net power transfer (which represents an effective energy transfer among the voltage and current sources) will result from their interaction. If the instantaneous voltage and current of this circuit are defined to be:

$$v = \sqrt{2}V\sin(\omega t) \tag{1}$$

and

$$i = \sqrt{2}I\sin(\omega t + \varphi) \tag{2}$$

then, the instantaneous power transfer is given by the product of the instantaneous voltage and current which is:

$$p = v \times i = 2VI\sin(\omega t)\sin(\omega t + \varphi) \tag{3}$$

Managing the terms in equation (3) with the use of trigonometric identities in order to group terms, we obtain:

$$p = VI\cos(\varphi) - VI\cos(2\omega t + \varphi) \tag{4}$$

Equation (4) shows that the instantaneous power transfer consists of an average value and an oscillatory component. Hence, there is a net interaction amongst the two sources when they are tuned to the same frequency which traduces in an effective energy sharing among the sources.

However if the frequencies of the voltage and current sources are controlled independently to be different, that is, if they are defined to be:

$$v = \sqrt{2}V \sin(\omega_1 t) \tag{5}$$

and

$$i = \sqrt{2}I \sin(\omega_2 t + \varphi) \tag{6}$$

again, it is possible to determine the instantaneous power transfer among the sources by calculating the product of instantaneous voltage and current which leads to:

$$p = v \times i = VI \sin(\omega_1 t)\sin(\omega_2 t + \varphi) \tag{7}$$

However, there is no way to obtain a non-oscillatory term from equation (7) by expanding and grouping the terms, in fact, when using the same identities to obtain equation (4), it results in the following expression,

$$p = VI \cos[(\omega_1 - \omega_2)t + \varphi] - VI \cos[(\omega_1 + \omega_2)t + \varphi] \tag{8}$$

which clearly shows no average value for the exchanged power, and hence it implies no net interaction amongst the sources. That is, no effective transfer of energy was accomplished from the sources interaction.

Fig. 10 presents the graphical representation of the calculated instantaneous and average power in both cases, for a specific circuit, with the instantaneous power in blue and the average power in red.

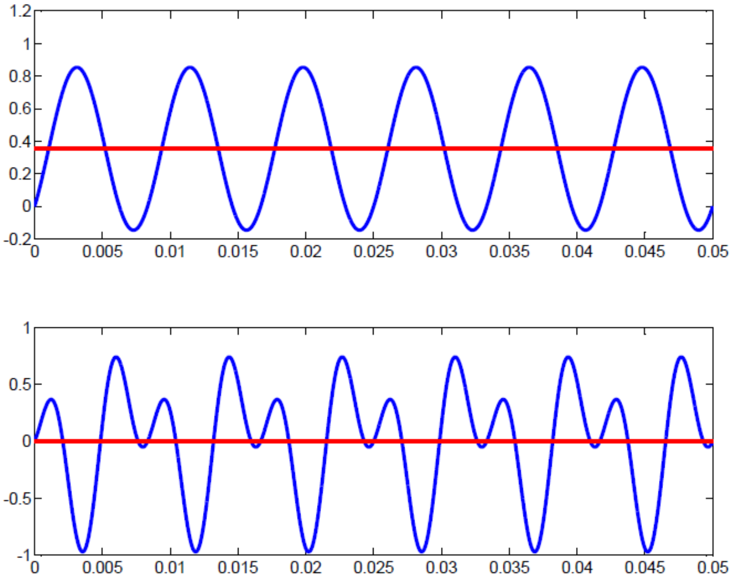

Fig. 10 Instantaneous and Average Power for Single and Multi-Frequency Case

The previous, is a mathematical demonstration of the concept of frequency selectivity. The superposition theorem allows for the possibility to combine the results of (4) and (8) on the same system, that is, have more than one frequency in the same system and have the system terminal components selectively interact with those operating at the same frequency. This is the principle over which the Multi-Frequency Power System (MFPS) is built on; it is the result of a combination of frequency selectivity and superposition.

B. Multi-Frequency Power System

As mentioned before, a Multi-Frequency Power System (MFPS) uses a combination of the superposition theorem and the principle of frequency selectivity of power to create multiple power transmission channels in the same transmission media. As we demonstrated in the previous section, two elements tuned at different frequency share zero average power over time and it is only this average power which is of interest to us as it is representative of the shared energy among the sources and loads.

From this, it follows that if two elements are tuned to a frequency different to that of the rest of the system, they will share energy with each other (in the average), but not with the rest of the system. This two elements constitute a "power channel" of the system, and thanks to the superposition theorem, it is possible to have many of them (power channels) in the same conductor. The main purpose here is to be able to identify power at each of these channels, and be able to consume power selectively from the desired source or channel.

a. Architecture of the power system

In developing such system, one of the first things that come to mind is the question of how to integrate these electric sources and loads at different frequencies as the presence of multiple frequencies in voltages and currents could be damaging to them. Besides, the question remains on how to make a passive load sensitive to a single frequency. For both cases, a filter is required to select the "tuned" frequency and reject all others.

For these purposes either passive or active filtering could be used. However, passive filtering is lossy, bulky and unreliable because is built with passive elements whose parameters change with usage (aging) which in consequence change the tuning of the filter. On the other hand conventional active filtering is designed to be destructive, that is, the components of the signal outside the designated bandwidth are destroyed. This will be troublesome in a power transmission scheme in which more than one frequency is used to transmit power. Besides, in active filtering, undesired components are burned which is inefficient. Therefore, a high efficiency filter capable of rejecting signals different to the "tuned" frequency without destroying them is necessary.

One possible solution is to develop an active filtering technique that allows the source or load to select the desired frequency, and reject all other components of the incoming signal without destroying them. At this point in our work we won't delve more into this topic, but the specific topology of the power electronic converter to be used and the description of the control will be presented in our design example, and the operation in that case will easily extend to the most general case.

Another subject of the utmost importance when developing a new power system transmission system, is the determination of the most suitable power system architecture for its implementation. With this we mean the selection among a current source or voltage source system. Also, at this point we need to functionally describe the components of the system. When considering the alternatives for our project, we focused mostly on the possibility to transition from the current distribution system architecture to a MFPS with minimum effort.

In order to explain the logic behind our power system architecture selection, a simplified one line diagram of a typical distribution system subdivision is shown in Fig. 11, which corresponds to a single distribution line fed by a distribution substation. The loads are represented by RL combinations, which are fed from the distribution line via a distribution transformer. The distribution substation reduces the voltage from transmission levels to typical distribution levels, and the distribution transformers, again reduce the voltage from distribution levels to those needed by the loads.

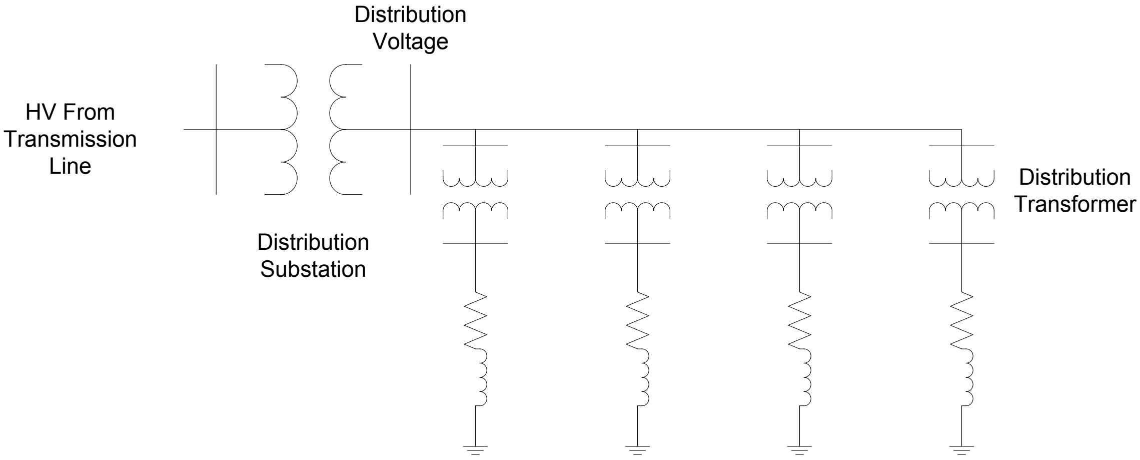

Fig. 11 Typical Distribution System

When observed in detail, we realize that this system can be modeled with simpler circuit elements without it losing its functionability. An equivalent model is presented in Fig. 12. Here, the distribution substation is represented by a voltage source, as the function of the substation in this system is determining the voltage, and we can assume that it has a very large current capacity when compared to the load.

In the same figure, each combination of distribution transformer and load model are represented as dependent current sources. This is possible as the combination of distribution transformer and load appear as a load to the source. Also, it is current what the loads demand from the system, and how much of it depends on the RL values of the load and the voltage of the line. Note that because the transformer and the RL combination of the load are passive, these dependent current sources are of the same frequency as the voltage source.

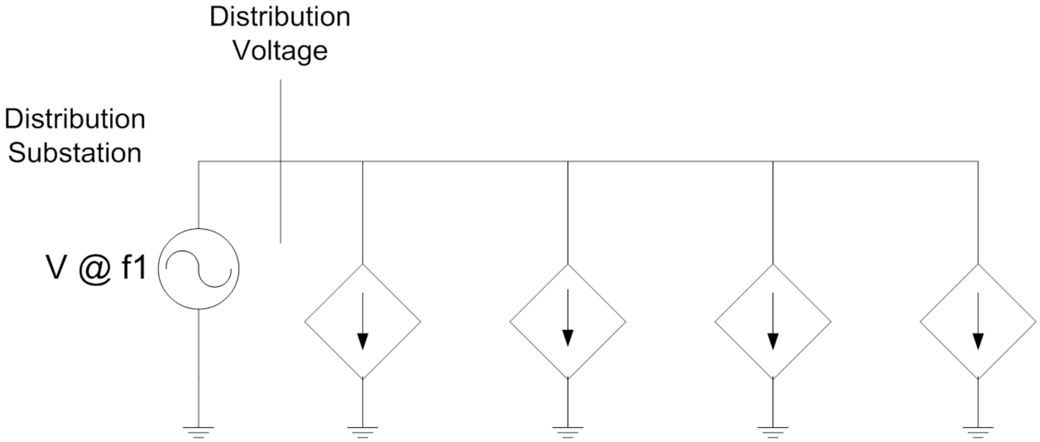

Fig. 12 Equivalent Model of a Typical Distribution System

Nevertheless, it is possible to conceive a dependent current source with an extra restriction, for example, that its frequency could also be independently controlled. If so, we will have dependent current sources whose current depend on the voltage applied to it, but only at a given frequency. A system with such an added restriction is shown in Fig. 13.

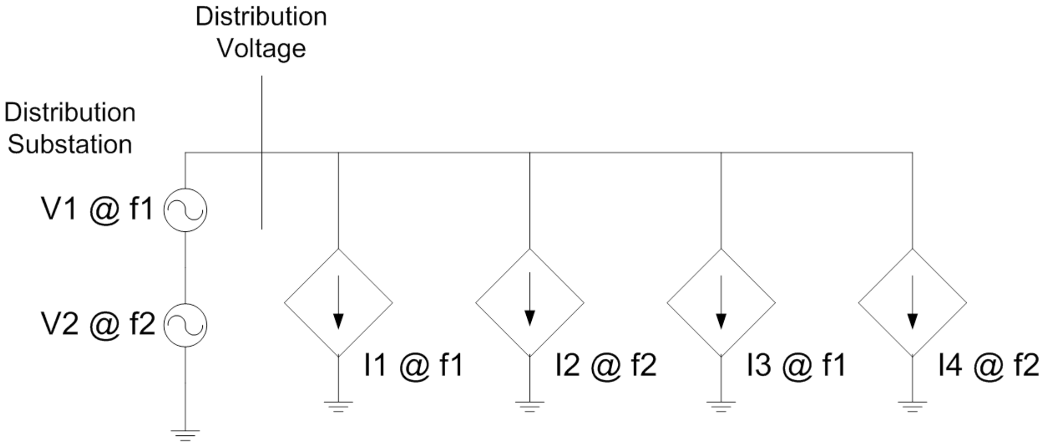

Fig. 13 Multi-Frequency Model of a Distribution System

The resulting system is effectively a viable topology for a Multi-Frequency Power Transmission System. In it, voltage sources at different frequencies are superimposed in series at the substation end of the transmission line, and the distribution transformer-load combinations are represented by frequency selective dependent current sources.

In this system, all the loads will be exposed to a voltage resulting from the addition of the superimposed voltages, and they will react only to the component of that voltage at their frequency. In the transmission line between the loads and the sources, a compound current will flow, the result of the addition of the currents at each one of the frequencies. The topology of the system has not changed from the original one, which makes transition possible, and the source and load terminal functions of the system can be enabled via power electronic converters.

The superimposed sources represent different energy sources being combined at the source end of the line. This might be the result of a number of scenarios:

- The integration of a distributed energy resource at the distribution substation
- The convergence of two different power transmission company lines at the same distribution substation
- The connection point of a hybrid isolated power system
- The connection point of the utility service and the co-generation of an industrial or commercial installation

Independently of what it represents, this superposition is achieved with the use of power electronics which would prevent the non-sinusoidal currents and voltages to propagate upstream into the rest of the system. There are many different converter topologies that would satisfy the needs of the system, and a description on the one used for our application is on the next chapter.

The realization of the frequency controlled voltage dependent current sources with which we modeled the load is of the utmost importance to this dissertation. As the load is passive (RL load), it will interact with any frequency it is exposed to, so in order for it to be frequency selective we need to provide a frequency selective filter. Although frequency selective filtering has been studied in other applications, as we said before filtering is generally destructive, i.e. all the undesired components of the signal are destroyed. In our application what is desired is picking the frequency at which the filter is designed, and rejects all other frequencies without destroying them. Our approach to this is to connect the load to the system via a power electronic converter, and operate the distribution side of the converter as a current controlled voltage source rectifier. The details of the topology of the converter and its control are included in the next chapter.

b. Frequency selection criteria

As can be inferred, in theory the number and values of frequencies that can be superimposed in a Multi-Frequency Power System are infinite. However, there are physical and technical factors that will limit them and that will indicate us where there is more potential for this system. These factors include, among others:

- The skin effect on the conductors and the losses related to it
- Our capacity to discern among different frequencies and how it is affected by the resolution of the power electronic converters used
- Switching frequency limitations of the power electronic converter

- Interference with other systems

When all this is taken into consideration, it makes sense to work out the technical difficulties of realizing a Multi-Frequency Power System with a minimum number of frequencies. This will enable us to develop the control rules of the system, improve the control algorithms of the converters and understand the effect of multiple frequency integration on the transmission capacity of the power system. Two frequencies will be enough to understand the fundamentals of the operation of these type of power systems, so this is the number of frequencies we will work with.

In terms of our example design, it is important to select two frequencies which are representative of a problem of practical importance, and whose results can be extrapolated easily into the most general case. Based on this, we have chosen to design a system in which DC power is integrated with 60 Hz AC power in a retrofitted 60 Hz AC power system. Such a system has practical value as most of the renewable resources are either DC or converted to DC at some point before their integration with the system, and in integrating them in DC several benefits are achieved:

- The inverter section of the power electronic converter in the renewable sources are eliminated
- The need for renewable frequency synchronization to the grid is eliminated, which makes the dispatch of the renewable resource cheaper
- Utilization of the distribution line is increased against using two AC frequencies
- Losses will rise with increasing AC frequencies and lowering the frequency might cause difficulties in sensing and protection

- AC and DC components are easily discernible, which makes for a robust control of the system

c. Possibilities for multi-frequency power systems

Ideally power selectivity would allow the distribution system to be operated as an open market, where broadcasters offer their power over the system operator hardware, and clients pick what channel they want to be served power by. These power broadcasters may operate substations and mix power from different sources in them to accomplish the best price, reliability or other characteristic they want to sell their customers. Then they broadcast this power at the assigned frequency.

Also, some loads don't require high quality or high reliability power, and they will be benefited by having low quality, low cost power when available (water pumping, hydrogen generation, energy storage, some large refrigeration and HVAC systems). This will also reduce the stress that is imposed on generators to provide very high quality power all the time, because it is easier to do so for a reduced number of loads.

Today, the user can't select what type of power do they use, or who generates it. They can only support certain types of power (by, for example, buying green energy credits), and their provider is determined by the geographical region they are in. A market structure in which more decision power is put on the hands of the users is highly desirable, and with power selectivity, they can select directly what type of power they want to buy, may it be for moral, economical or other reasons.

One problem that such a system may cause is the appearance of "power hackers". This is because the broadcasters respond to the total current being demanded at their frequency, without knowing exactly where is it being used. If this system is to ever be implemented, this is one very important issue to be solved.

As has been hinted previously in the dissertation there are many potential benefits to such a power system concept. Among them:

- The availability for identifiable power channels allows high quality and low quality power to be delivered separately so that clients can select what type of power to consume based on their needs
- Multiple companies can sell power over the same lines, which enables a different market structure
- Renewable integration can be enhanced by providing transmission over the existing lines, when renewable power is available and there is available capacity for its transportation
- DC sources and loads (i.e. distributed renewable resources and storage) can be integrated into the system in DC, increasing their efficiency and operability

CHAPTER IV

THE AC+DC POWER SYSTEM

In Chapter III it was explained why the AC + DC version of the Multi-Frequency Power System was our choice of study, as it is representative of an interesting problem in power transmission and distribution systems because of the importance of renewable resource and storage integration into the power grid. Also, the techniques developed for the control of the AC + DC power system, can be easily extrapolated to more general cases, where any other pair of frequencies is selected.

In this chapter the AC + DC power system will be discussed in detail. Both the single phase and three phase retrofitting will be explored. First, a description of the single phase AC + DC system is presented, and it will be explained how the voltages and currents are distributed among the conductors. Conditions limiting the possible operating points for such a system will be discussed and the range of permitted operating points will be derived from this information. Special attention will be given to the power electronic converters required by this power system topology, and both their control and operation will be explored.

After the single phase system discussion, a version of the AC + DC power system will be presented, which is suitable for three phase systems. The operating conditions of such a system will be determined and compared to those of the single phase AC + DC power system. From this result, an alternative version of three phase AC + DC system will be presented which has better operating characteristics, and the power system and converter diagrams will be shown.

A. The Single Phase AC + DC System

a. System description

The topology of the single-phase AC+DC power system is shown in Figure 14. In it, the sources are protected from the flow of undesirable mixed AC and DC currents by power electronic converters that besides serving as isolation, also serve to adjust the frequency and the voltage at which these sources are integrated into the system. Then, the outputs of these converters are connected in series, in following to our generalized multi-frequency power system architecture.

On the load side of the distribution line, the loads are provided with power electronic converters that transform AC+DC voltage present at the end of the line into the voltages required by the load (by regulating frequency, magnitude and phase), while consuming current at either the AC or DC frequency so that power selectivity is achieved.

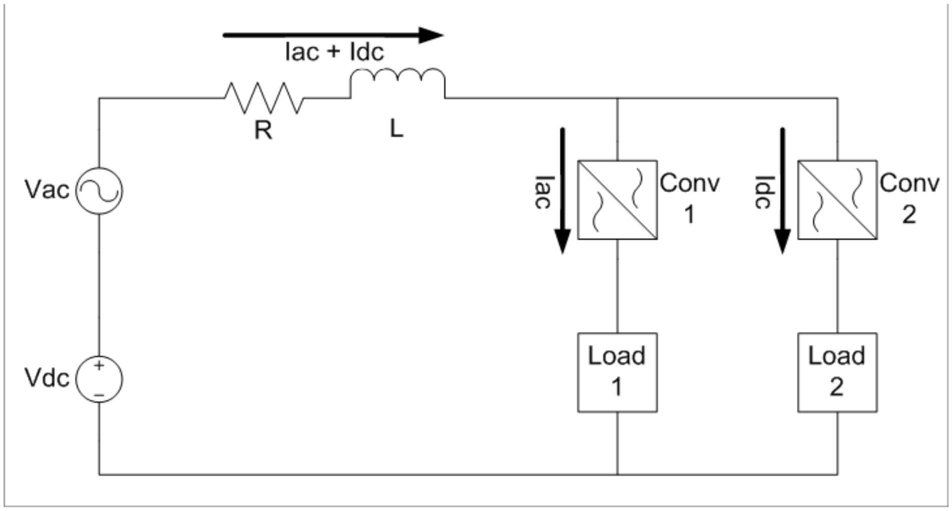

Fig. 14 Single-Phase AC+DC Power System

b. Operational characteristics

When operating a system under an AC+DC regime, especially if one is retrofitting a system designed for AC only operation (which is the central interest of our study), operational limits of the system must be determined and respected for safe operation. That is, our AC + DC operating points must not exceed the ratings for which the original system was design. Two limits are of importance, namely: thermal and insulation capacity of the conductors. Theoretical and experimental determination of these limits has been explored in the published literature for more conventional power transmission systems (AC or HVDC), and the analysis for an AC + DC power system is presented next.

The insulation capacity of the conductors is related to the peak voltage that the conductors can be sustained to, without failure. For the case of an alternate current system, this limit refers to the peak value of the sinusoidal waveform, in the case of DC power transmission, it is equal to the DC voltage value. In the case of an AC + DC system, the total maximum peak of the voltage must be within the insulation limitation which is given by the superposition of the AC and DC voltage values, that is:

$$\sqrt{2}V_{ac} + V_{dc} \leq V_{\max} \tag{9}$$

where, V_{ac} is the RMS AC voltage and V_{dc} is the DC voltage in the AC + DC system, and $V_{\max}$ is the maximum peak voltage allowed by the insulation. Equation 9 is the first of the limiting conditions that must be taken into account when determining the operating region of the single phase AC + DC system.

The thermal capacity of the conductor is related to the current flow in the conductor, the losses this flow causes and how these losses are dissipated and/or absorbed by the material of the conductor. This capacity is generally represented by a current rating for the transmission line. This rating is the result of a combination of effects which derive from the thermodynamics and material science of the problem. It depends on the thermal coefficient of the material with which the line is built with, the geometry of the conductor including its diameter and interstitial spaces (if stranded), the surface finish of the conductor, whether it is placed overhead or underground, the rate of flow of the wind, average humidity, temperature, among others.

However, the nature of this rating is not frequency related, because the capacity of a piece of material to absorb and conduct heat is not affected by frequency. Therefore, when under AC + DC operation the same limit must be observed, which does not means to conserve the RMS current rating. It is important to note that to comply with this restriction it is the losses that must be observed, and therefore it is the addition of the losses per frequency that must add to not more than the rated losses of the system (before retrofitting). That is:

$$I_{rated}^{2}R \geq I_{dc}^{2}R_{dc} + I_{ac}^{2}R_{ac} \tag{10}$$

where, I_{rated} is the RMS current rating of the conductor, R is the apparent resistance of the conductor at the frequency for which the current rating is given, I_{ac}, I_{dc} are the RMS AC and DC currents, and R_{ac} and R_{dc} are the AC and DC effective resistances respectively, while under AC+DC operation.

The effective resistance value for a conductor changes due to frequency because of the skin effect, which reduces the effective area of the conductor by pushing the flow of current closer to the surface. However, because of this reason, conductors in most applications are provided by some means to overcome the skin effect. Litz wire, stranded, twisted and tubular conductors are examples of this.

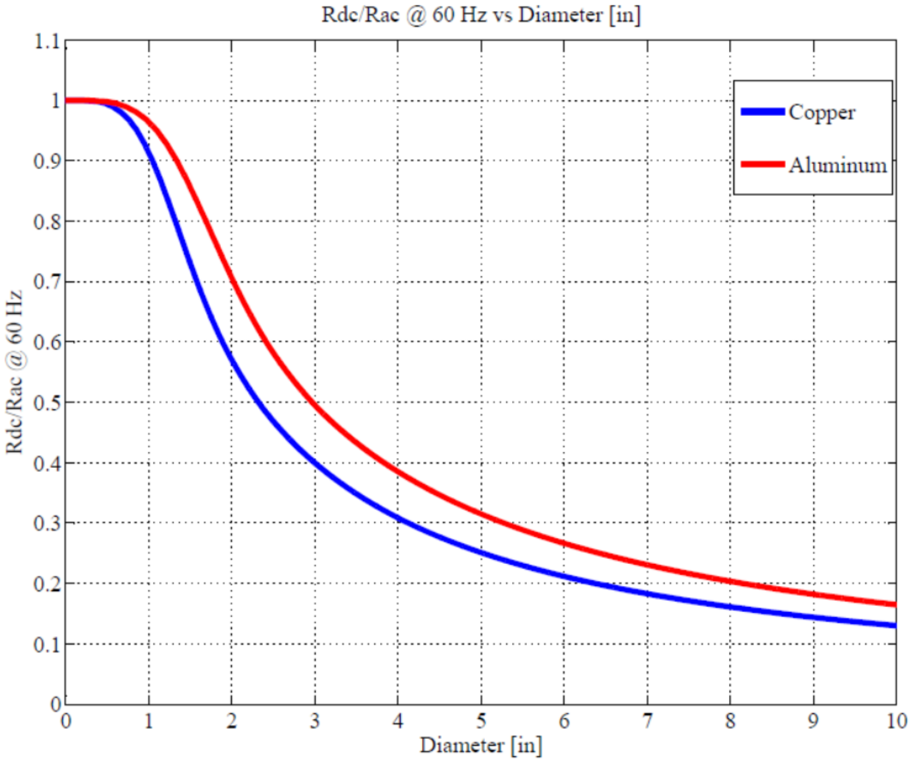

Fig. 15 Ratio of Rac to Rdc vs Conductor Size

In the case of distribution system conductors, a combination of stranded and twisted conductor construction and conductor size limitation reduces the evidence of the skin effect on the conductor behavior at the system frequency. Figure 15 shows a comparison of the ratio of DC to AC resistance (at 60 Hz) for solid conductors plotted against the conductor diameter. It shows the behavior for two popular conductor materials in energy transmission, copper and aluminum. As the figure shows, the variation of the DC to AC effective resistance value is minimal and increases only beyond a certain diameter, in the case of conductors used for distribution, this critical diameter is larger and the conductors are built below that size. And so, the frequency related resistance variation might be ignored in calculation (while using the 60 Hz AC effective resistance), giving us a more simplified version of equation (10).

$$I_{rated} \geq \sqrt{I_{ac}^2 + I_{dc}^2} \tag{11}$$

The conditions expressed by equations (9) and (11) can be used together to obtain the range of possible operating points of the single phase AC + DC power system. If the maximum system voltage and current capacities are used at all times (which will optimize the usage of the system), these equations describe a surface of total AC + DC transmitted power, shown in Figure 16. The data in the figure is normalized to AC current, voltage and power ratings. This figure can be used to determine the optimal operating point for the AC+DC power system.

The control of the AC + DC transmission system might respond to a number of control objectives, for example:

- AC power to be transmitted is fixed
- DC power to be transmitted is fixed
- Maximization of total transmitted power

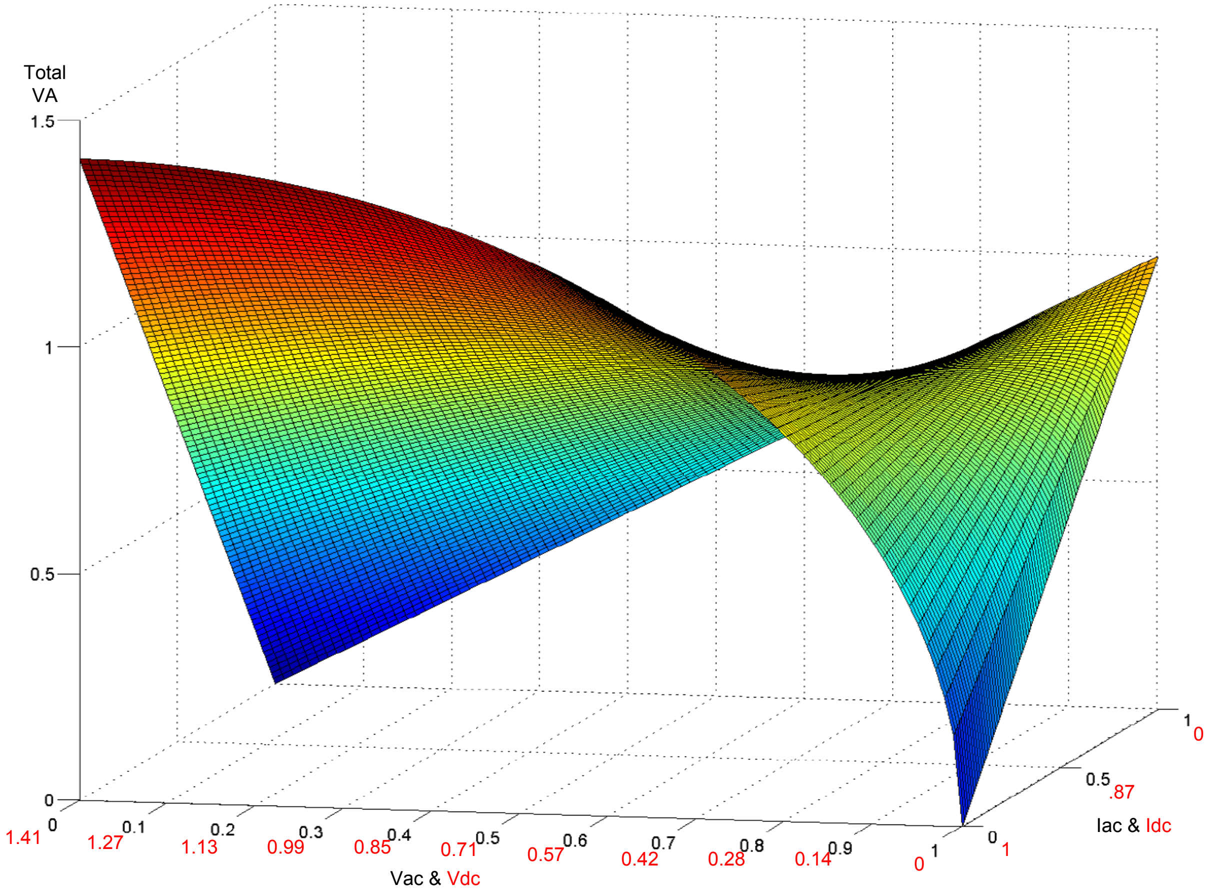

Fig. 16 Single-Phase Normalized Total VA vs. Voltage and Current

and any of these control objectives can be constrained by either maximum line usage, which as we stated before is achieved by keeping the loses constant at the rated value. Or it might be desired to achieve the transmission at minimum losses. Any of these possibilities might find an application, however, not all of them make sense in an AC + DC power transmission system which has been retrofitted from a conventional AC transmission line.

Fixing the DC transmitted power, makes no sense in a system where we will mostly integrate renewable or distributed energy resources in DC as these resources lack the reliability of the main utility power. Maximization of the total transmitted power in a distribution system isn't all that desirable in a distribution system. When we are feeding a load, it makes no sense to send as much power as possible, but to feed the load what it requires, when it requires. Because of this, we have selected an operation strategy in which the amount of AC power required by the load is determined, and in which our interest is to determine how power can be integrated in DC into the system with maximum utilization of the capacities of the line.

This control strategy for the system can be justified by a number of potential applications, such as:

- If the AC channel is used to transport power from the utility (or high quality/reliability source) to the user, and DC is used for a local inexpensive but not so reliable resource when available
- If the power is delivered to all users via the AC channel and the DC channel is only used to transport excess energy to distributed storage units owned by the utility.
- If the AC power is used to transmit power to the loads requiring high quality/reliability power and the DC channel transmits power to loads which can be fed only when power is available. These loads are in fact are demand leveling devices (some types of industrial ovens, refrigeration systems, irrigation systems and others)

Whichever the reasons, in the case that the amount of required AC power is known, we need to determine the maximum amount of DC power which can be delivered simultaneously by the system. This problem can be solved by combining equations (9) and (11) with the power equations for the AC and DC channels. For the AC channel,

$$P_{ac} = I_{ac} V_{ac} \tag{12}$$

solving for I_{ac} on equation (12) and for I_{ac} on equation (9) and replacing Vac, we have

$$I_{ac} = \frac{\sqrt{2} P_{ac}}{V_{\max} - V_{dc}} \tag{13}$$

Now, solving for I_{dc} on equation (11) and replacing I_{ac} with the result from equation (13)

$$I_{dc} = \sqrt{I_{rms}^2 - \frac{2P_{ac}^2}{\left(V_{\max} - V_{dc}\right)^2}} \tag{14}$$

Therefore, the DC power that can be delivered by the system is given by:

$$P_{dc} = V_{dc} \sqrt{I_{rms}^2 - \frac{2P_{ac}^2}{\left(V_{\max} - V_{dc}\right)^2}} \tag{15}$$

A simple algorithm consisting of equations (9) to (15) can be used to determine the maximum deliverable DC power in the AC+DC system for a given AC power value.

Figure 17 is a graphical representation of normalized AC and DC currents, as well as normalized total power for an AC+DC system all versus normalized AC voltage, where the AC power has been required to be 50% of the system full AC capacity.

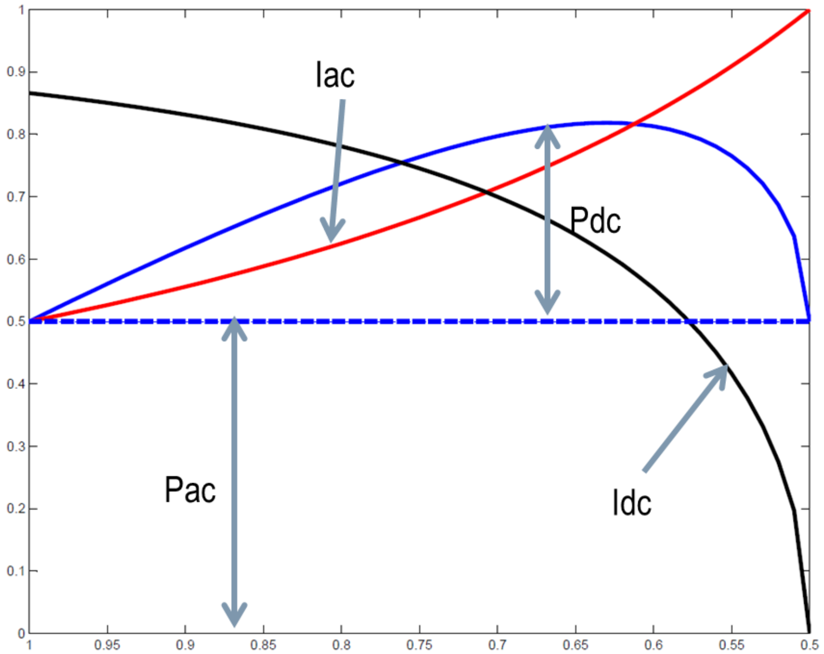

Fig. 17 Single-Phase Normalized Total Power, DC Current and AC Current vs AC Voltage

c. Terminal converter topology and control

i. Source Converters

In the single-phase AC+DC system, the sources are provided with voltage source power electronic converters that:

- Allow the series connection of the sources as required by our multi-frequency power system architecture
- Prevent AC + DC currents from flowing directly into the AC or DC sources
- Allow for voltage control of the sources, so that we can actively search for the optimal operating point of the AC + DC system

However important their function is, these converters are very conventional. For the AC source, an AC-DC-AC converter is necessary, which is voltage controlled (also called voltage source) on the secondary side. In the primary side, that is the side of the actual source, it can be either a passive or active rectifier depending on the power quality requirements of that side of the converter. The DC source needs a DC to DC voltage source converter to connect itself to the AC + DC system.

Among other things, when fed from a utility, the AC to AC converter will also increase the reliability of the power system in which this AC + DC sub-division is a part of, because the faults that can happen in the subdivision cannot be propagated passively to the system. This advantage is natural in power electronic rich power systems, and is also shared by HVDC and HVDC-Light systems.

ii. Load Converters

As presented in Chapter III, a very important component of a multi-frequency power system is the load terminal converter. This converter acts as a voltage dependent current source in which the frequency and phase of that current are also controlled to achieve power selectivity and, in the case of our implementation, unity power factor.

The converter topology selected for the load terminal converters is shown in Figure 18. It consists of a current-controlled unity-power-factor voltage source rectifier on the distribution side, and a PWM-controlled voltage source inverter on the load side. The two converters are conventional H-bridges with voltage switches connected by a capacitive link, and an input inductor is included, which will be used for the input current shaping.

Such a topology was selected because of its simplicity and the benefits derived from the fact that both switching modules (i.e. the input and output H-bridges) have identical configuration and a reduced number of spare parts are necessary. Also, the suitability of H-bridges for unity-power-factor single phase current-controlled PWM rectifiers has been demonstrated [Stihi and Ooi].

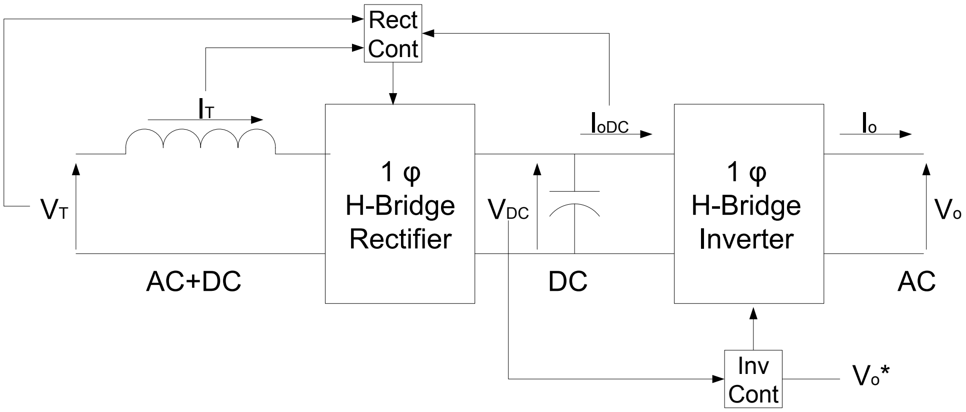

Fig. 18 Single-Phase Load Terminal Converter

The control of the load terminal converter is designed to achieve three control goals:

- Regulate the magnitude, phase and waveform of the input current
- Regulate the magnitude, phase and waveform of the output voltage
- Keep the DC link voltage inside safe boundaries

In order to achieve this, the input voltage, input current, DC link voltage and DC link current (on the load side) are measured. With these measurements, the necessary switching actions of the input and output converters can be determined.

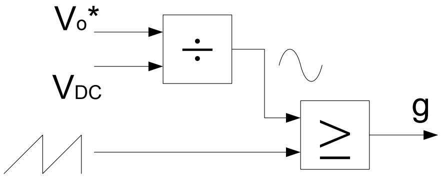

Fig. 19 Load Converter PWM Controller

The load side converter controller is depicted in Figure 19. In it, the commanded load voltage is scaled by the measured DC link voltage and this signal is compared with a triangular waveform to generate the required gating signals for the converter.

We are using a bipolar voltage switching scheme, so the output voltage consists of positive and negative pulses at the value of the DC link voltage. However the load converter can (and generally is) provided of a low-pass L-C filter so that only the effective output voltage appear on the load. Moreover, because the output voltage command is compared to the instantaneous value of the DC link voltage, perturbations on the DC link voltage won't appear on the output voltage.

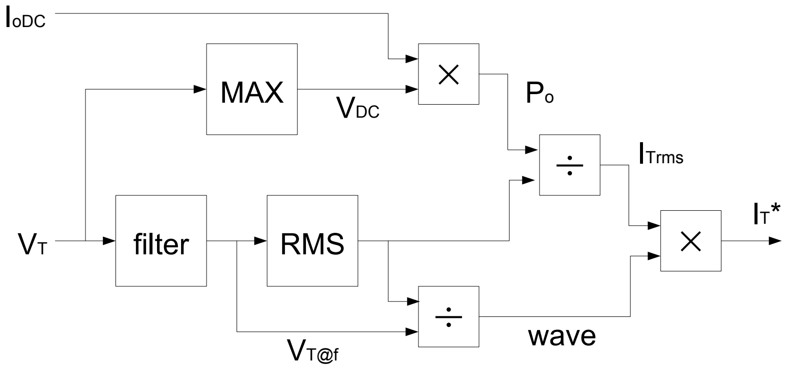

Fig. 20 Input Converter Controller

The simplified diagram of the input side converter controller is shown in Figure 20. The inputs to this converter are the measured input voltage, the load DC link current, the DC link voltage and the input current itself. The input voltage is measured and it is separated in its AC and DC parts, the voltage at the desired frequency is normalized by its amplitude, and this resulting signal is used as the waveform reference for the input current.

The product of the load DC link current and the DC link voltage is calculated and divided by the RMS value of the input voltage at the desired frequency, the result of this is the magnitude of the input current. This magnitude is multiplied by the input current waveform reference calculated before, and the resulting signal is compared to the measured value of the input current in a hysteresis controller to determine the necessary switching action.

Note that this controller has been developed using the concept of Power Input Power Output (PIPO) in power electronic converters, and although the losses aren't accounted for, it's performance is still acceptable because the regulation of the DC link voltage and the input current balancing inductor tend to be of a larger order of magnitude than the losses in the converter. However, due to its simplicity and the importance of keeping the DC link voltage safely within limits, a PI controller can be included in the DC link voltage loop as a measure of caution. This PI will reduce the error of the measured DC link voltage and the combined magnitude of the input voltage, which is the desired value for the DC link voltage.

B. The Three Phase AC + DC System

Electric power transmission is mostly done following a three phase scheme, and most of the distribution system subdivisions are nothing more than single phase derivations of three phase systems. Because of this and because of the fact that one of our primary objectives is finding a way to retrofit a conventional power system into an AC + DC system, special consideration must be given to the retrofitting of three phase systems into AC + DC power systems.

In the following section, AC + DC power system schemes are developed for three phase three and four wire systems, in a similar way as it was done with the single phase case. The limitations of the system are analyzed, and based on the observations another AC + DC power transmission scheme is developed in which the capacity of the system is better used.

a. Three wire configuration

First, we will develop an AC + DC transmission scheme for a three phase three wire system. In such a system, DC current can be superimposed over a balanced set of AC currents. The DC currents can be controlled in a similar manner to Barthold's current modulation of direct current transmission lines. That is, in order to avoid conductor damage, and the effects of unbalanced currents, the overloaded conductor is alternated. Figure 21 shows the current distributions in the system at one moment in time.

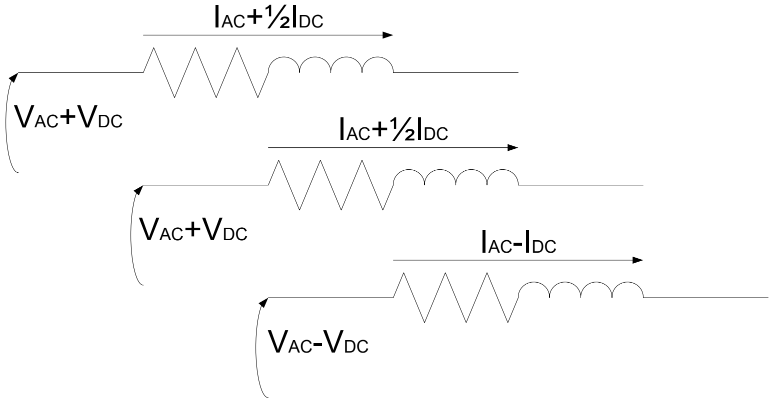

Fig. 21 Current Distribution for Three Phase Three Wire AC + DC System

Note that the DC total current is split in half, and transmitted by two of the phase conductors, and the total DC current is returned by the third conductor (the one being overloaded). Similarly to Barthold's system, the magnitude of the overloading current and the period of the change of the overloaded phase, depend on specific conditions of each transmission line.

Note that the conductor serving as the DC return has a different DC voltage polarity than the other two phases. In order to synthetize the necessary voltages for the operation of this system, the distribution side of the load converter would have to be composed of three individual converters similar to the one used for the single phase AC + DC system case. This will make the converter too complicated to control, and it presents problems to regulate the individual DC bus voltages of each converter.

b. Four wire configuration

Most of the distribution systems are 4 wire systems, and in many newer industrial distribution systems the neutral wire is of the same size of the phase wire. Because of this, it makes sense to explore the possibility of a four wire realization of the AC + DC system as an alternative for the retrofitting of 3 phase systems. In a 4 wire system AC + DC transmission can be achieved with a set of balanced AC currents and an superimposed DC current which is split evenly among the phase conductors and uses the neutral conductor as the DC return wire.

Figure 22 shows the current and voltage distribution among the phase conductors. Note that different from the three wire case, in the four wire case all the three phase conductors are at the same DC potential and the DC current flowing in them is equal. This allows for a simple six switches three phase converter to be used, instead of three independent single phase converters. This significantly simplifies the control required and reduces the part count and cost of the converter while increasing the converter reliability.

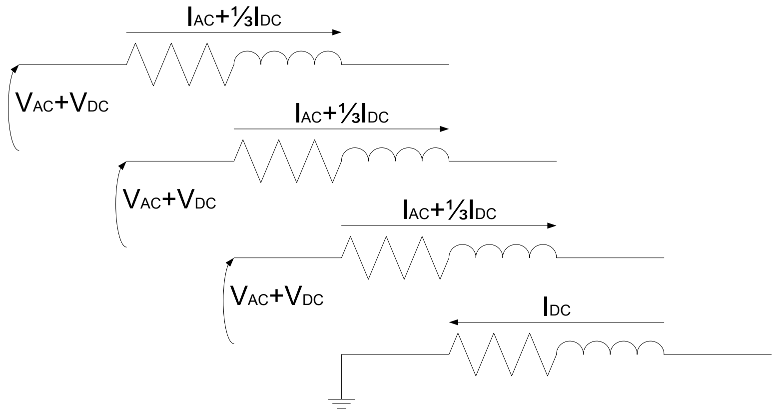

Fig. 22 Current Distribution for the Three Phase Four Wire AC + DC System

The selected topology for the load converter in a three phase four wire AC + DC system is shown in Figure 23. It consists of a three phase inverter, a DC bus capacitor and a three phase current controlled voltage source unity power factor rectifier. This circuit is a three phase version of the load circuit presented for the single phase AC + DC system. For this system, the current in the neutral conductor must also be controlled, so the rectifier consists of eight and not six switches. The added fourth leg of the converter is controlled with the resulting signal from the instantaneous difference of the other three phases.

The three phase PWM inverter in this load converter, can be replaced by any other converter which suffices the needs for the load (single phase inversion, DC to DC conversion) and it might also implement frequency and magnitude control (as in the case of a controlled load).

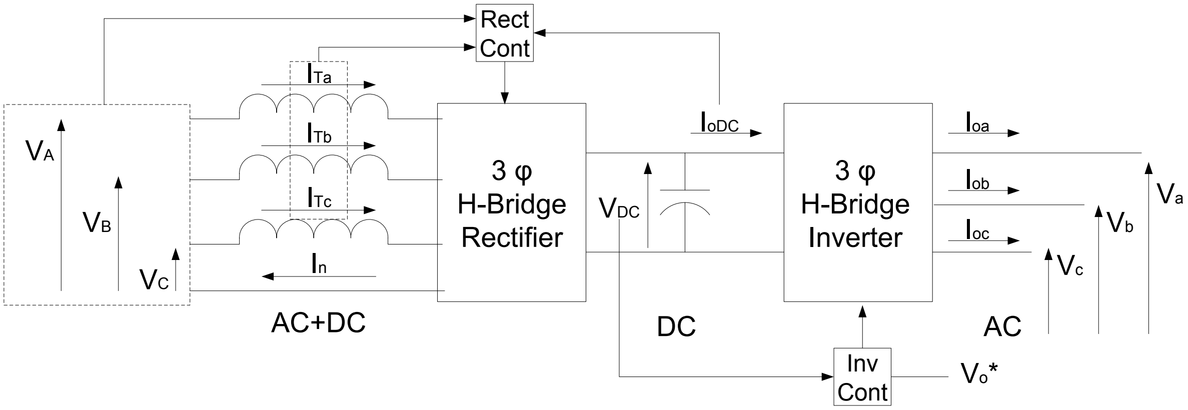

Fig. 23 Three Phase Load Terminal Converter

Similarly to the single phase case, we must determine the operational limits of the three phase four wire AC + DC System. The insulation and thermal limits are still given by equations 9 to 11 which are repeated here for completeness

$$\sqrt{2}V_{ac} + V_{dc} \leq V_{\max} \tag{9}$$

Thermal limit

$$I_{rated}^2 R \geq I_{dc}^2 R_{dc} + I_{ac}^2 R_{ac} \tag{10}$$

$$I_{rated} \geq \sqrt{I_{ac}^2 + I_{dc}^2} \tag{11}$$

As the neutral conductor is used as the DC return, its size will limit the DC current of the system. Then, assuming a fully rated neutral conductor

$$I_N \geq I_{DC} \tag{16}$$

If we combine the insulation and thermal conditions with the DC current limit based on the size of the neutral, we can obtain a surface representing the possible operating points for the three phase four wire AC + DC system. Figure 24 shows the normalized possible operating point surface for the three phase four wire AC + DC system.

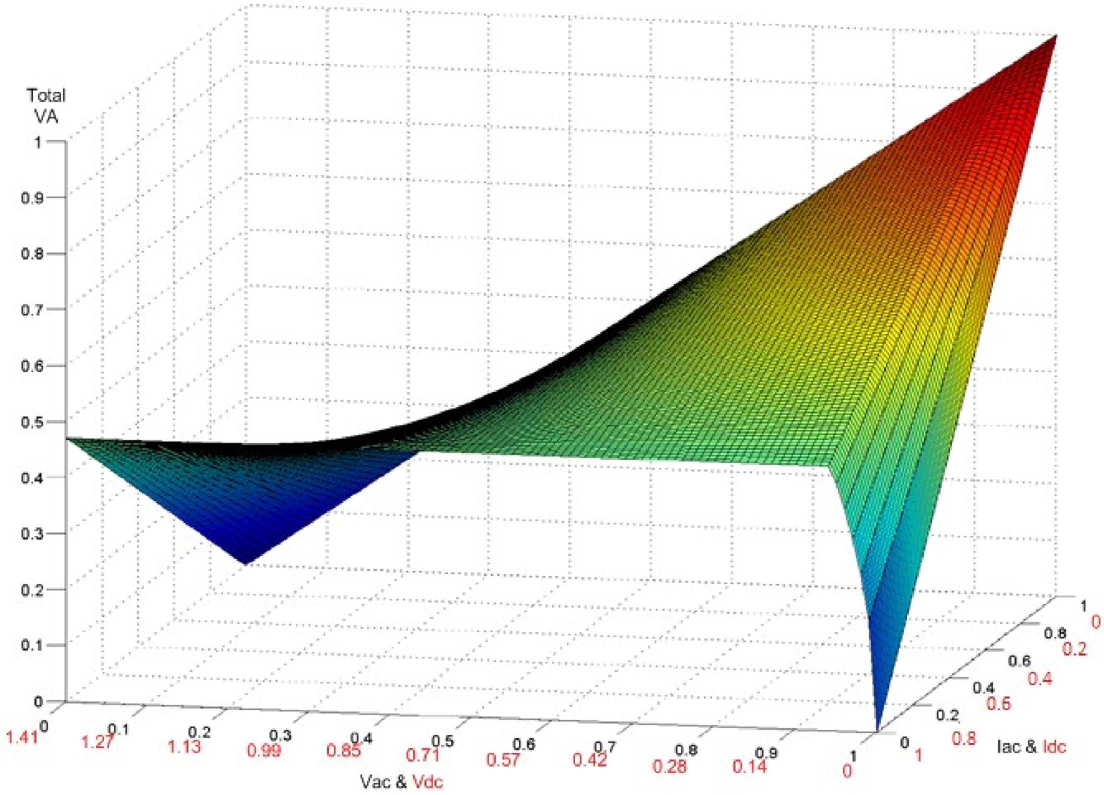

Fig. 24 Three-Phase Normalized Total VA vs. Voltage and Current

By observing this figure, we note that all the possible operating points of the system are belowthe original rating of the the three phase transmission line. Based on this, we must look for an alternative which makes better use of the hardware.

c. Alternative AC + DC configuration for 3 phase systems

As we mentioned before, in the three phase 4 wire AC+DC configuration the conductors are under-utilized. Then, an alternative solution for the AC + DC configuration is necessary. When considering one, we must observe the needs of the system. As we are talking about distribution systems, we know that most loads in the distribution system are single phase loads which will imply creating single phase subdivisions of a main three phase distribution line or connecting the load to two of the three phases of the three phase distribution line. Also, because we are working with a power electronic rich power system, three phase loads can be fed from converters with a single phase primary and three-phase secondary.

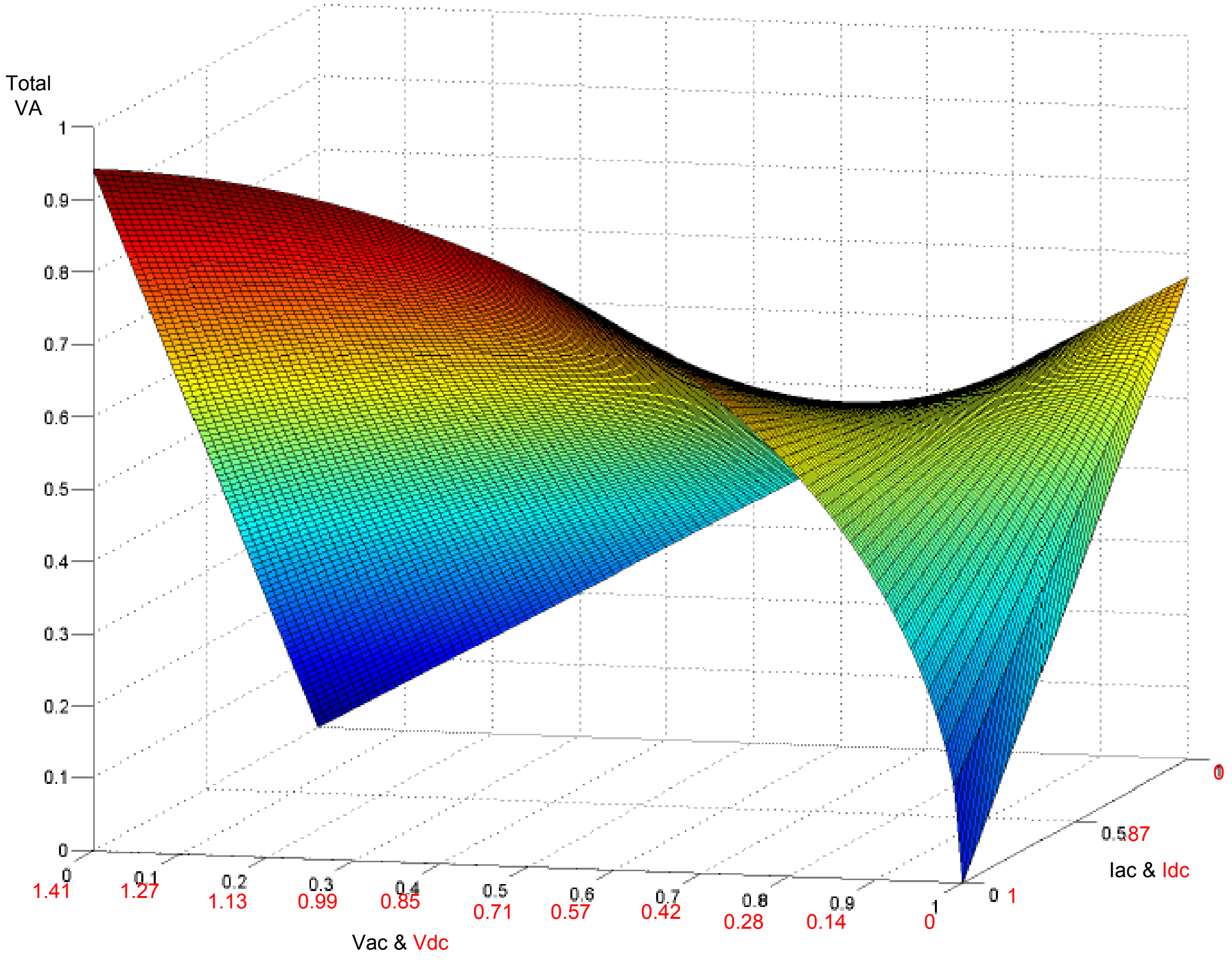

Fig. 25 Alternate Three-Phase Normalized Total VA vs. Voltage and Current

All the previous suggests that we evaluate a system in which the conductors in a 3 phase 4 wire configuration are connected in two single phase parallel circuits. Such a system will use the same configuration and terminal topology as the single phase AC + DC system, therefore, the same insulation and thermal restrictions apply. When taken into consideration the possible operating point surface for the alternate three phase four wire AC + DC system. The normalized surface is shown in Figure 25.

Altough the utilization of the system is still lower than the original ratings of a fully AC system, there exist a larger range of AC and DC voltage and current operating points on which the ratings are quite close to the original ones. The capacity reduction of the system when compared to a full AC circuit can be compensated with the increased flexibility of the system.

CHAPTER V

SIMULATION STUDIES

In order to study the behavior of a single phase AC + DC system, a simulation model was developed which was representative of a simple AC + DC based distribution system. The computer simulation was constructed using MATLAB Simulink. The simulation is designed to allow us observe the response of the system terminal converters in the occurrence of a number of events which are common in distribution systems. This chapter presents the details of this model, and the results obtained from the simulations.

A. Description of the Model

In order to simulate the system, we constructed a model using Simulink which follows the system shown in Figure 14. The overall view of this system is shown in Figure 26.

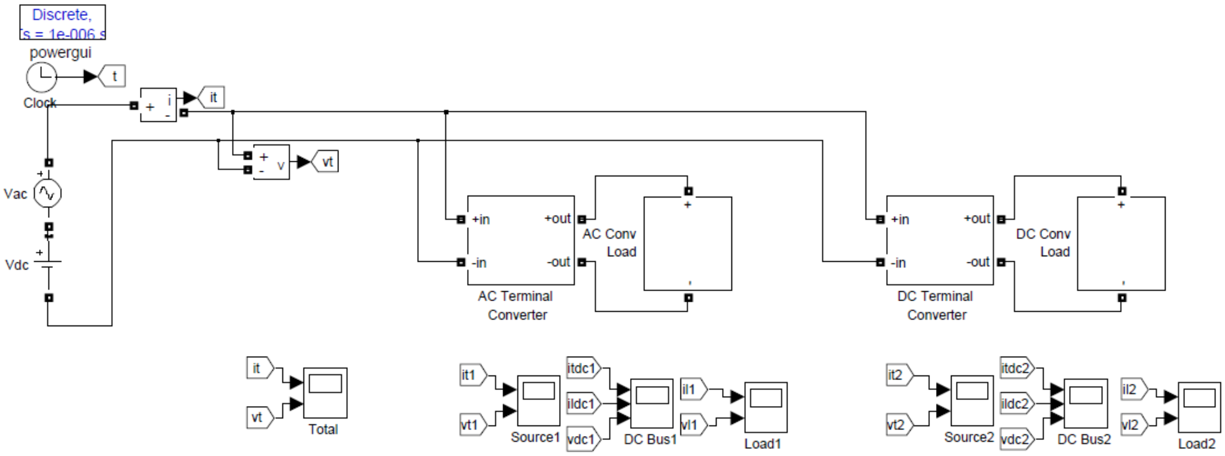

Fig. 26 AC+DC Power System Simulation Model

As mentioned before the converters used for the interconnection of the sources to this AC+DC system, belong to very mature and well-studied technologies, so for the sake of simplicity they aren't included in our model. Instead, their outputs are modeled by ideal AC and DC sources. It can be noted as well, that the transmission line impedance isn't introduced in the model because it is not relevant to the operation of the converters. And the interest of our study is to evaluate how the load converters behave at different operation conditions of the system. Simulation was done including the source terminal converters and the characteristics of the lines, however, the results of the test that will be presented here didn't change significantly and the increase in time consumption and the size of the resulting files for the simulation proved un-practical.

In the model of Figure 26, the loads have been modeled as sinusoidal current sources. Although the terminal converters are labeled as DC or AC, this labeling refers to the frequency from which the power is consumed, but both loads are modeled as AC loads as this is more common. Still, due to the topology and control selected for the output side of the load terminal converter, any desired frequency in the load is possible, and it could even act as a variable frequency drive. The model for the loads is shown in Figure 27.

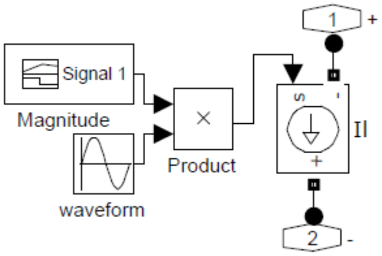

Fig. 27 Simulation Model for the Load

The Simulink model for the load terminal converter is shown in Figure 28. A disconnecting switch is included in series with the current balancing inductor on the input side. This switch is turned on after the input converter controller has had enough time to identify completely the input signal (after one cycle).

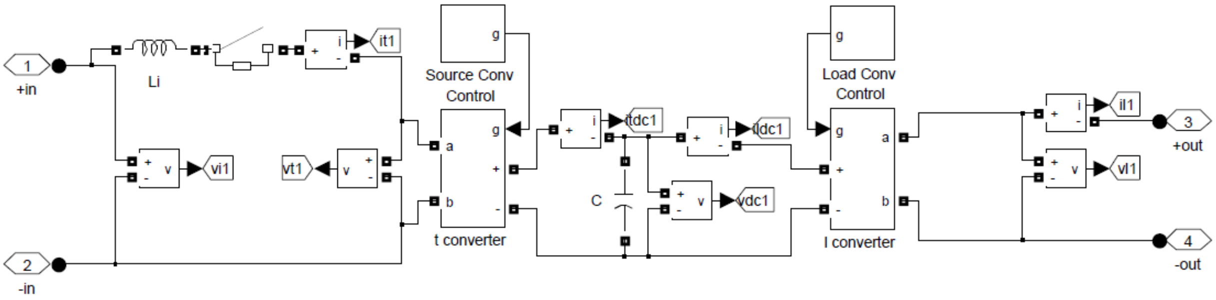

Fig. 28 Load Terminal Converter Simulation Model

Even though all the voltages and currents on the converter are measured, only four of them are used for control, the rest are measured during the simulation for monitoring only. However, other features can be added to the converter if some of these measurements were being used.

The model uses identical modules for the input and output side converters. This module is shown in Figure 29; it is built with four switches representing four voltage switches with their corresponding antiparallel diodes. The gating signals for the converter are generated per leg, and the upper and lower switches of each leg are toggled (as is common with bipolar voltage switching).

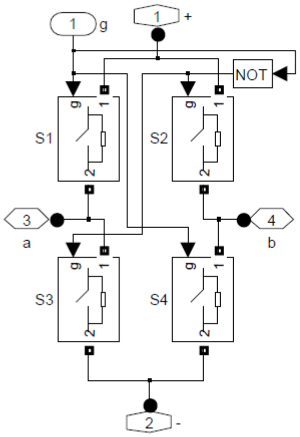

Fig. 29 Single-Phase Switching Module

As was presented in Chapter IV, the controllers for the load terminal converters are built around frequency identification. In order to implement that in Simulink, we use the Fourier block, which implements a fourier analysis of the input signal. Both controllers are coded quite similar, and as a matter of fact, they will be coded exactly the same in a microcontroller or DSP based controller, but as Simulink is graphical in nature, some of the blocks are different. Figure 30 shows the DC terminal controller, which includes the Fourier block for frequency identification, an averaging of the input current of the converter (that is averaging over the switching period) and the switching signal generation code which is based on a bipolar switching scheme.

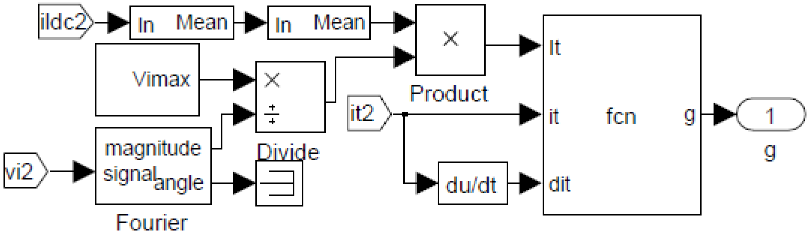

Fig. 30 DC Terminal Controller

Besides having the same elements as the DC controller, the Simulink implementation of the AC controller includes an averaging and subtraction functions that are used in order to obtain the phase and shape of the AC signal in the input voltage. The AC terminal controller, is shown in Figure 31.

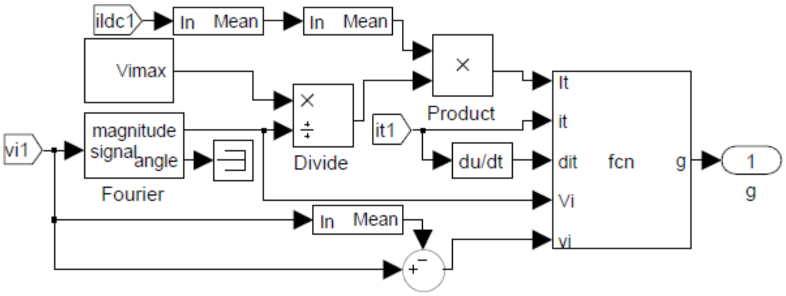

Fig. 31 AC Terminal Controller

B. Simulation Results

The simulation was developed around the concept of a distribution system subdivision. Two loads demonstrated to be enough to show the behavior of the system converters under different common system operating conditions. The parameters used for our simulation are shown in Table 1. The input DC and AC voltages were selected to optimize the usage of the insulation capacities of a 2.5 kV – AC line and the sizes of the loads, resemble average home loads to be found on rural or third world countries, where renewables integration might find a lot of support. Also, the input inductor and DC link capacitor sizes were selected to allow for good performance under both AC and DC load terminals operation, the idea behind this was to obtain a single design which had the flexibility of operating at multiple frequencies.

Table 1 Simulation Parameters

Parameter	Value
Input AC Voltage (RMS)	1.2 kV
Input DC Voltage	1.7 kV
Load Voltage (RMS)	120 V
AC Load	10 kW
DC Load	10 kW
Input Inductor	10 mH
DC Link Capacitor	2000 μF
AC frequency	60 Hz
Switching frequency	2 kHz

a. Dynamic studies

At first, load change studies were performed to see how the converters and their control will react to the dynamics present on the operation of distribution systems. The first of the performed studies was a simultaneous 50% to 100% back to 50% load change in both the AC and DC load. Figure 32 shows the AC and DC terminal current and voltages graphs.

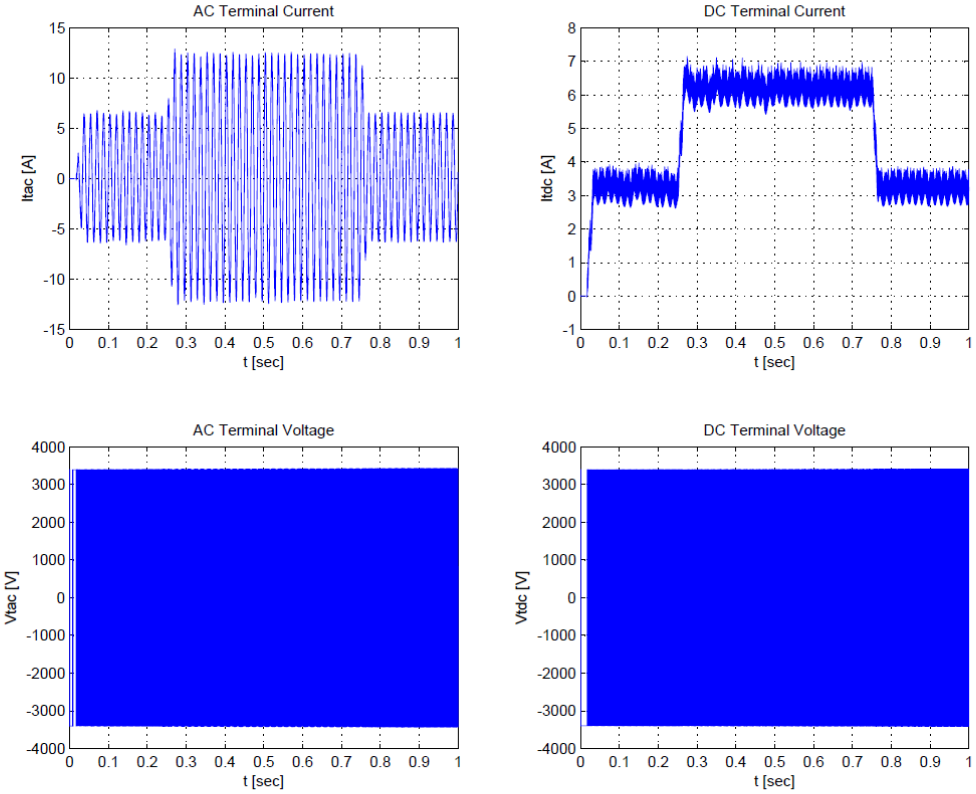

Fig. 32 Load Change AC and DC Terminal Current and Voltages

Besides showing the general dynamic of the system under the load change test, Figure 32 show us that the system is stable at constant load, and that the objective of controlling the terminal current is achieved with an acceptable resolution.

Figure 33 shows a closer look at the terminal current of the AC and DC load converters while under the load change test. The graphs show that there are not waveform alterations during the rise or fall of the load and any waveform perturbations are extinguished in one cycle of the 60 Hz signal. This demonstrates the robustness of the control because the rise and fall of the load is quite close (it happens within only half a second), and the changes are sizable (50%) and simultaneous, which makes this a very drastic operating test.

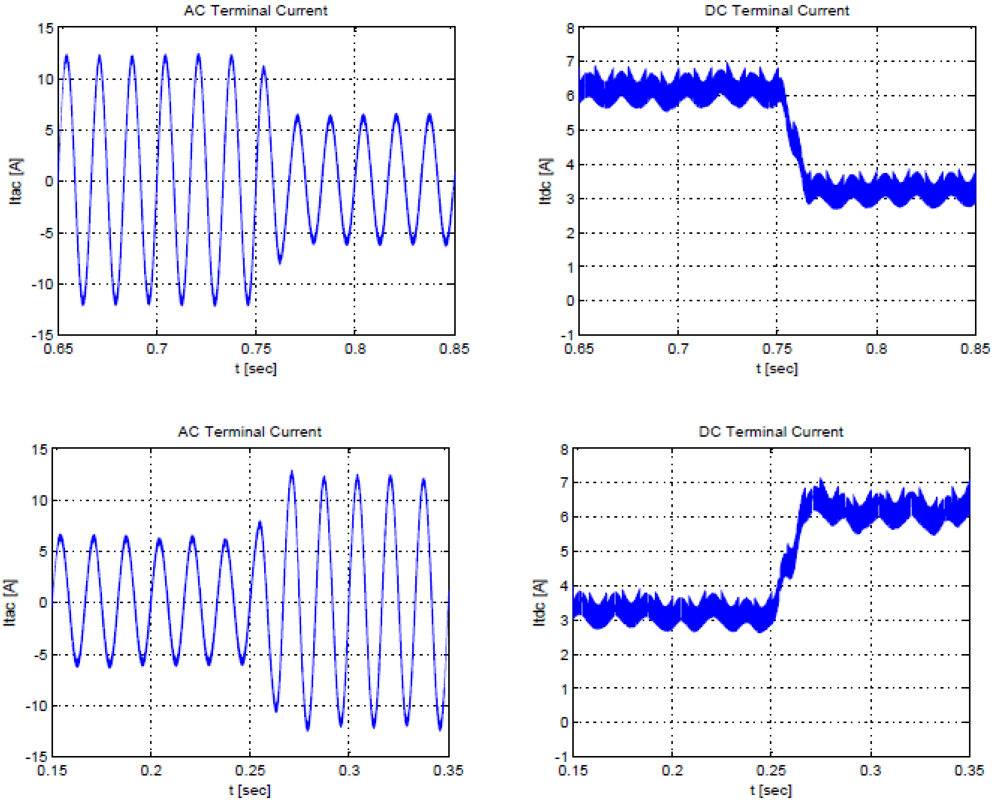

Fig. 33 Load Drop and Load Rise AC and DC Terminal Currents

Figure 34 shows the currents and voltages on the load side of the AC and DC terminal converters. As it was mentioned before, both loads were selected to be AC because is more conventional, and the naming of the terminals refers to the frequency at which the power is delivered between source and load. Figure 34 shows the load change in current, and that the value of voltage provided is stable, keeping its rms value (in red) at the desired value amid the changes. The stable value of load voltage amid changes in the load (which would imply changes in the DC link) is achieved by scaling the command for the load voltage with the measured value of the DC link voltage.

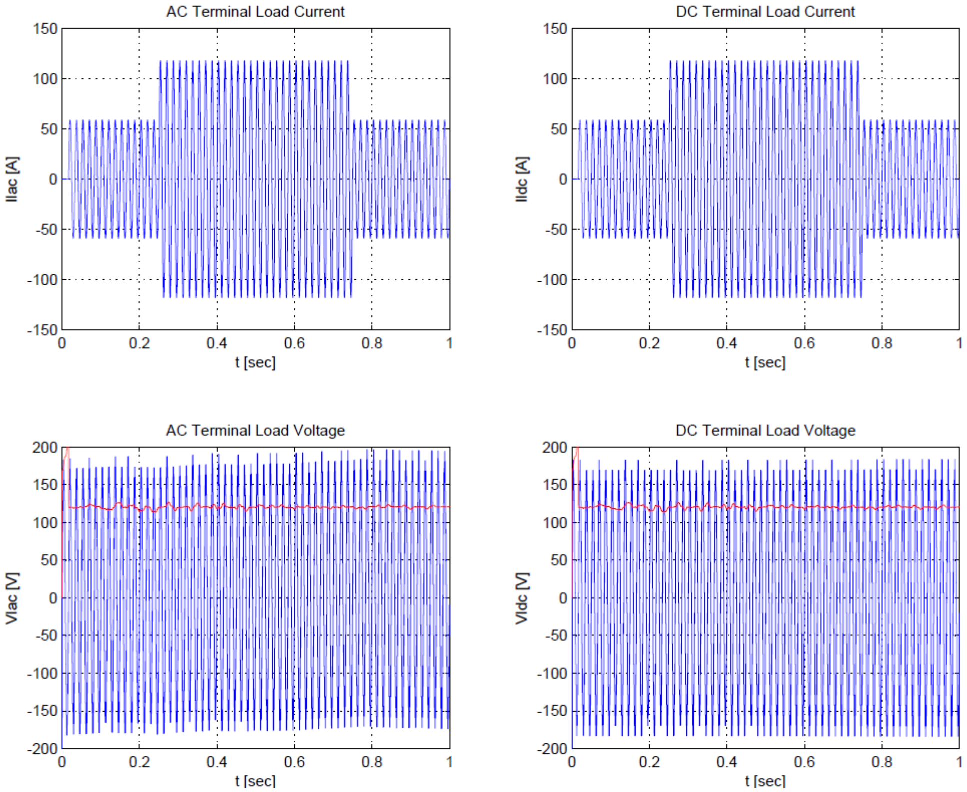

Fig. 34 Load Side Voltages and Currents Under Load Change

Finally, Figure 35 shows the DC link voltages and the power consumed by the AC and DC load converters. The power consumed by the actual load is shown in blue, and the power consumed by the converter from the system is shown in red.

As can be inferred from the comparison of the load currents and the source currents in Figures 32 and 34, the demanded power by the load is closely followed by the power demanded by the converter from the system. However, a steady state error is identified in the case of the DC terminal power, we have concluded that it responds to a combination of the switching frequency and the size of the input inductor. Although a larger inductor could be used in the DC terminal, it will not follow our desire to have a modular converter capable of operating at different frequencies, besides it will make the response of the converter slower, and that is not desirable in a distribution system. The switching frequency could also be increased, however, the error is well below 5% which would be much tolerable than the increased switching losses and cost that this will imply. Finally, a more carefully designed PI controller, will another way to eliminate that error, and designing one which improves the resolution of the converter without affecting the performance is another interesting topic to research in this area in the future.

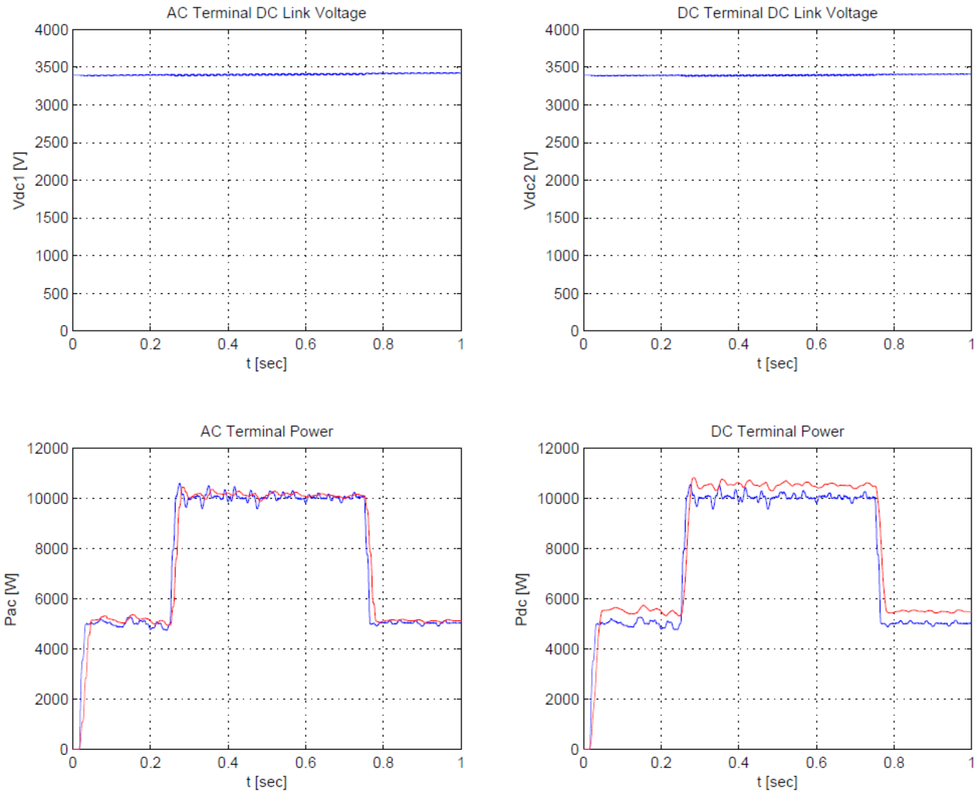

Fig. 35 DC Link Voltage and Demanded Power for AC and DC Terminals

Another interesting study to perform is the sudden introduction or removal of a load to the system. Here we need to evaluate the capacity of the system to respond to this change without reducing the quality of the service to other customers already connected, and without putting the system in danger (current or voltage spikes). Figures 36 and 37 show the terminal current, load demanded power (in blue) and converter demanded power (red) for both the AC and DC terminals for the case of a sudden 0 to 100% rise in AC power (Figure 36) and 100% to 0 drop of DC power (Figure 37).

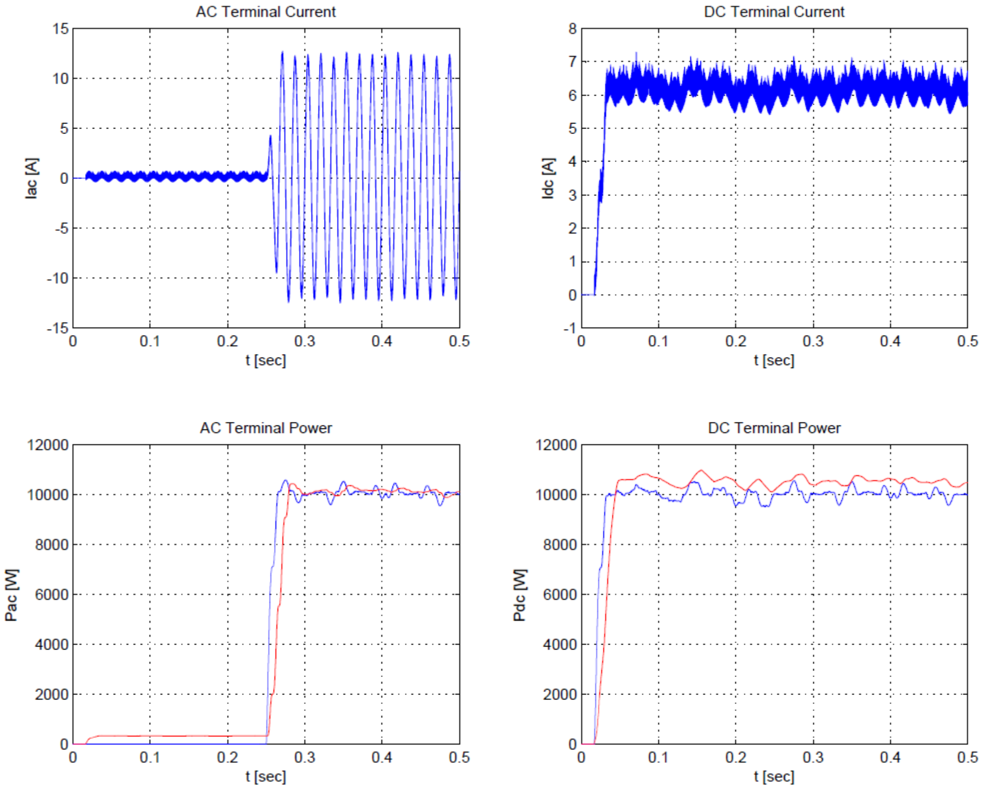

Fig. 36 0 to 100% Rise in AC Load

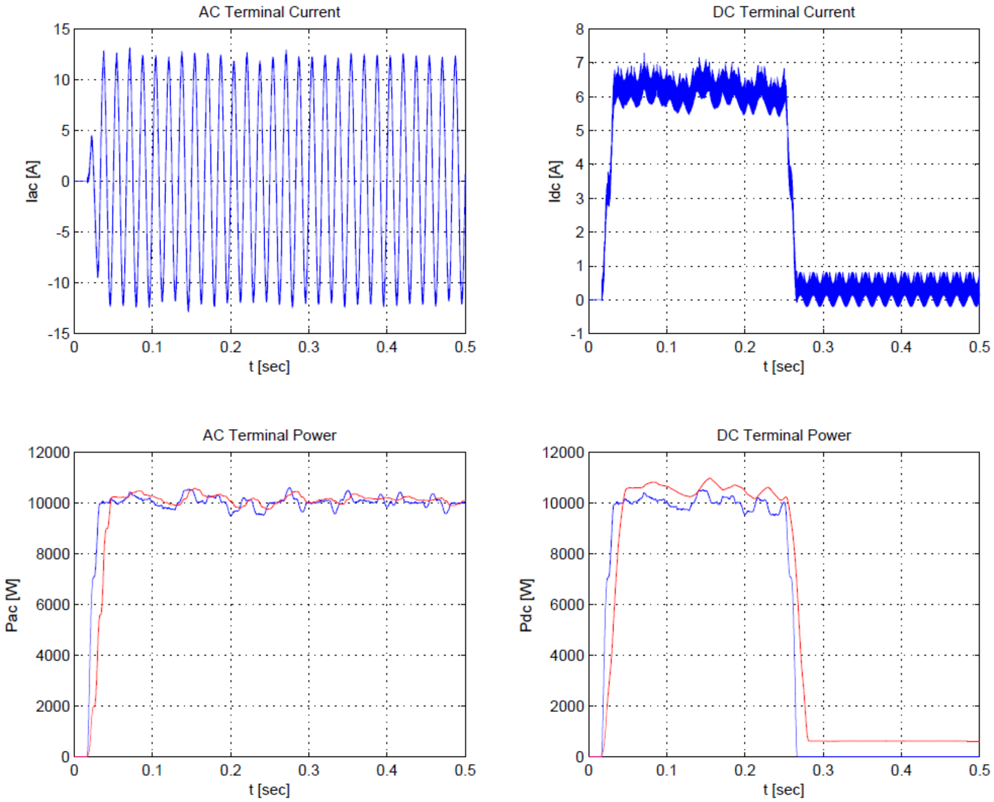

Fig. 37 100% to 0 Drop in DC Load

b. Fault studies

Another objective of our simulation of the system was to be able to observe the behavior of an AC + DC system under some common fault events. In the previous section, the test of 100 % to 0 drop of load has a similar effect to the loss of load or partial loss of the customers of the system. As was shown in those studies, the converters are quite robust when presented with those sudden changes of load. In this study, only faults involving the partial or total loss of load or source are of relevance to us. This section presents the last.

One type of fault that can happen in the AC + DC system is the partial loss of voltage in one of the channels. The capability of the system to keep feeding (at least partially) the load is of the utmost importance. Figure 38 and 39 show the currents and powers for the AC and DC terminals under a DC and AC brownout respectively.

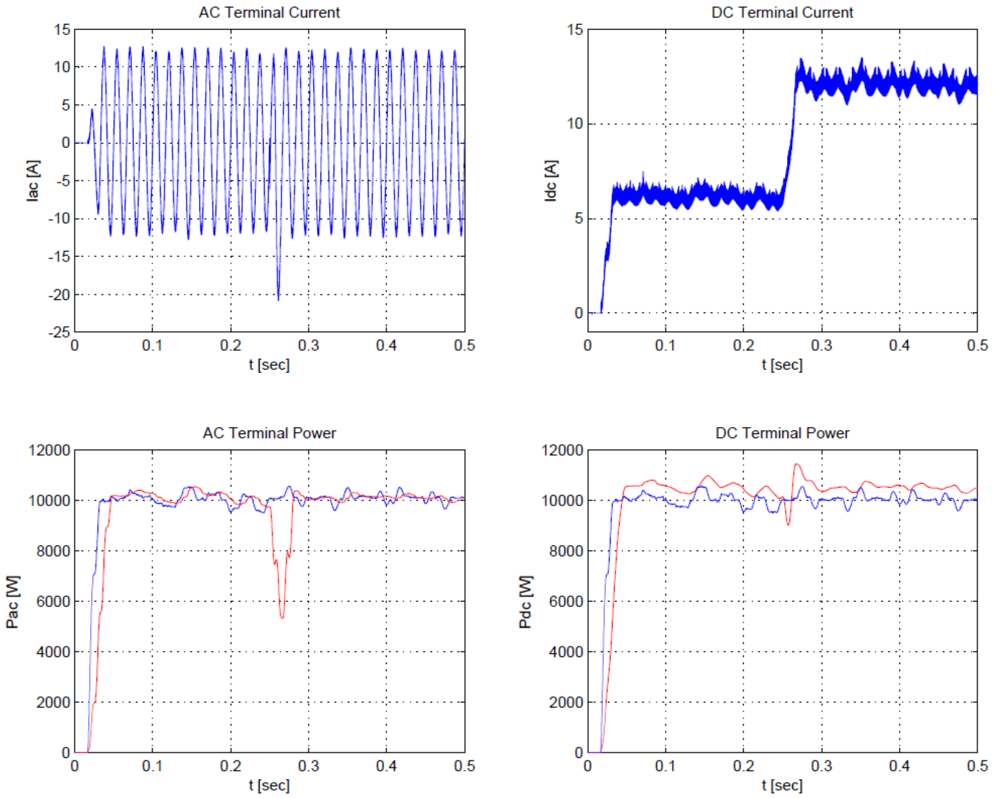

Fig. 38 DC Terminal Brownout

Figures 38 and 39 show that the AC + DC system is in fact capable of surviving a sustained brownout on one of the channels. A rise in current which was expected is the steady state result in the channel affected by the fault, and the perturbation in the other channel is a spike in current, which is dissipated in one cycle of the AC signal. In this regard, the fault produces no more perturbation than the startup of a large motor in an industrial installation, and the dissipation of the effect of the fault, is a lot faster.

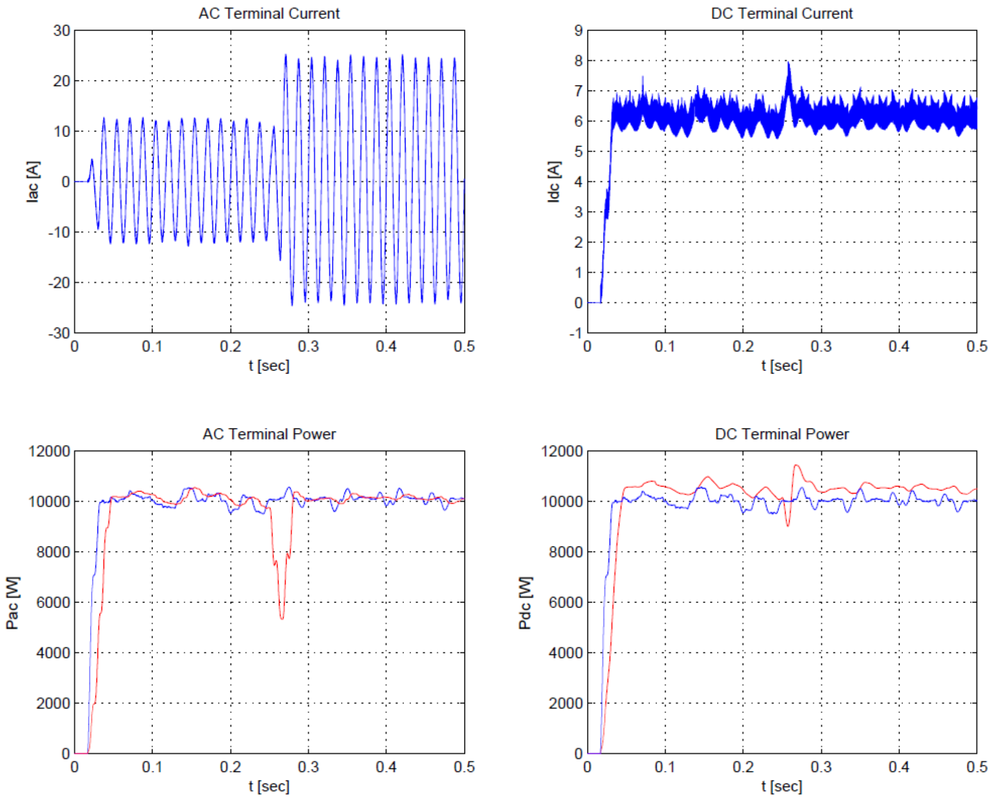

Fig. 39 AC Terminal Brownout

The other fault of significance in the AC + DC system that might affect the converters is the blackout of one of the frequency channels. In the absence of voltage, that channel must be shut down, but the remaining channel needs to “ride through” these fault without affecting the customers connected at the remaining frequency. The ability to do this will determine how well our converters are following the frequency selectivity principle for which they were designed.

The results of the blackout tests for the DC and AC channels are presented in Figures 40 and 41. These tests were performed using the same algorithm designed for the steady state operation of the system with the purpose of evaluating their performance under these circumstances. From the results, we could derive measures for the control of the effects of the fault.

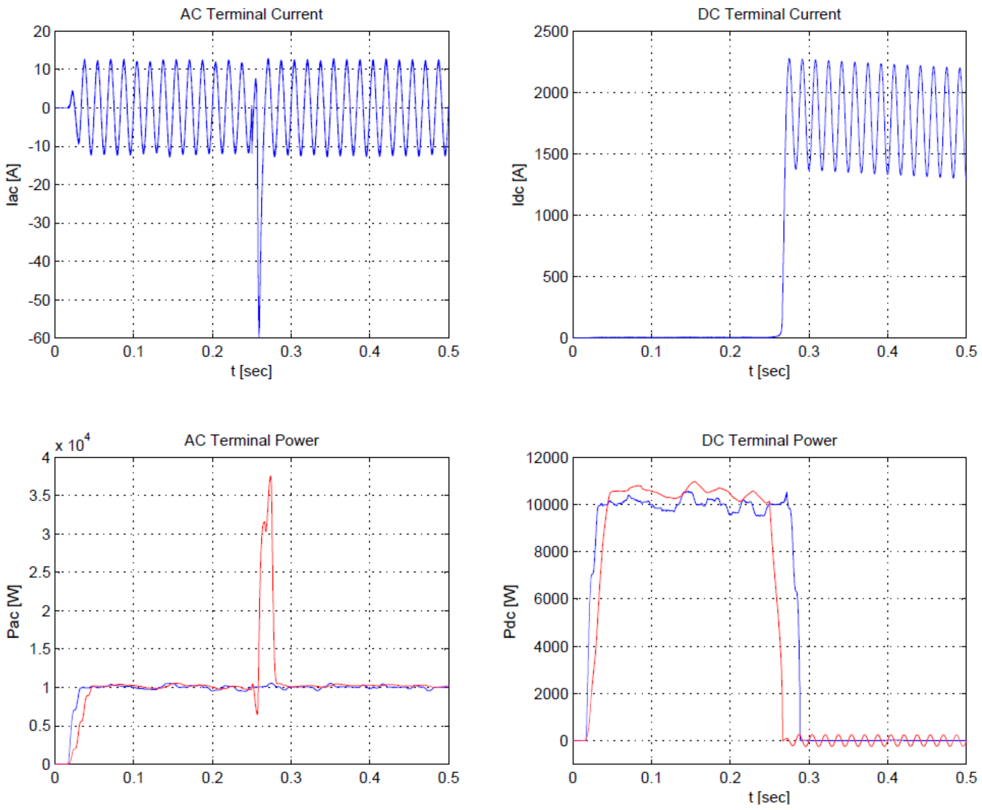

Fig. 40 DC Channel Blackout

Figure 40 shows the results of the blackout test for the DC channel. Following a DC blackout, the AC channel experiments a spike in both its terminal current and the power demanded by the converter from the source. These effects however, have the duration of the AC cycle, that is, they are the effect of the error caused in the controller by the sudden removal of the DC component of the voltage. The load connected to the DC terminal converter, remains passively connected to the system after the fault, which is undesirable.

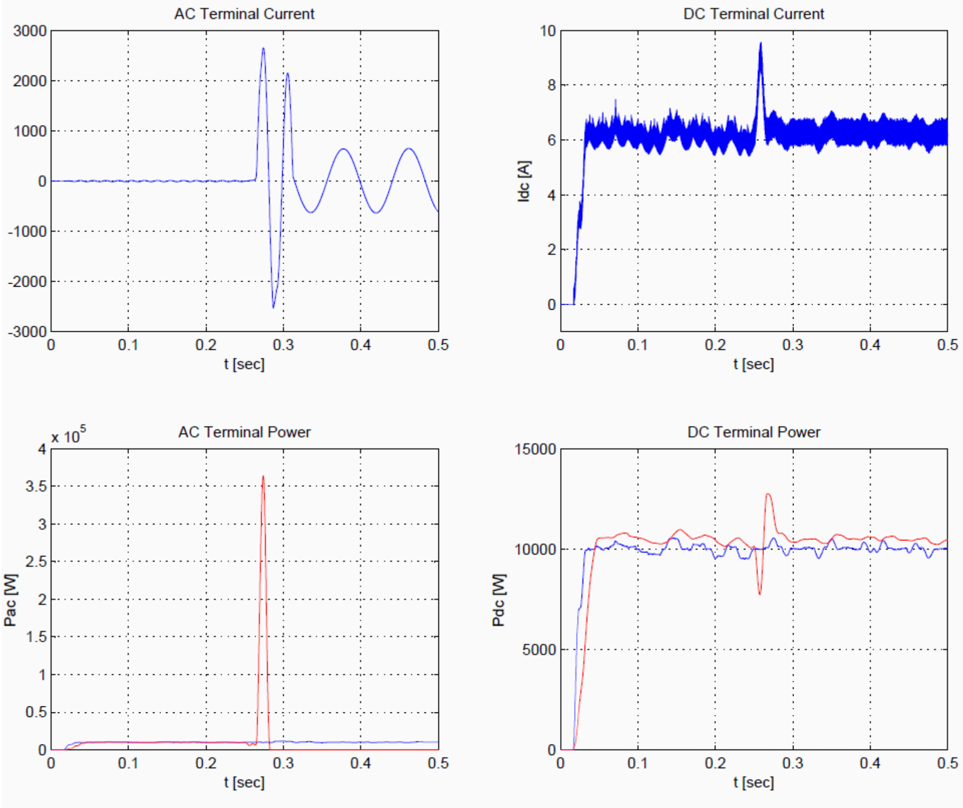

Fig. 41 AC Channel Blackout

Figure 41 shows the results of the blackout test for the AC channel. Similarly to the DC case, in this case the DC channel experiments a spike in both its terminal current and the power demanded by the converter from the source (although smaller), effects which last for only an AC cycle. However, the AC channel also experiments a quite large spike in current and power demanded by the converter, before settling passively into the system. A solution for both the DC and AC system problems with blackout faults will be to implement a current magnitude trip limit which will activate the disconnecting switch provided with each terminal converter. This won’t allow for large current spikes to flow into the system (if switched to a dummy load), and will prevent the load to passively connect to the system if there isn’t voltage in its channel.

CHAPTER VI

SUMMARY AND FUTURE RESEARCH

This chapter presents a summary of the work presented in this dissertation and the results of our research, as well as the contributions derived from it. Because of the potential new lines of work that can be originated from our work, we present a section on future research.

A. Summary of the Work

In this work, the concept of a Multi-Frequency Power System has been studied. We have developed this power system concept as a response to the needs of a modern power system based on the experience with other solutions. While the general concept was presented, a specific case was selected for our design and performance tests. The system selected needed to have significance to the modern power system, and of a practical use. In response to this we decided to design an AC + DC system when taking into consideration the value it could have for renewable power integration. This system was studied via simulation on Simulink, and tests on dynamic operation and fault conditions were performed. The results of these tests show that Multi-Frequency Power Systems, and AC + DC Power Systems in particular have acceptable performance under common operating conditions of a distribution system.

Chapter I presented an introduction to our work, describing the importance of the study and the objectives we wanted to achieve with it. It set the tone of the dissertation by describing how it was organized, and what were the results presented at each stage.

Chapter II is a description of other important power transmission technologies. Although these are not directly related to our development, knowing the operating characteristics of them and the objectives achievable with each of them was important in defining the objectives for our technology and serve as a comparison point for our work.

Chapter III presents the concept of our proposed solution. It starts by introducing the concept of frequency selectivity as it relates to power transmission, and from it, the concept of Multi-Frequency Power Systems was developed. A description of how the power architecture followed, as well as a description of the components of the system. Finally a discussion on the selection of frequencies for our design example was presented.

Chapter IV deals with the specific details and design considerations of an AC + DC system. Special attention was given to the converter topologies to be used, and the control of these converters. Equations describing the operating limitations of the system were described, which allowed us to generate a surface of possible operating points of the system. A discussion was presented as to how retrofit a three phase system into an AC + DC system, and a method to convert the system into a single phase dual circuit AC + DC system was presented as well as the considerations as to why this was the best option.

Finally, in Chapter V the model developed for our computer simulation is introduced. The model is described and it is explained how the model relates to real world conditions of a system such as the one designed. The justification for the tests performed is presented as well as the results for these tests. A description of the results for the dynamic and fault tests performed to the system is presented.

B. Description of the Contributions

The contributions of the research presented by this dissertation to the state of technology can be summarized as follows:

- Our work has demonstrated power selectivity based on frequency identification and a power transmission system scheme has been developed from this concept, which opens the door for a totally new energy exchange structure in distribution systems where sellers and customers can identify themselves and realize real time transactions
- It has been demonstrated that AC + DC power system integration seems especially suited for single phase systems retrofitting. Also an alternative of converting three phase four wire systems into two parallel single phase systems was developed, which enables the retrofitting of three phase systems into AC + DC power systems.
- A control and converter topology was developed that allows for selective power transmission to take place, which is based on conventional converters and is of modular construction. Also the control of the converter was designed so that it can be used at various different frequencies, enabling the capacity of the converter to switch channels.

- The AC + DC system developed besides the economic benefits which can be derived from power selectivity, has all the benefits of a power electronic rich power system (increased system's "smarts", reliability and phase control) which sets the multi-frequency power systems as an alternative for the implementation of Smart Grids

C. Future Research Initiatives

After culminating the research presented in this dissertation, we have identified numerous future lines of research related to the topic of Multi-Frequency Power Systems, from which we present the most inmediate:

- As multi-frequency power systems allow independent power channels to co-exist in the same transmission media, power selectivity can also enable further size reduction of specialty power systems (space, vehicular and computer applications). An investigation of the possible applications benefits and drawbacks in such systems will be of the utmost interest.
- We have selected for our operation the strategy that maximizes the DC transmitted power for a fixed amount of AC power, however, optimized AC+DC operation of distribution systems for minimum losses will be of interest, especially when evaluating the retrofitting of a distribution system into a Multi-Frequency Power System
- The system and concept we have presented in this dissertation is of integration of multiple known frequencies. Integration of "wild

frequency” resources into a distribution system is of interest regarding the variable frequency power extraction from wind turbines, and further study on this topic will be encouraged.

- Analysis of the effect of MFPS transmission technology on economic dispatch of distributed energy resources and studies of open market schemes based on MFPS technology and the effect on energy prices to consumers and utility revenue will definitely be the next step to take on this topic. The results from these studies will be helpful in guiding the further development of the technology, as it will teach us the needs of this new type of energy market. This study must include new concepts to the distribution systems, such as the existence of energy resellers and the participation of energy producers and users in a real time energy market.

REFERENCES

[1].Singh, R.; Singh, A.; , "Energy loss due to harmonics in residential campus — A case study," In 45th International Universities Power Engineering Conference (UPEC), pp.1-6, Aug. 31 2010-Sept. 3 2010

[2].Todeschini, G.; Emanuel, A.E.; , "Wind energy conversion systems as active filters: Design and comparison of three control methods," *Renewable Power Generation*, IET , vol.4, no.4, pp.341-353, July 2010

[3].Valenzuela, J.; Pontt, J.; , "Real-time interharmonics detection and measurement based on FFT algorithm," *Applied Electronics*, 2009. AE 2009 , pp.259-264, 9-10 Sept. 2009

[4].Gordon, M.; Shahidehpour, M.; , "A living laboratory [The Business Scene]," *IEEE Power and Energy Magazine* , vol.9, no.1, pp.18-98, Jan.-Feb. 2011

[5].Saber, A.Y.; Venayagamoorthy, G.K.; , "Plug-in vehicles and renewable energy sources for cost and emission reductions," *IEEE Transactions on Industrial Electronics*, vol.58, no.4, pp.1229-1238, April 2011

[6].Mohr, R.A.; Moreno, R.; Rudnick, H.; , "Insertion of distributed generation into rural feeders," In CIGRE/IEEE PES Joint Symposium on Integration of Wide-Scale Renewable Resources Into the Power Delivery System, pp.1-10, 29-31 July 2009

[7].US Department of Energy (2008). The smart grid: An introduction [Online]. Available: http://www.oe.energy.gov/SmartGridIntroduction.htm

[8].Massoud Amin, S.; Wollenberg, B.F.; , "Toward a smart grid: power delivery for the 21st century," *IEEE Power and Energy Magazine*, vol.3, no.5, pp. 34- 41, Sept.-Oct. 2005

[9].Levene, J.; Kroposki, B.; Sverdrup, G.; , "Wind energy and production of hydrogen and electricity – Opportunities for renewable hydrogen," National Renewable Energy Laboratory, Conference paper NREL/CP-560-39534, March 2006

[10].Arrillaga, Jos; *High Voltage Direct Current Transmission*, London, IET press, second edition, October 1998.

[11].Kimbark, E.W.; *Direct Current Transmission, Volume 1*, New York, John Wiley & Sons, 1971

[12].Mohan, N.; Undeland, T.M.; Robbins, W.P.; *Power Electronics: Converter, Applications and Design*, New York, Wiley, 3rd edition, 2002

[13].US. Patent No. 6,714,427 B1, Mar. 30, 2004

[14].US. Patent No. 6,861,825 B1, Mar. 1, 2005

[15].Edris, A.; Barthold, L.O.; Douglas, D.A.; Litzenberger, W.H.; Woodford, D.A.; "Upgrading AC transmission to DC for maximum power transfer capacity," In 12th International Middle East Power System Conference (MEPCON), pp.44-49, Mar. 12-15 2008

[16].Hingorani, N.G.; Gyugyi, L.; *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, Piscataway, NJ, IEEE Press, 2000.

VITA

Ronald Yoel Barazarte Conte received his Bachelor of Science degree in electromechanical engineering from The Technological University of Panama in 2005. He entered the doctoral program in Electrical Engineering at Texas A&M University in the fall of 2006. His research interests include power electronic applications for power systems, renewable sources and their integration to the electrical grid, control and operation of electrical machines and energy sustainability. He plans to return to the Technological University of Panama to do research and teach in these topics.

Mr. Barazarte may be reached via e-mail at ronald.barazarte@utp.ac.pa, or through Dr. M. Ehsani, Power Electronics Laboratory, Electrical Engineering Department, Texas A&M University, College Station, Texas 77843-3128.