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Thesis Title

Abstract

The abstract

Contenido

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List of Acronyms

AC	Alternate Current
APF	Active Power Filter
CSSMP	Calculation of Steady-State Modulation Parameters
DC	Direct Current
DE	Designable Element
DGU	Distributed Generation Units
DO	Design Objective
EC	External Conditions
ED	Exact Design
EHD	Extended Harmonic Domain
EHD 1P	EHD Single Phase (simplified) model
EHD 3P	EHD Regular model
EHD AS	EHD Approximated (simplified) model
EHD ES	EHD Exact (simplified) model
FACTS	Flexible AC Transmission System
GSSA	Generalized State-Space Averaging Algorithm
hf-EHD	High Switching Frequency EHD model
HSS	Harmonic State Space
LCL	Electric circuit arrangement made of series inductor - parallel capacitor - series inductor
LTI	Linear Time Invariant
NLSQ	Non-linear Least Squares
OC	Operating Condition
PCC	Point of Common Coupling

PEC Power Electronic Converter

PES Power Electronic System

PLL Phase-Shift Locked Loop

PWM Pulse Width Modulation

RTDS Real-Time Digital Simulator

SOA State of the Art

SPWM Pure Sinusoidal PWM

SVPWM Space Vector PWM

THPWM Third Harmonic Injection PWM

UPS Uninterrupted Power Supply

VSC Voltage Source Converter

List of Symbols

$a_{(n)}$ Time when the carrier signal $c(t)$ changes it slope

C Generic sine-based modulation signal gain

$c(t)$ Modulation signal of PWM

$\mathbf{D}^{(hf)}$ hf-EHD model derivation matrix

$d(t)$ DC-DC converter modulation signal

e Generic sine-based modulation signal harmonic error

$\mathbf{D}$ EHD derivation matrix

$\mathcal{G}(t)$ Time dependent orthogonal basis of the complex Fourier series

$\mathbf{I}_d$ EHD Identity matrix of size $(2h + 1 \times 2h + 1)$

$X_{\langle k \rangle}$ k-th harmonic element of the EHD (vector) variable X.

$\mathbf{X}_{ss}$ Steady-state EHD (vector) variable

$[\cdot]$ Generic Toeplitz matrix formed with the harmonic content of its equivalent time domain signal

$\mathbf{X}$ EHD (vector) variable equivalent formed with the harmonic content of time domain signal $x(t)$

f_0 Fundamental frequency in Hertz

f_{sw} Switching frequency of PWM

$f_{h_{sw}}$ Switching frequency of hf-EHD models

T_0 Fundamental period in seconds

$H(\mathbf{x})$ System of nonlinear equations to solve of a nonlinear problem

h_h High order maximum harmonic of hf-EHD model

h_l Low order maximum harmonic of hf-EHD model

$\mathbf{J}$ Jacobian matrix

m_a Modulation index of sine-based PWM modulation signal

h Maximum harmonic considered in the EHD model

$M_{\mathbf{EHD}}$ EHD Measurement vector of EHD-based estimation algorithm

m_f Modulation index

$[\cdot]^{(hf)}$ hf-EHD model multiplication matrix

m_{hf} Modulation index of hf-EHD models

MoP Modulation Parameters

$M_{\mathbf{VSC}}$ System measurement vector of EHD-based estimation algorithm

ω_0 Fundamental angular frequency in rad/s

OpC Operating Condition

$OpC_{\mathbf{ref}}$ Reference Operating Condition

PCV Passive Component Value

ρ Weight constant of NLSQ algorithm

s_x Phase switching signal

s_x^m Phase modulation signal of PWM

$t_{x(n)}$ n-th switching instant of a switching signal

θ Phase shift of sine-based PWM modulation signal

$x(t)$ Generic time domain signal

$x_{np}(t)$ Generic non-periodic time domain signal

T_s Numerical simulation step size in seconds

$\mathbf{x}$ Solution vector of nonlinear problem

$\mathbf{X}^{(hf)}$ hf-EHD model (vector) variable

$X_{(i\,\mathbf{m_{hf}})}$ hf-EHD model variable sub-vector

y Number of coupling terms considered in the high order harmonics of hf-EHD models

List of Contributions

PUBLISHED

JOURNAL CITATION REPORTS

- **"An exact method for analysis and component design of grid connected VSC-based power devices"**. *Miguel Esparza and Juan Segundo-Ramírez.* International Journal of Electrical Power & Energy Systems. June 2016.
- **"A Comprehensive Design Approach of Power Electronic-Based Distributed Generation Units Focused on Power Quality Improvement"**. *Miguel Esparza, Juan Segundo-Ramírez, Ciro Nuñes, Xiongfei Wang and Frede Blaabjerg.* IEEE Transactions on Power Delivery. 2016.

INTERNATIONAL CONFERENCES

- **"Optimal design of power electronics converters using the extended harmonic domain"**. *Miguel Esparza and Juan Segundo-Ramírez.* 2014 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC).
- **"Switching based modeling of grid interconnected hysteresis current controlled VSC converters"**. *Miguel Esparza and Juan Segundo.* 2016 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC).
- **"Measurement of Phase Dependent Impedance for 3-phase Diode Rectifier"**. *Jun Bum Kwon, Xiongfei Wang, Claus Leth Bak, Frede Blaabjerg, Michael Hwang, Alan R. Wood, Neville R. Watson, and Miguel Esparza.* In Proc. Conference of IEEE Industrial Electronics Society (IECON), Oct. 2016.

SCIENTIFIC DIVULGATION

- **"Los armónicos y su importancia en la energía eléctrica"**. *Miguel Esparza and Juan Segundo-Ramírez.* Universitarios Potosinos. Número 176, Junio de 2014.

TECHNICAL REPORTS

- **"Modeling of hysteresis current control"**. *Miguel Esparza.* Technical report for Enercon - Aalborg University research collaboration, August 2016.

UNDER REVIEW

JOURNAL CITATION REPORTS

- **“Modeling of VSC-Based Power Systems in The Extended Harmonic Domain”**. *Juan Segundo-Ramírez, Miguel Esparza, Jum Bum Kwon, Xiongfei Wang and Frede Blaabjerg*. Transactions in Power Electronics. Third-round revision.

TO BE SUBMITTED

JOURNAL CITATION REPORTS

- **“Characterization of lumped parameter models of Grid-Connected VSC-Based Systems”**. *Miguel Esparza, Juan Segundo-Ramírez, Nancy Visairo-Cruz, Carlos Gurrola-Corral and Ernesto Barcenas*. IEEE Journal of Emerging and Selected Topics in Power Electronics.

- **“EHD small-signal modeling of VSC-based systems.”**. *Miguel Esparza, Juan Segundo-Ramírez, Jesús Rico, Xiongfei Wang and Frede Blaabjerg*. Transactions in Power Electronics.

- **“Modeling of high-switching frequency VSC-Based Power Systems in The Extended Harmonic Domain”**. *Miguel Esparza, Juan Segundo-Ramírez and Jesús Rico*. Applied Mathematical Modelling.

- **“An optimal-losses design of grid connected VSC systems using the Extended Harmonic Domain”**. *Miguel Esparza, Juan Segundo-Ramírez and Iván Hernández*. Transactions on Industrial Electronics.

Dedicated to ..

Acknowledgments

To God, …

To my ..

Introduction

Power electronic systems have been widely employed in daily life applications. From their usage, huge developments in industrial, transportation, aerospace, commercial and residential technologies have been achieved over within few decades, concerning applications from very low power (portable electronic equipment) to very high power (transmission systems). Since their main usage is related to energy handling, there is a constant research and development focused on improving energy efficiency at all power levels.

The definition adopted in this thesis work of power electronic system (PES) is: a system containing at least one power electronic switch, any number of passive electrical components (transformers, resistors, capacitors and/or inductors) and any number of ideal current and voltages sources[1]. As mentioned in the definition, a power system is directly tied to the presence of power electronic switches on its topology. The above mentioned technological widespread and constant improvement have been guided by the development of material technologies from which those power switches are constructed. The power electronic systems era began in the 50's with the first commercial thyristor, the Silicon Controlled Rectifier (SCR). This was the former device from which new devices with improved capabilities were developed and in most cases keep the development until nowadays, such as the bipolar junction transistor (BJT) in 1970, the gate turn-off thyristor (GTO) in 1973, the metal oxide field effect transistor (MOSFET) in 1978, and the insulated gate bipolar transistor (IGBT) in 1983.

As result of the development of fully controlled power switches, such as the BJT, GTO, MOSFET and IGBT, sophisticated applications mainly based on classical and modern control theory were able to be implemented. Among the most developed fields, the energy conversion field excels due to high variety of energy sources available, where power electronic converters (PEC) are the core devices used by this field. A power electronic converter is a PES, realized through a variety of configurations, driven by a control/protection system[2]. The PEC's main purpose is to regulate and shape the current and/or voltage wave-forms obtained from a source in order to be efficiently used on a load. Three main forms of power conversion devices can be summarized:

- direct-current to direct-current (DC-DC) converters.
- alternating-current to direct-current (AC-DC) (or vice versa).
- alternating-current to alternating-current (AC-AC) converters, also known as cyclo-converters.

Despite this rough characterization of the PECs, there is a huge diversity in topologies, technologies, and concepts within each type of device. This thesis is focused on AC-DC (or vice versa) converters, since the Voltage Source Converter (VSC) is a specific configuration of PECs within this category.

The VSC is an AC-DC converter in which the direction of the power flow is determined on the direction of the direct-current (DC) side of the converter. Hence, the VSC DC side is typically connected to large capacitor to resemble a DC voltage source. This allows the usage of unipolar electronic switches to construct these kind of devices. However, VSC requires reverse-conducting switches (anti-parallel diodes) or switch cells which combine both devices. The basic configuration of a two level VSC (half-bridge) is given in Figure 1. From this basic configuration more sophisticated topologies can be realized. The single-phase full bridge, three-phase two-level, neutral point clamping and multilevel configurations are among the most widely adopted and developed.

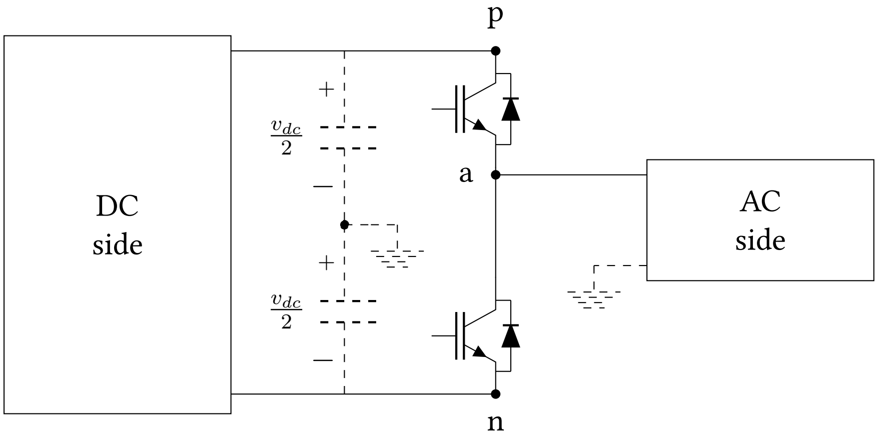

Figure 1: VSC basic structure

Despite the used topology, the operation and capabilities offered by the VSC are closely tied to the control strategy and the modulation scheme employed that control the switching signals to drive the power switches. Although both the modulation and the controller are independent systems connected to the VSC, they play a key role in the derivation of accurate, reliable and reduced-order mathematical models. Very important tasks such as: design and analysis of the control strategy, design and analysis the converter behavior, and time-domain simulation of the VSC-based system, among others, are able to be used if an appropriate mathematical modeling of the system is available. Table 1 summarizes some of the available modeling approaches able to be used for VSC-based systems.

In Table 1 a clear division between averaged-modeling-based approaches and phasor-based modeling approaches can be identified. The modeling approaches of the first three rows are based on neglecting the switching process, while the last two explicitly include it by considering the generated harmonics as state-variables. As stated on Table 1, the most used approach is based on the averaging model, for which a deeper explanation regarding the foundations and considerations of this modeling approach is given in the following Subsections, with specific details for VSC-based systems.

Table 1: VSC-based systems modeling approaches.

Modeling Approach	Fundamentals	Characteristics	Usage	Refs.
DQ Averaged	Averaging permits the neglecting of switching discontinuities to obtain continuous models[3], its extension to the AC systems is possible by the usage of the Park's transformation.	- Results in continuous state-space dynamic models. - Compatible with elements widely used in conventional PES. - Dynamics of the d- and q-axis are tightly coupled. - Neglects the switching effects. - Assumes pure sinusoidal conditions.	- Designing of linear and nonlinear controllers for PWM VSC-based systems. - Deriving LTI models to perform stability analysis. - Not suitable for non-fully-controlled PEC. - Most used modeling for VSC-based systems.	4,5,6,7,8
Impedance-based	Each load and source is described by its input and output impedance, obtained from a SISO-LTI model.	-A system model is readily obtained in the form of a linear network. -Complex PES can be modeled and analyzed as impedance-load subsystems.	- Studying interactions between AC-DC converters and other grid elements. - Identifying stability problems of large networks and pointing to possible solutions.	9,10,11,12,13,7
Harmonic Linearization	Technique that develops a small-signal linear model for a nonlinear system along a periodically time-varying operation trajectory[7]	- Superimposes a harmonic perturbation to the system in order to extract the resulting components of interest. - Can be directly used in impedance-based system stability analysis	- Modeling input impedance of various non-fully-controlled ac–dc converters. - Not suitable for analyze harmonic interaction within VSC-based systems.	14,15,16,17
Dynamic Phasor / Generalized state-space averaging (GSSA)	Is based on the representation of a signal on the fundamental period interval by the Fourier series.	- Results in time-invariant dynamic models with the complex Fourier coefficients of the circuit state-variables. - Is based on an averaging operator and two analytic operations: derivation and multiplication.	- Takes into account the modulation process. - Mainly applied to switching frequencies (< 2Khz) systems. - Not feasible for further derivation of impedance based models.	18,19,20,21,22,23
Extended Harmonic Domain (EHD) / Harmonic Steady State (HSS)	Generalizes the GSSA using a matrix-based formation allowing its compact and handy state-space formulation.	- Derivation and multiplication are defined as matrix-based operators. - Allows the concept of harmonic transfer functions. - Considers well-defined EHD (vector) variables for each time-domain variable. - It could derive in increased order state-space models.	- Analyzing the transient behaviors of harmonics on FACTS[24] and wind turbine based systems[25]. - Analyze bi-directional harmonic coupling on closed-loop systems[26]. - Optimal design of VSC-based systems	27,28,29,26

HYBRID SYSTEM MODELING

The inherent presence of switching devices on any PEC produces complex dynamics, especially at the switching instants. However, if ideal switches are considered, the system can be seen as an hybrid dynamical system which by definition is a collection of dynamic systems with a set of rules for jumping from one to another[30]. The set of dynamic systems are assumed to be continuous state space systems and those are collectively called continuous dynamics. Since PES are formed with passive elements, the derivation of the *continuous dynamics* is usually a simple task carried out by regular circuit analysis. Certain set of rules determine which discrete state is active, those are collectively named *discrete dynamic states*. In a PES the discrete dynamic states are represented by the position of the system switches, and for VSC-based systems those are independent of the state-variables[1]. Despite the accurateness and well description of the PES given by the hybrid systems modeling, few works regarding this modeling are found in the literature[31,32] due to the very limited and complex tools developed for the solution, analysis and design for these kind of systems. Its practical usage for control design and performance analysis has been restricted to digital nonlinear controllers such as predictive control[33].

SWITCHED MODELING

A special case of the hybrid model for PEC is the so called switched model. This model is generally derived by combining the state space continuous dynamics states of the different discrete states into a single unified model. In order to do so, it is required that all the discrete dynamic states are able to be synthesized by switching functions that properly describe the jumping among the continuous states. In this way, it is obtained a dynamic system model which considers discrete switching variables on its formulation[34].

It is worth to point out that this modeling approach cannot be derived for all the topologies and configurations of a PES. However for the specific case of VSC-based systems, it is very likely to derive such kind of models in their basic configurations (half-bridge, full-bridge and three phase), especially if some assumptions and considerations are made, such as: ideal switches approximation[2] and forbidden switching combinations.

AVERAGE MODELING

Small-signal analysis is the study of the small deviations from an operating point for a system subjected to small disturbances. The assumption made by this modeling method is that the system can be described by a linear model for small variations around the selected operating point. As long as the disturbances in the system fail to be ”small”, the derived model will be more inaccurate to represent the system performance. However, the small-signal model is easier to manipulate and treat, and for many applications the trade-off between model accuracy and simplicity is worthwhile.

Small-signal modeling is a widely used approach to derive easily and tractable mathematical models. Its usage on PECs can be seen from two different perspectives: 1) to linearize the switching instant behavior using the hybrid system model and 2) to linearize a derived switched model.

Linearization over switching instants is the base for modeling of PECs without periodic pulse with modulation (PWM), such as bang-bang controlled DC-DC converters[35,36,37]. A more sophisticated approach, but based on the same principle, was also proposed to obtain small-signal models of PECs, including VSC-based systems by Love[1]. These small-signal models linearize the effect of jump from one discrete stage to another in a hybrid system and their modeling is independent of the modulation scheme used. Although linear, the derived models for VSC-based systems can be quite complex and hard to use with the well-established control design theory developed for continuous linear systems[38,1].

A more widely adopted small-signal derivation is to use the switched model along with the PWM modulation scheme to perform the linearization considering the duty cycle as input instead of discrete switching signals, in order to derive the so called *average model*. Such approach was originally developed for DC-DC converters[39,40] and was latter extended to VSC-based systems by considering sinusoidal duty cycles in the modulation[41,42,43,4]. This model has been intensively used for investigations and development of modern VSC-based systems such as micro-grids and distribution automation, FACTS devices, design of control algorithms for interfacing and coordination of DGU, among others. From its usage, linear and non linear continuous dynamic models of VSC-based systems are able to be obtained, which allow their design, analysis and simulation. However, the average modeling approach is not able to represent the phenomena associated with the switching harmonics. Therefore, it is important to keep in mind this limitation when considering medium and high frequency effects and phenomena[8].

State-of-the-art in the modeling of VSC-based systems

Table 2 chronologically lists the most used applications for VSCs. Virtually all the applications listed in Table 2 are designed based on a cascaded control structure in which the VSC is directly used on the inner current feedback loop by means of a PWM modulator. This structure has its origin on the DC motor drives structure, in which a DC-DC converter was used in the inner current loop on the speed or position control of a DC motor[44]. By using space vector representation for three-phase systems (and single phase systems) the control topology along with the analysis and design tools derived for DC drives were able to be adapted to VSC-based systems. Particular details for each application are given below, focusing on the particular differences in respect with the original DC drive structure along with its derived challenges, solutions and open issues.

Table 2: Most used PEC applications of VSCs.

Application	Importance and Impact	Refs.
Alternating current (AC) motor drives	AC motors are used in virtually all the industrial sectors due to their robustness and reliability since AC drives provides speed and position control.	[45,46]
Active filters	Active filters provide a solution for power quality assessment to address harmonic distortion generated by PES, specially based on non-fully controlled devices. Those are fairly used in industrial applications which have an increased penetration in number and/or in power level of PEC.	[47,48,49,50,51,52]
PWM rectifiers	These are employed as front-end power processing units which allow power factor correction, bidirectional power flow and power quality assessment in applications such as: locomotives, downhill conveyors, cranes, advanced AC drives, etc.	[53,54,41,55,43]
Uninterrupted power supply (UPS)	These are reliable sources of continuous electric power during outages or line problems. They are used worldwide, helping to supply a wide variety of critical loads, such as telecommunication systems, computer sets, and hospital equipment.	[56,57,58,59,60]
Interconnection of distributed generation units (DGUs)	The DGUs offer on-site highly reliable and good quality electrical power supply. This approach is becoming a part of the strategic plans of most countries to address current challenges associated with energy management.	[61,7,62,63,64]

AC DRIVES

Due to the advent of PEC, PWM techniques, sophisticated control strategies, and improved estimation methods, AC-drives have been gained market place on variable speed applications, pushing the DC drives towards obsolescence[65]. In addition, the availability and reduction in cost of digital resources, such as Digital Signal Processors (DSP), powerful micro-controllers and Field Programmable Gate Array (FPGA) devices, allow the fast and easy implementation of complex modulation techniques and control strategies. In this way, by means of the coordinates transformation of three-phase average models, the vector control is the base for most of the developed converters in the AC drives field. This permits the design of linear and nonlinear control strategies, since the average instantaneous positions of voltage, current and flux space vectors are available at any instant in both steady and transient state. However, these advantages are given only if the instantaneous position of the rotor flux vector and the machine parameters are known or fairly approximated in the model. Since the machine parameters are dependent on the rotor speed and the rotor flux is impractical to measure them. Hence, the faced challenges and developed research in this application have been focused mainly on observers and adaptive controllers towards reliable control strategies with a reduced number of sensors[66].

The switched averaged model, either in the synchronous or stationary frame, is the main modeling framework used to design the controller and analyze the performance of AC drive systems. This model is usually enough to perform all the design and analysis tasks regarding a regular industrial performance[65], as confirmed by the high penetration of commercial devices based on this modeling approach. However, emerging research interests such as efficiency improvement[67,68], DC link capacitor reliability, machine reliability[69,70], and harmonic and inter-harmonic phenomena[71,72] are not able to be analyzed by this modeling approach. For these purposes, alternative models have to be used in order to consider the switching related phenomena not able to be described by the average model.

Active Power Filters

Active power filters (APFs) are PESs generally used for controlling current harmonics in supply networks from low to medium voltage level or for controlling reactive power[73]. The earlier applications where focused on compensate the power quality at the point of common coupling (pcc) of traditional industry, focused mainly on harmonic compensation[49]. In the second half of the 2000's the research on this field was pointed out towards the development more sophisticated capabilities, such as optimal design[74], harmonic compensation[75] and unbalanced compensation; due to the penetration of renewable resources as distributed generation units.

As in the AC drive application, the control design is mainly performed by means of average modeling using space vector theory, although it is common to find direct current control methodologies such as the current hysteresis control[48]. In this sense, it is desired to achieve the highest speed response in the current control loop to compensate as many harmonics as possible. In addition to the current controller, some challenges arise regarding the generation of the reference current[76] and the design of passive elements, especially under hybrid configurations[51]. Analogous to the outer loop devoted to speed control used in AC and DC drives, APFs have an outer control loop in charge of maintaining the DC link voltage. All the above mentioned design and analysis challenges have been addressed by usage of average modeling, in both the synchronous and stationary frame, by considering decoupled control loops.

Although proper performance have been achieved, there are many challenges to tackle in order to have widespread commercial solutions, as in the case of AC drives application. Most of them are regarding stability issues when interconnecting switched loads[77] and the interaction among the inner loop, the outer control loops and the reference signal when the decoupling assumptions are hard to sustain as the power level increase and the performance is moving towards multiple function devices.

PWM rectifiers

PWM rectifiers are PESs designed to convert AC to DC voltage (or current) with high power factor, low harmonics injection and the capability of reverse the energy flow to the source (power regeneration) in case needed. Examples of these applications are locomotives, electrical vehicles, downhill conveyors, cranes, ans so forth[53]. From this topology, many more sophisticated with increased capabilities devices are constructed, such as Uninterrupted Power Supply (UPS) systems and Flexible AC Transmission Systems (FACTS).

The control strategy most used is the cascaded control inherited from the drives application. Average modeling is the main tool used for the design the inner and outer control loops, even when considering nonlinear control methodologies[78] on them. In addition, this application requires a the phase-lock loop, used to provide synchronicity with the grid. This tipple looped control approach has been successfully used to design and analyze these models even considering post-fault conditions on the AC side[79]. However on this applications, the switching effect impact of the VSC over the control loops start to be notorious in the overall performance of the systems, especially in the presence of low to medium switching frequencies and digital implementations. The overall effect of the VSC was able to be introduced on the averaged small-signal model by considering it as a delay[80]. Although this introduced element is nonlinear, a linear approximations is used in order to maintain the linearity of the average model[81].

Based on average modeling, widely accepted approaches for the overall design and control of PWM rectifiers have been proposed and validated, such the proposed by Liserre[82], even in the presence of high order filters at the AC side of the converter[83,84,85]. These design approaches are focused on ensuring the stability of the control loops, and it is usual that they derive on very conservative results, which are unrealizable as the power rating of the converter increases. In this sense, there are some gaps not able to be addressed by average modeling regarding optimal design[86], impact of the PWM methodology on the transient and steady-state performance[87], harmonic interactions between the filters and the control loops[88], interaction with other switched systems[89,90], among others. Nowadays research interest of these devices are focused on developing applications for medium to high voltage while the overall efficiency and reliability are improved.

Uninterrupted power supply systems

UPS systems provide continuous, reliable and high-quality power for sensitive or vital loads, such as medical facilities, expensive computer and server systems, life supporting equipment, among others. Some of their main tasks are devoted to protect sensitive loads against failures in the normal operation of the electrical system, providing the necessary support to maintain ideal operating conditions to them. The underlying topology is usually comprised by at least one VSC along with an energy storage element (battery). The VSC configurations could be implemented either as PWM rectifier or as PWM inverter; in any case, they operate with cascaded control, designed by average modeling of the system[56,60], as explained in the previous Subsection.

From average modeling approach, the performance of UPS application has been improving to the point of a widespread of commercial devices to a high number of applications, specially at low power levels[91]. Nowadays research interests of UPS application are focused on parallel interconnection to increase the operating power level[91], reliability improvement[92], predictive failure diagnosis[93], optimization of resources[94], among others. For these purposes, modeling approaches different from the average model have to be used in order to consider the critical phenomena neglected by this modeling approach.

DISTRIBUTED GENERATION UNITS

In recent years, there have been an increased number of grid-connected DGUs through power electronic interfaces, by taking advantage of the development in the power rating of the power switches and in the digital platforms where signal processing algorithms, controllers, and modulation techniques are implemented[62]. In addition, the well-established cascaded control structure and the maturity in the design and analysis methodologies, based on average modeling, permitted the widespread of these generation systems up to medium power levels[95]. In this sense, previously proposed design methodologies for passive filters, connected to the end terminals of VSC can be used on these systems[96,83,97,98,99,86].

However, due to the relative novelty of this application, there are still many challenges to address in order to catalog it as mature. Most of these challenges are of research interest and are mainly related to the harmonic distortion introduced by the power switches. Some of the adverse effects are the interference between the communication systems, control and protection systems, the reduction of the equipment lifespan, create additional losses in the power system, resonance and stability problems[100,101], among others. As stated before, most phenomena found in systems with high harmonic penetration are not able to be captured by average modeling such as harmonic generation, the interaction of controls and harmonic components, passive filter resonances, and harmonic stability issues, among others[102].

In this way, there are many challenges to tackle on this application, since the tendency is to increase the power level and the penetration of DGU into the grid. Research interest are mainly focused on increase their functions[103], design[104], stability analysis[105], harmonic mitigation and analysis[95,106,107], multiple DGU interconnection[108,77], among others.

EMERGING CHALLENGES IN THE MODELING OF VSC-BASED SYSTEMS

Modeling of PECs is an essential step that enables simulation, design, analysis and verification of diverse operating conditions. The primary objective is to represent in comprehensive form, usually mathematically, the behavior of a physical system in order to predict and analyze its performance under several expected conditions. The accurateness and detail in the model is dependent on the particular phenomena or characteristic to explain. A bad selection of a model could lead to:

- Neglect the phenomena or characteristics of interest, if a very general model is selected.
- End up with very complex or intractable mathematical description of the system, if to much detail is taken into account.

For all the previously mentioned applications of VSC-based systems, the main interest has been traditionally placed on the controller design and the stability analysis, for which average models offer a good trade-off between simplicity and accurateness. In this way, the system is modeled by continuous large or small signal models which can be treated by linear theory tools, either classical or modern, and even by nonlinear control tools. Under this approach, the harmonic distortion is considered as a minor secondary side effect which has no impact in the overall system performance and can be addressed by a proper filter design. This approach is very successful especially for DC-DC converter-based and AC-DC converter-based applications where the power level is low and the switching frequency is high. Although there are still open research interests for these cases regarding phenomena not captured by the average modeling (as mentioned in the previous Section), these side-effects are not always a big source of malfunction, and could be analyzed as a decoupled phenomena.

However, there is an increasing penetration of VSC-based applications, with high power and low switching frequency, which does not lie within the average modeling assumptions. Those are present in all the applications mentioned above in major or lesser extent, but there and increasing interest on those where the VSC is directly connected to the grid at high power levels such as active filters and DGUs. For these applications, there are open challenges regarding the VSC switching effects which require the development of modeling tools which represent the systems beyond the average model. The clearly identified research trends regarding this challenges are mainly focused on the control design and analysis of multi-parallel-connected converters[109,110,111], the optimal design of passive components focused on cost, losses and/or reliability[112,113,114,115], development of filter design and damping resonance techniques[116,117], grid impedance estimation[118,119,120], detection and suppression of harmonics[121,122], among others.

Among the modeling perspective used for this purpose, two main approaches can be identified. The first is to develop additional capabilities that introduce these effects to the already developed average model which allows to take advantages of all the previously developed tools for the analysis and design. A clear example of this approach is the previously mentioned consideration of the VSC effect on the control loop as a delay in the average model. Similar to this example, there are recently developed concepts and analysis tools which lie within the concept of extended capabilities of the average modeling such as the dynamic phasor[23,123,124,22,125,126] and impedance modeling approach[12,127,15,128]. These permit the consideration of not modeled effects by using concepts, such as harmonic stability[13,129] and complex transfer function[130]. In this way, there is a research interest on developing tools that provide additional capabilities to the well-established analysis tools to address the emerging challenges in the modeling of VSC-based converters.

Although the modeling perspective of keep using average modeling with increased capabilities is the most widely accepted and followed to face the modeling emerging challenges, since it follows the conventional research path where all the previous experience is used. However, this perspective has an intrinsic limitation for capturing the switching effects and their interaction with other systems, since its core formulation neglects this phenomena. For this reason, there will be state-of-the-art challenges that will not be able to be properly tackled by this modeling approach even if additional capabilities are added to it.

Another modeling perspective is the usage of innovative methods, algorithms and modeling approaches which allow the explicit consideration of the switching process. This approach is enhanced by the rapid progress in hardware and software which allow the implementation of sophisticated methodologies for the modeling, analysis, and design of VSC-based systems. Under this condition, alternative time-domain, frequency-domain and hybrid-domain modeling approaches specially designed for harmonic analysis[100] emerge as options to simulate, design and analyze the harmonic phenomena of PECs. Most of these harmonic analysis approaches were derived for power systems analysis on which the phenomena and characteristics to model are conceptually different for those in power electronics, although equivalent in many cases. Despite the conceptual differences, these modeling approaches can be exploited to tackle the emerging challenges of VSC-based systems by adapting their core formulation for its usage in PECs, in order to permit the explicit consideration of the harmonics. In this regard, the Extended Harmonic Domain (EHD) modeling framework emerge as an ideal framework due to its harmonic based state-space formulation[27]. However, there are still many challenges to address in order to propose an alternative modeling approach based on the EHD that address the above mentioned emerging challenges of VSC-based systems. In this way, there is an opportunity on this modeling approach focused on deriving, adapting and validating innovative modeling methodologies, such as the EHD, with a correct balance between simplicity and accurateness for VSC-based systems which tackle the state of the art challenges.

Thesis Objectives

Based on the previous state of the art and motivated by the emerging challenges on the modeling of VSC-based systems, this thesis has the following general objective:

General objective

To propose a standardized modeling methodology in the Extended Harmonic Domain for two-level VSC-based systems, considering large and small power networks which allow the development of techniques and algorithms that offer an alternative to address the emerging challenges in the design, analysis and simulation of their main applications.

Specific objectives

Derived from the stated general objective, the following specific objectives are presented:

1. Modeling of power converter in the EHD.

   This objective is aimed to develop efficient and reliable EHD models that exploits the symmetry properties of three phase balanced systems, complex conjugate Fourier coefficients of real systems and the dimension reduction by the consideration of dominant harmonics. The developed models should aim for analytic, continuous, lineal and time invariant representations, determined by explicit algebraic formulations.

2. Analysis of VSC-based systems using the EHD steady-state.

   This objective is aimed to develop analysis methodologies for VSC-based systems which consider the effect of the switching process, such as the modulation technique in their steady-state behavior based on the EHD. These methodologies are aimed to evaluate the impact of variations in passive component parameters, energy sources and demanded load in the steady-state operating conditions while considers the harmonic phenomena introduced by different PWM-based modulations schemes.

3. Design and estimation of passive components in EHD.

   All the VSC-based converters consider passive elements (resistances, inductors, and/or capacitors) for grid interconnection and filtering purposes. This objective deals with the development of optimization models and algorithms for the optimal design and estimation of these elements under different topologies, design objectives, and operating conditions.

4. Control design of power converters in EHD.

   This objective is aimed to establish structured modeling strategies which to develop efficient EHD models which explicitly include the modulation technique and the control strategy for analysis and design purposes.

5. Modeling of direct current control strategies of VSC based systems.

   Average modeling has been developed for PWM-based controllers of VSC-based systems. However, there is a significant penetration of direct current controllers which are not able to be modeled by this mean. This objective is aimed to propose modeling approaches for direct current controllers, such as the hysteresis controller, for the development of design and analysis methodologies which explicitly consider the harmonic phenomena derived from their time-varying switching frequency.

THESIS OUTLINE

Chapter 1 presents the proposed EHD modeling approach which is based on the switching instants calculation. Three simplified EHD models are also introduced in order address the order-size of the regular

EHD model. Both, experimental- and simulation-based validation for the developed EHD models are carried out by means of a LCL-filter-based PWM converter used as a case study.

In Chapter 2 an extension to the regular EHD model is presented for high switching frequency systems. This proposal is based on considering the dominant harmonics of the system for which a modified EHD vector variable is considered. Modified derivative and multiplication EHD matrices are derived to implement this EHD model extension. A high frequency battery charger was used as case study to validate the introduced proposals.

Chapter 3 presents an EHD steady-state based methodology for the analysis and design of grid connected VSC-based systems. Calculation of steady-state modulation parameters (CSSMP) and exact design (ED) of passive filter parameters are introduced as analysis and design methodologies bases on the EHD steady-state solution. In order to show the improved capabilities of these proposals, a case study based on a L-filter PWM converter is proposed in which the operating conditions and the passive filter parameters are calculated, even under the consideration of load and source voltage variations.

In Chapter 4 the EHD Exact Design proposal is extended to the EHD optimal design. The EHD steady-state is also used as base to state a optimization problems based on the fulfillment multiple design objectives. Two case studies are presented to illustrate the implementation of the optimal design proposal, the first for optimizing the overall efficiency of an L-filter PWM rectifier and the second for designing the LCL filters of multiple interconnected DGUs based on power quality restrictions.

Chapter 5 proposes a light, flexible, and yet reliable estimation algorithm that allows the estimation of multiple parameter values. This approach combines the nonlinear least squares (NLSQ) fitting algorithm and the EHD steady-state model. This allows the usage of harmonic characteristics of the system to propose a fitting problem to estimate the parameters for which the EHD model resembles the real VSC-based system performance. Details of the implementation are provided by an experimental case study in which the grid equivalent (Thevenin voltage, inductance, and resistance), the AC-side filter (inductance and resistance), and the converter loss resistance (switching and conduction) are accurately estimated under three different operating conditions.

Chapter 6 proposes a novel modeling approach based on the accurate calculation of the switching times for time and frequency analyses for grid interconnected hysteresis current controlled VSC converters. From this proposal, analytic formulations in the time domain and frequency domain of the harmonics generated by the controller are drawn. These are used to develop analysis and practical design methodologies based on numerical methods on these kind of systems. The modeling proposal is used to derive an EHD model of the grid-connected L-filter hysteresis current controlled VSC converter.

Let us dismiss the question, "Have you proven that your model is valid?" with a quick NO. Then let us take up the more rewarding and far more challenging question: "Have you proven that your model is useful for learning more ... "

James B. Mankin, Jr. (1977)

1

Modeling of Voltage Source Converter based Systems based on Hysteresis Controller.

1.1 Introduction

In this Chapter the developed work regarding modeling of hysteresis current controllers during the research internship at Aalborg University is summarized.

Section 6.2 presents the state of the art (SOA) bibliography on this matter. The SOA is focused on modeling approaches and applications for grid interconnected systems. Notice that although hysteresis controllers have been widely used decades ago for drives applications and recently for active filtering, their usage for interconnected systems have been barely mentioned and very few applications are reported.

Section 6.3 introduces the intended modeling approach for these kind of systems. This basically separates the dynamic and steady-state behavior to analyze their isolated impact. In this way, all the power quality issues (inter-harmonics, variable switching frequency, resonances, etc) can be analyzed by means of the harmonic current introduced to the system. Also, all the stability phenomena regarding dynamic behavior (weak grids, parallel connection of multiple systems, outer loops controller coupling, etc) can be analyzed by means of the derivation of a first order transfer function.

Section 6.4 summarizes the developed work seeking the proposed modeling approach using as base a single phase system. The main approach used is the numerical calculation of the switching instants. The developed work has satisfactory results in the modeling of the harmonic current.

In Section 6.5 an attempt to obtain the closed-loop transfer function of the model is carried out, in which the extended harmonic domain (EHD) is used to derive a feasible small-signal model which leads to a closed loop transfer function. This is an ongoing work which may results in satisfactory outcomes in the objective of derive useful and reliable models for this kind of systems. Another proposal can be made in which a closed equation to derive an approximated first-order closed-loop transfer function can be provided, based on fitting algorithms; using the already developed switching times calculation. Once this is accomplished, it is expected to extrapolate the derivations to three-phase systems.

Finally, Section 6.6 presents the conclusions and intended future work on this subject.

1.2 STATE OF THE ART

Power electronic converters have rapidly emerged as one of the main used devices to interchange energy with the utility grid, at several power and voltage levels. In this context, VSC based converters are among the most preferred interfaces to perform the interconnection, especially for integration of distributed energy sources, active filtering, and power supply applications due to the development in the devices material technology and in the control strategies development.

Among the current control strategies devoted to performing the above mentioned interconnected tasks, hysteresis control offers the benefits of very robust control, fast dynamical response, built-in overcurrent protection, easy and reliable implementation, among others. However, hysteresis current control has the disadvantages of varying switching frequency and complex operating conditions dependent on the dynamical response; this supposes a problem since, although easy to implement and robust, from the modeling point of view, their dynamical and steady-state response is hard to be approximated by a reliable mathematical model. This situation complicates the design and analysis tasks, especially when interfacing with other systems. For this reason, very widely used modeling approaches and design methodologies such as average modeling, impedance modeling, frequency response based filter design, stability analysis, among others, are not able to be directly implemented over on this control strategy.

Average models for hysteresis current controllers have been obtained based on the switching times calculation when fixed hysteresis bands are considered[131]. This approach was later extended to a single phase inverter where a variable hysteresis band is considered[132]. These approaches assume that the commanded current reference is followed by the output average current, with a small time delay. However, these models do not explicitly consider the harmonic contain nor its effect over the average model. References[133,134,135] propose an analytic approximation to calculate the harmonic spectrum of the output current for a single phase two-level inverter. The analytic expression to perform the calculation is based on first order Bessel functions; however, this approach considers periodic switching functions and neglects the phase of the reference current compared with the grid voltage source. In reference[136] the perfect hysteresis model, which considers that the reference is perfectly followed by the output current, is analyzed and improved to derive two average models which offer better results under over-modulation conditions. However, the models presented are mainly focused in simulation-based design purposes.

The intention of this research work is to model the hysteresis current control for both in order to capture its nonlinear associated phenomena by simple and reliable models which allow the analysis of this kind of systems under different topologies.

1.3 MODELING APPROACH

Consider the following power electronic system in which a current hysteresis controller is used to shape a the grid current i_t based on a given reference current i_{ref}.

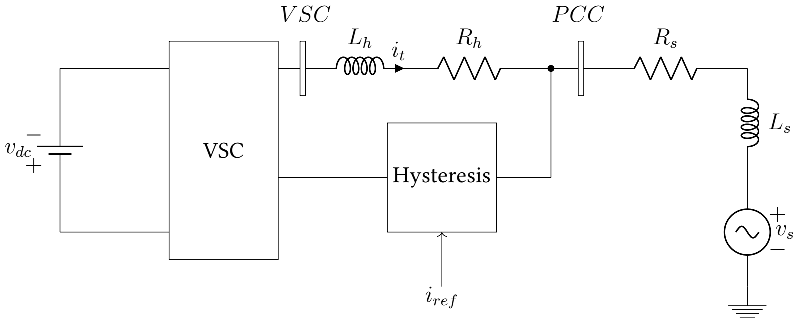

Figure 1.1: Generic hysteresis current control loop.

On this control strategy, there are not external modulating signals, such as in PWM based controllers, to operate the VSC power switches. The gate signals that drive them are self-obtained from the comparison of the current output current i_t with two hysteresis band signals constructed from the reference current i_{ref}. Hence, the concept of average control inputs, obtained from an independent and tunable controller, could not be directly and accurately applied to model the hysteresis controller, especially under time-varying system parameters, such as grid interconnected applications.

The basic set of equations that model the system of Figure 1.1 is given by

$$R_{L_h} i_t + L_h \frac{d(i_t)}{dt} = v_{VSC} - v_{PCC} \tag{1.1}$$

where v_{VSC} is the voltage at the AC side of the converter, and v_{PCC} is the grid voltage. If those voltages are able to be expressed by linear functions, then the system has a linear time-invariant (LTI) representation. However, in the presence of a hysteresis controller, v_{VSC} is function of V_{dc}, and the highly nonlinear hysteresis function among hysteresis band functions constructed from i_{ref} and the current i_t, is defined for the sake of simplicity as follows,

$$\text{hys}(i_{ref}, i_t) \tag{1.2}$$

Hence, if (1.2) is substituted in (1.1) the system equation becomes nonlinear.

To deal with this modeling, let us consider that the current (i_t) can be constructed from the known reference current (i_{ref}), and the harmonic distortion current (i_h), introduced by the hysteresis process. Since the dynamic of the hysteresis controller is very robust and fast, the hysteresis current can be neglected for transient analysis purposes.

Hence a complete model of the system proposed in 1.1 can be approximated as

$$i_t = G_{\text{CL}} i_{ref} + i_h \tag{1.3}$$

where G_{CL} is the closed-loop response of the current hysteresis controller. This modeling proposal considers that only the fundamental reference current i_{ref} is directly associated with the dynamic response of the system, modeled by the closed-loop transfer function G_{CL}, neglecting the harmonic current i_h. Similarly for steady-state analysis, it is considered that $G_{\text{CL}} = 1$ and the output current i_t can be constructed directly from the hysteresis current term i_h and the reference current i_{ref}. This is graphically depicted in Figure **??**.

For me, the idea of a creation is not conceivable without invoking the necessity of design. One cannot be exposed to the law and order of the universe without concluding that there must be design and purpose behind it all.

Wernher von Braun

2

Design and Analysis Based on the Extended Harmonic Domain Steady-State

2.1 INTRODUCTION

There is an increasing interest in the developing of VSC-based converters due to its high controllability of active and reactive power along with their faster dynamic responses. These characteristics make this component suitable for many applications such as distributed power generation[63,61], smart grids[137], electric vehicles[138], offshore subsea compressors based on oil and gas[139], VSC-HVDC systems[99] and spacecraft applications[140]. Despite all their benefits, the VSC-based systems present two main drawbacks: 1) the injection of undesired harmonics to the supply network and 2) the difficulty to connect them to traditional electric supply systems due to their inherent nonlinear behavior[141,142,143].

In order to mitigate the harmonics injection of VSC-based systems, the connection of passive filters at their inputs and outputs is required. The most simple filters are constructed by only one element; an inductor for AC side and a capacitor for the DC side. This approach usually requires large passive component values to efficiently mitigate the harmonic impact in the power quality of the signals[144]. Hence, more sophisticated filters have been proposed in order to reduce the size of their passive components values. In this matter, the LCL filter[82,85] has gained a wide acceptance due to its smaller size as compared with the simple inductor filter. Another recently introduced solution is the trap topology, also known as LLCL filter[145] which uses an additional inductor in series with the filter capacitor.

The difficulty in the filters design of power converters, in any topology, is that their inclusion modifies the overall dynamic and steady-state performance of the system. The design problem becomes more challenging with the consideration of the power quality restrictions on the DC and AC sides of power electronic converters. In one hand, filters with high passive components values attenuate the undesired high-frequency components of the electric waveforms. On the other hand, large passive component values could lead, in the best case, to unnecessary construction expenses due to oversized components, but in the worst case, to unreachable operating conditions for the control system. If along with these factors we consider some level of uncertainty in the utility (voltage, demanded load, network parameters, among others) the filter task design becomes very complicated.

There are in the literature many passive filter design approaches based on well-known theory such as Laplace transform, frequency response, power exchange, among others[83,146]. Those approaches give conservative results since they do not explicitly consider the operating conditions nor the nonlinear and discontinuous nature of the VSC-based components. In most cases, some untenable simplifications and experience by the designers are assumed, in order to use them properly. On these designs, it is common to result in oversized passive elements with no guaranty that when connected the operating conditions on a closed loop system are reached. Additionally, it should be pointed out that the modulation technique is discarded from these traditional design approaches. All those factors usually cause multiple iterations between the design stage and the simulation/implementation stage before obtaining a proper design.

An opportunity arises to propose more accurate design approaches that save time and effort in the implementation of the system. The proposal must consider the nonlinear and discontinuous nature of the converter along with the reachable operating conditions established in great extent for the modulation technique. The traditional approaches lack of this consideration because they are based on simplified mathematical models to perform the design. These simplifications neglect the harmonic content of its switching signals in order to have mathematically treatable formulations. However, most of the power quality indexes are expressed as harmonic measures, for which simplified models are not the best suited to perform the design.

As shown in the previous Chapters, the extended harmonic domain (EHD) permits the representation of dynamic periodic systems, like the VSC-based systems, by linear time invariant (LTI) models[27]. This formulation can be used to perform detailed analysis and design on this kind of systems explicitly considering the switching process since the harmonic distortion inherently produced is gathered by the model.

This Chapter proposes the usage of the EHD model of VSC-based power systems to perform the passive components design of their AC and DC side filters. The proposed approach is named here exact design (ED) due to the fact that its formulation requires the proposal of reference operating conditions and power quality restrictions under which the converter will exactly behave in steady-state condition.

This design proposal is an extension of the also presented calculation of steady-state modulation parameters (CSSMP) technique. The CSSMP is used to calculate the modulation parameters (control variables) required to meet certain reference operating conditions (control objectives) in steady-state, explicitly considering the switching process and the modulation technique used. Both proposals assume that the control of the system is working properly (references are met) and that the system has reached the steady-state. It is important to point out that both methodologies are particular implementations of the generic harmonic power flow formulation, from a power systems point of view.

An L-filter active rectifier is used as case study in order to show the usage of the proposals and their usefulness. Several cases of passive component design are presented considering three different modulation PWM techniques: the sinusoidal (SPWM), the third harmonic injection (THPWM) and the space vector (SVPWM). All the designs presented in the EHD are validated by time domain simulations in Simulink. Additional to the designs results, further analysis based on these approaches are presented in order to show that useful conclusions can be obtained from their use. Those regarding control design, feasible operating region, design of passive components considering voltage source and load disturbances, among others.

2.2 Advantages of EHD models for power electronic converters

The main purpose of using the EHD models on power switched based systems is to work with a mathematical model that explicitly includes the harmonic distortion in its formulation. From these models, the performed analysis is much more accurate because it explicitly considers the switching functions of the power switches. The effects of these discontinuous functions over the systems signals are directly related to the switching frequency and the modulation technique used. Since the EHD modeling approach properly includes those characteristics on its formulation, the decisions made and the conclusions obtained, especially those relating to harmonic behavior, will be more reliable than the ones offered by other models that do not explicitly include the harmonic distortion in their formulation.

A general structure of a two level three phase VSC-based converter is presented in Figure 2.1. In this Figure, the VSC control inputs are a set of discrete signals ($s(t)$) generated in the modulation block. The inputs to this block are the modulation parameters (MoP), i.e. m_a, θ and m_f for SPWM, THPWM and SVPWM modulation techniques. These parameters could be fixed or established by the control strategy as controls signals. If the control block works as designed, the MoPs eventually will settle around steady-state values for which the system meets imposed references. The AC filter and DC filter mitigate the harmonic distortion on both sides of the converter, for which, their passive component values (PCV) have to be designed to maintain the filter output signals within the required levels of harmonic distortion. Hence, the overall steady-state performance of the system is determined by the

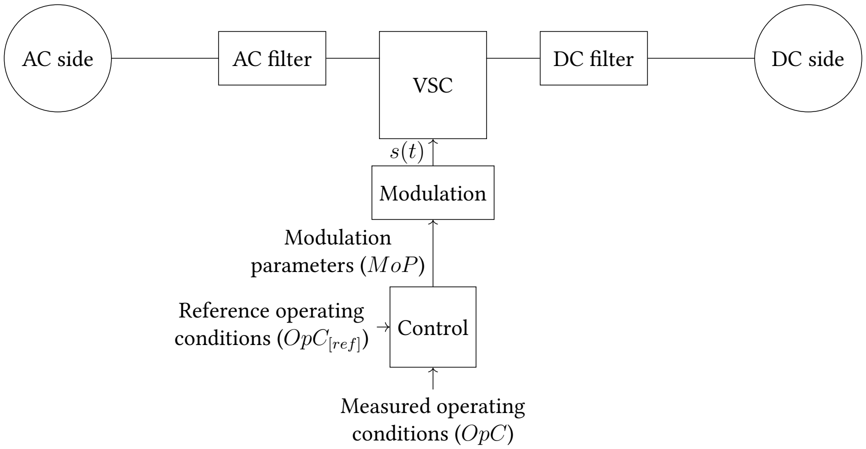

Figure 2.1: General structure of a VSC based power system.

values of both, the PCVs and the MoPs.

Any modification in the PCVs of any filter will be reflected in the MoPs required to meet the reference operating conditions ($OpC_{[\mathrm{ref}]}$) of the control system. Average time domain models are unable to properly perform detailed analyses and designs of VSC-based systems since they do not provide enough information about the interaction between the PCVs, the MoPs and the operating conditions (OpC) in the system while the harmonic content of the signals is considered. The EHD is a better modeling domain since the consideration of the harmonics in the power network is allowed as state variables in a linear time-invariant (LTI) model. As stated in Chapter 2, for systems such as the one in Figure 2.1, obtaining the EHD model is always possible.

Conclusions

This thesis work presented the modeling of VSC-based systems in the Extended Harmonic Domain (EHD). For this purpose, a switching instant-based modeling proposal is introduced which allow a straightforward deriving of EHD models from the time-domain switched model. Three order-size simplifications named EHD single-phase (EHD 1P), EHD exact simplification (EHD ES) and EHD approximate simplification (EHD AS) are proposed to address the main disadvantage of the EHD model when a the maximum harmonic considered is high. In addition, an modeling extension to derive EHD model for high-switching frequency VSC-based systems is introduced named hf-EHD modeling. This approach is also based on the switching instants calculation and uses a modified EHD (vector) variable which considers only the relevant harmonics on its formulation.

Based on the modeling proposals mentioned above, several applications were proposed to show the benefits and capabilities offered by the EHD modeling. The Exact Design (ED) methodology for the selection passive component values, based on the fulfillment of power quality indexes was introduces. This methodology is based on the also introduced computation of steady-state modulation parameters (CMMPS) methodology which allows the obtaining of the required modulation parameters form which the VSC-based system behaves under certain desired operating conditions. The ED was used as a base to propose more sophisticated design methodologies based on the establishment of optimal problems, using as the core the EHD model. In addition an estimation algorithm was proposed in order to calculate the lumped parameter values of a physical system from experimental measurements. Those applications show that the proposed EHD modeling is an excellent option to address the emerging challenges in the modeling of VSC-based systems and opens the window to exploit its characteristics towards the improvement of the above-mentioned introduced proposals and the development of new approaches based on this modeling framework.

A

Calculation of parameters using the harmonic information.

RMS voltage:

$$V_{\text{rms}} = \sqrt{\left(\sum_{n=-h}^{h} V_{\langle n \rangle} V_{\langle -n \rangle} \right)} \tag{A.1}$$

RMS current:

$$I_{\text{rms}} = \sqrt{\left(\sum_{n=-h}^{h} I_{\langle n \rangle} I_{\langle -n \rangle} \right)} \tag{A.2}$$

Apparent power:

$$S = V_{\text{rms}} I_{\text{rms}} \tag{A.3}$$

Active power (average):

$$P = \sum_{n=-h}^{h} V_{\langle n \rangle} I_{\langle -n \rangle} \tag{A.4}$$

Reactive power at fundamental frequency:

$$Q_{\langle 1 \rangle} = \frac{V_{\langle 1 \rangle} I_{\langle 1 \rangle}}{2} \sin\theta \tag{A.5}$$

Distortion power:

$$D = \sqrt{(S^2 - P^2 - Q^2_{\langle 1 \rangle})} \tag{A.6}$$

Power factor (total):

$$\mathrm{PF}_t = \frac{P}{S} \tag{A.7}$$

Power factor (shift phase)

$$\mathrm{PF}_{sf} = \frac{I_{\langle 1 \rangle [\text{rms}]}}{I_{[\text{rms}]}} \cos\left(\angle I_{\langle 1 \rangle} - \angle V_{\langle 1 \rangle}\right) \tag{A.8}$$

Total harmonic distortion:

$$\mathrm{THD}_V = \frac{\sqrt{\sum_{n=2}^{h} |V_{\langle n \rangle}|^2}}{|V_{\langle 1 \rangle}|} \times 100\% \tag{A.9}$$

Ripple in the signal

$$\text{Ripple in } v = \frac{\max\left(v(t)\right)}{|V_{\langle 1 \rangle}|} \quad \forall\, t \in (0, T_0) \tag{A.10}$$

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