A Procedure for Power Electronic Converters Design with Controllability Verification Based on the Nonlinear Dynamical Model

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***Abstract*—In this work a design procedure of Power Electronic Converters (PECs) is proposed, which is based on system knowledge and systems theory. The proposed design procedure is composed of 4 stages and 10 steps and it allows to obtain all PEC parameters and its control structure such that established system operating requirements are satisfied. In this proposed design procedure, system controllability is tested based on set theory in control. The main achievement of this design procedure is to allow the PEC design to take into account its inherent dynamical nature, with verified controllability, but without fixing any control structure.**

***Index Terms*—power electronic converters, design procedure, dynamical modeling, set theory in control, controllability, controller design**

I. Introduction

Today, almost all technologies that require power conversion utilize Power Electronics (PE) technology [1].

PE systems field became interdisciplinary. At high power level, PE systems deal with static and rotating equipment for generation, transmission, and distribution handling large amount of power [2]. For consumer electronic applications, PE systems are important for information processing employing microprocessors, including microcontrollers, Digital Signal Processors (DSP), and Field Programmable Gate Arrays (FPGA) [3]. In the control field, PE systems deal with stability and closed-loop requirements of dynamical performance due to feedback loops [4]. Finally, with the development of Very Large Scale Integration (VLSI) and Ultra-Large-Scale Systems (ULSS), advanced control systems could be used to develop new PE systems topologies [1].

An important issue in PECs field is the design of these devices. Traditionally, PECs design is carried out in a sequential form, i.e., first the converter topology is selected, second passive elements are sized, and, finally, a control structure is designed. In above design procedure, it is possible to include economic criteria for both converter topology selection and passive elements sizing. Furthermore, it is possible to include open-loop and closed-loop dynamical performance criteria based on operational requirements. However, this form of PECs design has some drawbacks, as a converter exhibiting poor dynamic performance or unexpected behavior against both disturbance and uncertainties [5].

Methodologies that take into account both system design and its control are an alternative to deal with drawbacks in traditional methodologies. These methodologies include dynamical criteria from the beginning of the design stage and are known as Integrated Design Procedures. The above due to the fact that achievable PEC dynamic performance is an inherent system property. This work explores these procedures design not only in PECs field, but also in mechanical and chemical engineering fields since in these two fields Integrated Design Procedures are a mature subject. Then a design procedure is proposed based on ideas of these two fields. This proposed design procedure is composed of 4 stages and 10 steps and it allows to obtain all PEC parameters and its control structure such that established system operating requirements are satisfied. Main features of this design procedure are that this allows PEC design to take into account its inherent dynamical nature and with verified controllability, but without fixing any control structure.

System controllability is a property that must be verified before control structure design. However, generally, in PECs design process this property is not verified. In this proposed design procedure, system controllability is tested based on set theory in control.

Remaining of the paper is organized as follows: Section II presents the literature review. This section summarizes design procedures for Integrated Design available in PECs, Chemical Engineering and Mechatronics fields. This section also summarizes several works where set theory in control is employed for system controllability verification in Chemical Engineering and as method for system design in PECs field. Section III presents design procedure for PECs. The proposed design

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procedure is based on found Integrated Procedures from literature review and it allows to design PECs with controllability verified and quantified via set theory in control. Section IV concludes.

II. Literature Review

PECs design is an engineering process that, in general, is carried out in a sequential form as follow: *(a)* PEC structure is selected, then *(b)* passive elements are established such that both cost and losses are minimized, and finally *(c)* PEC control structure is designed such that PEC dynamical performance is optimized. Some works that present this design form are [6]-[10]. However, this sequential schema disregards dynamical nature of the system in stages *(a)* and *(b)*, and properties such as controllability are not tested. Thus, designed PEC can be difficult to control, it can exhibit a poor dynamical performance and/or an unexpected behavior against both disturbance and uncertainties [5].

In PECs field only few works that take into account integration of system design and control have been carried out [5], [11], and [12]. In [11], integrated design and control of a Buck DC-DC converter is investigated. This paper simultaneously optimizes passive elements size and control parameters such that both a control energy and an output error functions cost are minimized. Design process is cast as a non-linear constrained optimization problem which allows the use of existing numerical solution methods. Averaged linear model is employed as converter model. Covariance Control Theory (CCT) is adopted as method to control structure design. CCT is a method for parameterization of all-stabilizing controller in terms of the closed-loop covariance matrix. This research showed the interaction between both converter structure and control. In this paper, feasibility of simultaneously designing power stage and controller of a PEC was demonstrated.

Authors in [12] investigate how to maximize dynamical performance of a Buck-Boost DC-DC converter using an integrated design and control approach. This paper leads to a dynamic non-linear optimization problem in terms of dynamic variables of closed-loop system and decision variable. Decision variable includes both unknown circuit and control system parameters, under constraints of dynamic model and closed-loop specifications, either in equality or inequality form. A linearized averaged model is considered to simplify the problem. As controller, a PID controller is selected. Averaged model and controller parameters to be tuned are state variables dependent, this is why a non-linear optimization problem is obtained. Several Buck-Boost DC-DC converter reference trajectories are taken as reference to measure the converter dynamical performance using a quadratic function cost. Quadratic function cost is composed of accumulated quadratic errors, that is, the differences between set point and measured value of state variables. Sequential quadratic programming is then used to solve non-linear optimization problem. An optimum design was obtained as the solution for a constrained dynamic optimization problem. This work showed the advantages of using integrated design over traditional sequential approach.

The two approaches presented by [11], [12] fix the control structure. They provide optimal parameters for fixed control structure, but they do not, in general, provide optimal controller. A reason that avoids finding out optimal controller is the necessity to test iteratively all possible control structures to find the optimal one.

Authors in [5] tackle the gap between methods that optimally design circuit parameters with a non-optimal controller and optimal control methods. The scope of this work is to optimally design circuit parameters for control purpose that give a performance close to limits of the converter, but without imposing any control structure. Considered design objectives are dynamical performance and energy efficiency. In that work is proposed a simultaneous optimization of converter parameters and control input using a variable substitution technique and a decomposition of the general min-max problem into two simple min-max problems. First min-max optimization problem yields optimal sequence of state for the worse case load, which is unique, one of sought converter parameters and an auxiliary control input which embeds the effect of other disturbances. These results are used in a second min-max optimization problem to obtain real optimal control input and remaining circuit parameters. As a result, converter parameters are optimally design such that a performance close to converter limits is obtained.

In contrast, integration of system design and control is a mature field of research in chemical engineering known as Integrated Process Design and Control or simply Integrated Design (ID) [13]. Although, in mechatronics field some works that integrate system design and control have been carried out [14], [15]. ID conception produces significant economic benefits as well as improvement of system dynamical performance regarding the important relation between its cost and its controllability [13].

The different possibilities of the integration of design and control are evidenced in recent literature reviews that have been published in the chemical engineering field [13], [16]-[20]. Authors in [16] remark on efforts made in ID and control fields and it is made a classification of methods in four categories, as follows: *(a)* process characterization and controllability, *(b)* methods of integrated process design and control, *(c)* plantwide interactions of design and control, and *(d)* extensions of the integrated process design and control. Methods based on state controllability are good candidates to apply in PECs design process, since these methods: *(a)* take into account system dynamical behavior from initial stages of design process; *(b)* are, in general, based on phenomenological model of the system; *(c)* do not require, in general, system model linearization; and *(d)* do not fix the control structure, although system controllability is assured.

In the work presented in [21] a comparison between differential geometry and set theoretical methods in control based on randomized algorithms to test nonlinear state controllability is presented. Authors conclude that both methods are equivalent to verify if the system is controllable or not.

Authors in [22] present a detailed methodology description to assess non-linear state controllability in ID framework. This approach is named by the author Simultaneously Process and Control Design (SPCD). Controllability verification method employed in [22] is based on differential geometry.

Finally, authors in [23] propose a (SPCD) methodology where state controllability is tested based on set theory in control. This approach, unlike [22] approach, allows to quantify system controllability, not only establishes if the system is controllable or not. Robust reachable and controllable sets are computed to verify robust reversible set existence, which is a sufficient condition to verify system local controllability. Then, a Controllability Index (CI) is proposed to quantify system controllability based on both robust controllable and reversible sets sizes.

In conclusion, set theory in control is an alternative framework to solve system controllability problem. Based on set theory in control, controllability problem refers to determine the state-space subset that can be reached from the admissible control signals set such that states restrictions are satisfied. The advantages of analyzing system controllability via set theory in control are: *(a)* inclusion of inputs and states restrictions in controllability analysis; *(b)* system does not need to be input-affine; and *(c)* it is possible to verify the "*robust*" controllability. Moreover, recent works [23]-[25] have shown that from obtained results of controllability analysis via set theory in control, it is possible to carry out an optimization process in order to maximize system controllability.

In PECs field, set theory in control has been used as method to verify PEC design [26], [27] and to integrate reliability into the design of fault-tolerant power electronics systems [28].

Following conclusions are derived after literature review: *(a)* in PECs field, only few works that include system dynamical inherent nature are carried out, and works carried out have following limitations: *(1)* control structure is fixed and/or *(2)* design process implies sophisticated optimization stages. *(b)* Integrated design and control is a mature field in chemical engineering and, despite that most of the developed methodologies include any optimization stage, well-founded analysis such as controllability analysis can be applied as preliminary step before applying any optimization method to process design. *(c)* State controllability analysis are preferred over input-output controllability analysis due to the fact that state controllability analysis, in general, are based on system phenomenological models and they allow to have a complete knowledge of internal system evolution. *(d)* Within state controllability analysis, such analysis based on set theory in control are highlighted due to the fact that not only test if the system is controllable or not but also they quantify system controllability. *(e)* Set theory in control has been used as method to verify PEC design and to integrate reliability into the design of fault-tolerant power electronics systems, but it is not used as method to verify system controllability as preliminary step before applying any optimization method to PEC design.

III. Design Procedure of Power Electronic Converters

Here, a design procedure of PECs is presented. Design procedure was built from main ideas of literature review. The design procedure is based on system knowledge and systems theory since this framework gives a roughly mathematical support. Proposed design procedure is composed of 4 stages and 10 steps. Design procedure is presented in a sequential form, however, it is not strictly necessary to follow this sequence. Moreover, once the system model is obtained, any order to system design can be adopted. This proposed design procedure allows to obtain all PEC parameters and its control structure such that established operating requirements are satisfied. In this proposed design procedure, system controllability is tested based on set theory in control. Main achievement of this design procedure is to allow PEC design taking into account its inherent dynamical nature and with verified controllability, but without fixing any control structure. Proposed procedure design employs linear as well as nonlinear tools to analyze the system. However, control structure can be linear or nonlinear.

Design procedure is summarized in Table I.

Stage 1: Dynamical Modeling

First stage in design procedure is concerning to converter topology selection and development of a dynamical model. The aim of this stage is to obtain a converter that can fulfill all operating requirements and to develop a dynamical model of the converter that can be used as tool to analyze converter characteristics as dynamical system. This stage is composed of steps 1 – 6.

Step 1: To set both structure of the system and desired operating requirements

Concerning to system structure, DC-DC, DC-AC, and AC-DC are some structures for the system. All of these structures have different objectives and they are selected according to the need. Currents and voltages waveforms, currents and voltages THD, power factor, power quality, harmonic cancellation, efficiency, operation mode, among others, are typical system desired operating requirements.

Step 2: To apply conservative laws to the system

Tools for this step are Kirchhoff's laws, which give a set of nonlinear coupled differential equations. This set of differential equations is known as system phenomenological-based dynamical model and represents internal system time evolution. This dynamical model describes the interactions among state variables and inputs, and it can be employed directly for system design and simulation.

Step 3: To obtain a suitable structure for the system phenomenological-based model

Switched structure in its general or bilinear form is desired for the dynamical model. This structure describes basic low-frequency dynamics, as given by energy accumulation variations, and it captures switching dynamics (high-frequency dynamics) of power electronic converters as well. Switched forms offer a starting point to obtain other type of models, such as averaged or reduced-order models.

TABLE I. PROPOSED DESIGN PROCEDURE OF POWER ELECTRONIC CONVERTERS

Stage	Step	Analysis tool	Required model	Result
Dynamical modeling	1. To set both system structure and desired operating requirements.	Knowledge of the problem to be solved.		The system structure and a set of operating requirements.
	2. To apply conservative laws to the system.	Kirchhoff's circuit laws.		A set of nonlinear coupled differential equations.
	3. To obtain a suitable structure for the system phenomenological-based model.	Systems theory.	Phenomenological-based model.	Switched model in its general or bilinear form.
	4. To apply the average operator.	Fourier transform.	Switched model.	Continuous-time averaged model.
	5. To apply the Taylor series expansion.	Taylor series theory.	Continuous-time averaged model.	Small-signal model or linearized state-space model.
	6. To apply a state-space to transfer functions realization.	Systems theory.	Small-signal model or linearized state-space model.	System transfer functions (frequency-domain model).
Passive elements design	7. To apply inductor volt-second and capacitor charge balance principles.	Energy conservation laws.	Continuous-time averaged model.	Steady-state model.
	8. To apply circuital laws.	Energy conservation laws and Ohm's law.	Steady-state model.	Expressions for efficiency, power electronic converter operation mode and passive elements boundaries.
Controllability verification	9. To apply state controllability analysis based on sets theory control.	Sets theory control.	Continuous-time averaged model.	Robust reachable, robust controllable, and robust reversible sets.
Control structure design	10. To apply control theory.	Control theory.	Switched model, averaged model and/or small-signal model.	A control structure that guarantee system operating requirements.

Step 4: To apply the average operator

Averaged model focuses on capturing low-frequency behavior of power electronics converters while neglecting high-frequency variations due to circuit switching. Averaged model is a continuous-time model, one which is easier to handle by classical systems theory analysis and control formalisms.

From the work presented in [29], it is possible to conclude that average models could be the best option to PECs representation due to the following characteristics: *(a)* they are continuous and allow conducting large-signal time-domain transient studies of the system with multiple power electronic modules, controllers and mechanical subsystems; and *(b)* they allow small-signal analysis, where frequency-domain transfer functions and impedance characteristics are typically required for the design of controllers and stability analysis of the overall system.

Step 5: To apply Taylor series expansion

If Taylor series expansion is applied over the continuous-time averaged model a small-signal model or linearized state-space model is obtained. Small-signal model is useful to carry out a modal analysis of the system and to implement linear control structures. This model is useful tool for transfer functions deduction.

Step 6: To apply a state-space to transfer functions realization

System Bode analysis, system poles and zeros analysis and single-input-single-output control techniques are commonly tools employed in power electronic converters field that uses the system transfer functions.

Stage 2: Passive Elements Desing

Second stage is concerning to passive elements design. This stage is composed of steps 7 and 8. There is not a consensus regarding to the design method for all converter topologies. However, the main interest in this stage is to find expressions for system efficiency and power electronic converter operation mode such that passive elements boundaries are derived from these expressions.

Step 7: To apply inductor volt-second and capacitor charge balance principles

By setting to zero the system averaged model, it is possible to obtain steady-state input-output characteristics, i.e., location of the equilibrium point, represented by a nonlinear curve in the input-output plane. Next, steady-state model of the system can be derived and equilibrium conversion ratio can be deduced.

Step 8: To apply circuital laws

Energy conservation law and Ohm's law are the suggested circuital laws to be applied. Desired results are expressions for efficiency, power electronic converter operation mode and passive elements boundaries.

When a converter is implemented by using current-unidirectional and/or voltage-unidirectional switches, one or more new modes of operation known as Discontinuous Conduction Modes (DCM) can occur. DCM is commonly observed in DC-DC converters and rectifiers (AC/DC converters). DCM can also occur in inverters or in other converters containing two-quadrant switches. The key to design power electronic converters keeping both electric requirements and dynamical performance is to select suitable values for inductors and capacitors such that constraints like maximum physical admissible currents and voltages, converter efficiency, and Continuous Conduction Mode (CCM) are satisfied.

The analysis of voltages and currents ripples is suggested as approach to passive elements sizing due to the fact that this approach gives lower boundaries for inductors and capacitors as function of some system operating requirements [30].

Stage 3: Controllability Verification

Third stage is concerning to the design controllability-oriented verification method. This stage is composed of step 9.

Step 9: To apply state controllability analysis based on set theory in control

Set theory in control is adopted due to the fact that controllability verification throughout this method not only allows to verify this system property, but also to quantify it. Moreover, controllability verification method based on set theory in control is equivalent to state-controllability verification method based on differential geometry [21]. Results from controllability analysis via set theory in control can be used to redesign the system such that system controllability is maximized [23].

Set theory in control is an alternative framework to solve controllability problem. Based on set theory in control, controllability problem refers to determine the state-space subset that can be reached from the admissible control signals set such that states restrictions are satisfied. The advantages of analyzing system controllability via set theory in control are: *(a)* inclusion of inputs and states restrictions in controllability analysis; *(b)* the system does not need to be input-affine; and *(c)* it is possible to verify the *robust* controllability. Moreover, recent works [22], [23], and [25] have shown that from obtained results of controllability analysis via set theory in control, it is possible to carry out an optimization process in order to maximize system controllability.

It is important to remark that in the nonlinear systems case, only local controllability is verified via Lie algebra as well as via set theory in control. Controllability verification via Lie algebra theory requires computation of Lie brackets to evaluate the rank accessibility condition for an input-affine system, where accessibility is a weakly property than controllability. Controllability verification via Set theory in control requires computation of reachable, controllable and reversible sets, where system controllability is guaranteed if the interior of reversible sets is not empty. Furthermore, the system does not need to be input-affine and disturbances can be included.

Gómez in her Doctoral Thesis [31] presented a Monte Carlo based algorithm to compute an approximation of both reachable and controllable sets. This algorithm was extended by Alzate in his Master Thesis [24] for robust reachable and controllable sets case. Moreover, author by [24] presented a Controllability Index (CI) for not only to verify but also y/o quantify system controllability.

Stage 4: Control Structure Design

Fourth stage is concerning to control structure design. This stage is composed of step 10. Control paradigm and associated design methods chosen to solve PECs control problem depend on complex factors that include converter role, desired closed-loop dynamics, operating range, safety issues, control input limitations and so on. In the relevant literature, a wide plethora of control structures that have been employed to solve PEC control problem can be found. Linear as well as nonlinear control structures, each of them with their advantages and limitations. Furthermore, controller design task can differ in each case and a particular structure o method is not proposed here.

IV. Conclusions

In this work a design procedure of Power Electronic Converters (PECs) was proposed, which is based on system knowledge and systems theory. The proposed design procedure is composed of 4 stages and 10 steps it and allows to obtain all PEC parameters and its control structure such that established system operating requirements are satisfied. In this proposed design procedure, set theory in control is proposed as controllability verification method. This approach allows not only controllability verification, but also controllability quantification. Furthermore, it is an approach for nonlinear controllability verification. The main achievement of this design procedure is to allow PEC design taking into account its inherent dynamical nature and with verified controllability, but without fixing any control structure.

Proposed design procedure resulted in an effective proposal to design PECs such that all operating requirements were satisfied. The main features of proposed PECs design procedure were: *(a)* all system parameters were selected based on physical system knowledge, *(b)* inherent syst2011.em dynamical nature was taken into account in the design process, *(c)* designed PECs were controllable and it was possible to quantify their controllability, and *(d)* no control structure were fixed, therefore, design procedure will be applied to other PECs applications.

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