T.C.
ISTANBUL AYDIN UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

DISCRETE-TIME ADAPTIVE IDA-PBC CONTROL FOR DC-DC BOOST CONVERTOR WITH UNCERTAIN CONSTANT POWER LOAD

MASTER'S THESIS

SYED TAIMOOR ALI

Department of Electrical and Electronics Engineering
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Thesis Advisor: Assist. Prof. Dr. Mohammed ALKRUNZ

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APPROVAL PAGE

DECLARATION

I hereby declare that the research I submitted for my master’s thesis, "DISCRETE-TIME ADAPTIVE IDA-PBC CONTROL FOR DC-DC BOOST CONVERTOR WITH UNCERTAIN CONSTANT POWER LOAD," was written independently from the Project phase to the conclusion of the thesis and that the only works from which I drew inspiration were those listed in my Bibliography.

Syed Taimoor Ali

FOREWORD

Throughout my master’s education, I would like to thank my university and faculty for their support, outstanding guidance, and encouragement. I would like to thank my supervisor, Assist. Prof. Dr. Mohammed ALKRUNZ, for all the assistance, advice, and direction he provided throughout this research project. It was a pleasure to work with him.

I’m very grateful to my wonderful family, and I’ll always owe them something because they've always kept me in their prayers. lastly, I want to thank my friends for giving me the energy and compassion I needed to finish my research work successfully. Most of all, I want to thank the Almighty for his blessings, which have helped this thesis be a success.

April, 2022 Mr. Syed Taimoor Ali

DISCRETE-TIME ADAPTIVE IDA-PBC CONTROL FOR DC-DC BOOST CONVERTOR WITH UNCERTAIN CONSTANT POWER LOAD

ABSTRACT

In this study, the problem of the output voltage regulation of the dc-dc boost converter considering unknown constant power load is addressed. The dc-dc boost converter with uncertainty in the power load is formulated in discrete-time setting in the structure of port-controlled Hamiltonian system based on the average dynamics of the power converters. An adaptive discrete-time interconnection and damping assignment passivity-based controller (IDA-PBC) for the considered uncertain dc-dc boost converter is presented. Besides, the technique method of the immersion and invariance (I&I) is used to design the estimator of the unknown power load in discrete-time setting by guaranteeing asymptotic stability of the estimator using Lyapunov theory providing an automatic update for the IDA-PBC controller. The proposed adaptive IDA-PBC controller is applied to the dc-dc boost converter and the converter's performance is tested by MATLAB/SIMULINK. The simulation results illustrate that the proposed adaptive controller successfully preserves the stability, effectiveness, and robustness of the system under large-scale variations in the constant power load.

Keywords: boost converter, IDA-PBC, immersion and invariance (I&I), port-controlled Hamiltonian system, Adaptive Control

BELİRSİZ SABİT GÜÇ YÜKÜ ILE DC-DC BOOST DÖNÜŞTÜRÜCÜ IÇIN AYRIK ZAMANLI UYARLANABILIR IDA-PBC KONTROLÜ

ÖZET

Bu Tezde, bilinmeyen sabit güç yükü dikkate alınarak DC-DC boost dönüştürücünün çıkış voltajı regülasyonu sorunu ele alınmıştır. Güç yükünde belirsizliğe sahip dc-dc boost dönüştürücü, güç dönüştürücülerinin ortalama dinamiklerine dayalı olarak port kontrollü Hamilton sisteminin yapısında ayrık zaman ayarında formüle edilmiştir. Belirsiz olduğu düşünülen dc-dc boost dönüştürücü için uyarlanabilir ayrık zamanlı ara bağlantı ve sönümleme ataması pasiflik tabanlı denetleyici (IDA-PBC) sunulmuştur. Ayrıca, teknik daldırma ve değişmezlik yöntemi (I & I), IDA-PBC denetleyicisi için otomatik bir güncelleme sağlayan Lyapunov teorisini kullanarak tahmincinin asimptotik stabilitesini garanti ederek, bilinmeyen güç yükünün tahmincisini ayrık zaman ayarında tasarlamak için kullanılır. Önerilen uyarlanabilir IDA-PBC denetleyicisi dc-dc boost dönüştürücüye uygulanır ve dönüştürücünün performansı MATLAB / SİMUL INK tarafından test edilir. Simülasyon sonuçları, önerilen uyarlanabilir denetleyicinin, sabit güç yükündeki büyük ölçekli değişiklikler altında sistemin kararlılığını, etkinliğini ve sağlamlığını başarıyla koruduğunu göstermektedir.

Anahtar Kelimeler: boost dönüştürücü, IDA-PBC, daldırma ve değişmezlik (I&I), port kontrollü Hamilton sistemi, Adaptif Kontrol

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ABBREVIATIONS

I&I: Immersion and Invariance

IDA-PBC: Interconnection and Damping Assignment Passivity Based Controller.

PBC: Passivity based controller.

PCH: Port-controlled Hamiltonian System.

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I. INTRODUCTION

With both energy demand and energy supply on the rise, more and more people are starting to take an interest in renewable energy (H. Kikigano, 2010). A great deal of distributed renewable energy resources, like solar photovoltaic (PV) systems and wind turbines, have been added to utility power grids in recent years. Power quality in utility grids may be impacted, however, if many distributed generation units are integrated. Microgrids can be built to integrate controller in a specific area, managed centrally within the microgrid, and connected to the utility grid in a way that meets power quality standards at the microgrid's point of connection. Microgrids can be split into two distinct types: those that use alternating current and those that use direct current. Most microgrids use alternating current (ac) distribution, the same technology used by traditional power companies (Zeng ,2013). Specifically, inverters link dc power sources like PV systems, fuel cells, and energy storage systems to the microgrids. To lessen energy waste during the conversion from dc sources to dc loads, DC microgrids have been proposed and studied. Dc microgrids are feasible because of the rise in popularity of low-power electronic devices and the possibility of employing light-emitting diodes to cut down on lighting loads (K. Doran and P. Pasrich, 2010). When a dc microgrid with constant power loads (CPLs) operates in the island mode, the technical challenges associated with its operation and control are particularly significant. DC microgrids typically use dc-dc boost converters to connect DC sources to the grid (C. lai and Cheng ,2012). It is well known that when using traditional linear controllers, the dc-bus voltage may oscillate or become unstable due to the negative incremental impedance property of a CPL. Many studies have focused on perfecting nonlinear control methods for converters that use CPLs. Examples of such controllers include the sliding mode controller for buck converters, the hybrid model predictive control for boost converters, and the passivity-based controller (PBC) for buck, boost, and buck-boost converters with CPLs. Compared to other nonlinear control methods, PBC takes advantage of the structural properties of physical systems (K. Doran and P. Pasrich, 2010) to arrive at a control law that can be implemented with relative ease. Stability analysis of a dc microgrid has been performed using the PBC in conjunction with the interconnection and damping assignment (IDA) method. However, after being designed for a typical operating condition—such as a fixed power level of the CPL and a fixed voltage on the dc-bus—the IDA parameters were typically determined through simulations and locked in. The values of system state variables typically fluctuate over time in practical applications. As a result, when the operating condition of the system shifts, the IDA's optimal performance will suffer if its parameters remain constant. In addition, the PBC needs accurate values for the state variables in order to maintain the system at a predetermined operating point. However, a discrepancy between the actual and desired operating points may occur when employing a PBC due to estimation or measurement errors of the state variables (Zang and Qiao, 2013). In thesis, the idea we suggest is a novel adaptive IDA-PBC for a CPL-equipped dc-dc boost converter. An IDA-based virtual circuit is derived from the port-controlled Hamiltonian system (PCHS) to design the controller's parameters. The virtual circuit analysis can be used to determine the optimal values for the controller parameters, allowing for the dc-dc boost converter with a CPL to operate in one of three modes: underdamping, critical-damping, or overdamping. Moreover, due to its highly nonlinear properties, the dc-dc boost converter makes it difficult to design a control algorithm that is robust against load variations. This study presents a complementary controller that, when used in conjunction with the IDA-PBC, can correct the steady-state error in the output voltage brought on by changes in the load.

In chapter 3, IDA-PBC with I&I is explained with relevant figures and graph to further explain the working of whole system.

II. LITERATURE REVIEW

In this section I have mentioned the research which had already happened by various researchers in field of port controllers:

Every day, significant concerns and efforts are directed toward the development of high-performance control systems that are modeled using the Hamiltonian structure. This is particularly the case for multivariable electromechanical systems.

Modern modeling and control techniques have made use of the port-Hamiltonian system. The emphasis is on the flow of energy within and between systems. Power converters, on the other hand, are gadgets that take in electrical energy and transform it so that its output has the desired quality. For this reason, a Port-Hamiltonian model lends itself well to the regulation of power converters. In the paper written by (David NAVARRO, Domingo CORTES) they build on previous work by proposing a Port-Hamiltonian method for controlling DC-DC power converters. The proposed controller uses a time-varying inductor current, which is one of its distinguishing features. This allows for a closed-loop response that is both quicker and less prone to overshoot during start-up and load disturbances.

The paper by (N.M. Trang Vu and L.Lefevre) explores the connections between Linear Quadratic (LQ) optimal control and Interconnection and Damping Assignment-Passivity Based Control (IDA-PBC) design. The impact of a specific optimal control on the closed-loop system's architecture is studied first, and then the feasibility of using an optimal criterion to direct the development of IDA-PBC parameters is explored. While additional options could be considered, this work explores the case of a trivial relation between the optimal control gain and the desired total power in the IDA-PBC design. Utilizing a linearized pendulum, the method is successfully demonstrated. The paper emphasized the similarity between IDA-PBC and linear quadratic optimal control. This equality allows us to understand the significance of the optimal control gain and its effect on the design parameters of the closed-loop system. On the other hand, this similarity could serve as a principle for deciding upon IDA-closed-loop PBC's parameters. This theory has been successfully implemented in a working model of a linearized pendulum system.

Nonlinear system analysis, specifically as it pertains to the port-controlled Hamiltonian system, is widely regarded as a top research priority. The problem of stabilization continues to play an important part in a variety of studies. In this way, we are going to mention some studies like the ones that are listed below. In another research have constructed appropriate stability testimonies in order to examine the non-linear time-delay systems that are modeled in PCH structures in order to determine whether or not these systems are stable in Kao and Pasumarthy (2012). A rule for the output feedback stabilization of a class of non-holonomic systems in the PCH model was proposed by Sakai and Fujimoto (2014). The underlying principle of the rule was the similarity between the asymptotic stability of a state feedback system and the corresponding output feedback system. As part of their proposal for the design of a simultaneous controller for the PCH, the researchers in that study looked into the possibility of simultaneously stabilizing a collocation of PCH systems. An augmented PCH system is produced because of the collection of PCH systems being combined through the utilization of the dissipative properties of the Hamiltonian form. According to paper (Xi, 2002),

They investigated the stability of a group of constrained Hamiltonian systems as well as the control design for those systems. Some stability criteria are derived by starting with the structural properties of Hamiltonian systems and working backward from there. In addition, the authors talked about feedback stabilization and made an H-infinity control law for Hamiltonian systems with constraints. In order to stabilize two multi-input PCH systems at the same time, in parallel, with actuator saturation, they came up with a brand-new method that they called the energy-based method by (Airong and Yuzhen, 2008) .

The stabilization problem of time-varying PCH systems with input-delay was studied in a paper proposed by (Su and Fu, 2014). The paper proposes a feedback controller using energy shaping and the Lyapunov-Krasovskii theorem to guarantee the asymptotic stability of the closed-loop of time-varying PCH with input delay.

When it comes to passivation, (Ortega and Spong ,1989) are the ones who first introduced Passivity Based Control (PBC), which is widely regarded as a potent stabilization control design method. So, in this approach, the stabilizable controller makes use of a storage function that has a minimum at the target equilibrium points. Additionally, a second condition for ensuring asymptotic stability is that the passive output be detectable (Ortega and Spong, 1989). For physical systems modeled by the Euler-Lagrange (EL) motion equations, the Passivity Based Control (PBC) method provides a potent strategy for robust controller design (Xi, 2002). In addition, for mechanical system regulation problems where the potential energy can only be shaped (or stabilized), the Passivity Based Controller (PBC) method maintains the structure of Euler-Lagrange (EL). The closed-loop energy function is thus set to be the controller's energy function minus the system's energy function. If the authors are correct, then achieving stability requires first balancing the energy flows. The EL-PBC, on the other hand, loses its attractive properties when used in contexts where the shaping of total energy is required, such as the electrical, electromechanical, or some underactuated systems. To address the stabilization issues of the aforementioned energy-balancing mechanism and to guarantee the invariance of the structure, a new PBC theory tool called "Interconnection and Damping Assignment (IDA-PBC)" is developed (Ortega et al, 2013). To this end, they looked at the Port-Controlled Hamiltonian (PCH) models produced by simulations of energy-efficient physical systems with lumped parameters and discrete storage elements, rather than the Euler-Lagrange (EL) structure form. They are complete representations of the EL class model. In IDA-PBC, the storage function to be assigned comes first, and the controller that guarantees the storage function assignment is designed while still allowing the storage function to remain non-increasing.

When selecting the appropriate energy function, interconnection, and damping structure matrices, the IDA-PBC method's closed-loop energy function is calculated by solving the resulting partial differential equations (PDE)(Ortega et al, 2002).Unfortunately, it is not a simple problem to solve PDEs by finding their solutions. In particular, in the IDA-PBC method, solvable PDEs are obtained by parameterizing the PDEs in terms of interconnection and damping matrices that can be selected wisely with respect to physical concerns (Ortega et al, 2013; Ortega et al , 2002). But the IDA-PBC approach is still considered "universally stabilizing" because it gives all the asymptotically stabilizing controllers for the PCH systems, even though the IDA-PBC approach method requires that explicit conditions exist for the solution of these PDEs. The challenge of determining such a feedback control rule has been investigated (Fujimoto, 2001).

Mechanical systems' kinetic energy can be altered in the IDA-PBC method by choosing an appropriate desired interconnection matrix. For example, in (Ortega et al, 2002) they applied this benefit to the inverted pendulum system with an inertia disk and the ball and beam system for global stabilization. In addition, some links to the controlled-Lagrange controller discussed in (Block et al , 2000).

Repeatedly in the controller design, In research mentioned in (Yalçın and Sümer, 2010) they have relied on the discrete-time Hamiltonian system model. For mechanical systems where the desired closed-loop continuous-time model of the aforementioned system is known, the study directly derives the discrete-time version of the IDA-PBC controller, in this case the energy-shaping and damping injection controller terms of the PBC. The effectiveness of the proposed controller was demonstrated through simulation on two examples, one of which was a non-separable Hamiltonian system and the other was an underactuated Hamiltonian system. In contrast to emulating the continuous time version of the controller, which could lead to system instability, the authors have demonstrated that the direct discrete-time version of the controller for the sampled PCH yields good performance.

However, a new instrument for nonlinear stabilizing control and adaptive control has been presented by (Astolfi and Ortega, 2003) . The design problem of the stabilization and adaptive control rules was broken down into smaller, more manageable subproblems using system immersion and manifold invariance, two classical tools of geometric nonlinear control and nonlinear regulator theory for general nonlinear systems. The term "immersion and invariance" (I&I) describes this strategy. And in particular, the stabilization and adaptive control of I&I. In cases where the desired dynamics are of a reduced order, I&I is a viable strategy. For situations where classical adaptive control has its limits, like when one is working with a nonlinearly parameterized system, this alternative method is also investigated. Many different types of physical systems, including energy systems, electrical systems, and mechanical systems, are used to demonstrate the efficacy of the Immersion and Invariance I&I method. But in new method they have introduced the I&I method for stabilization of the nonlinear systems, and this method is further developed by several studies and researches where they have summarized these publications (Astolfi and Ortega , 2007).

However, IDA-significance PBC's as a stabilizable controller in a number of application examples is comparable to that of the I&I approach in the field of control theory. More recent efforts have been made to find sets of design parameters that are suitable for the assigned dynamics. Both the well-known I&I and IDA-PBC approaches require the solution of some partial differential equations (PDEs) that determine the controller laws in similar structural contexts. In contrast to the IDA-PBC design approach, I&I design procedures allow a lower-dimensional target system to be tracked as a port-controlled Hamiltonian system in a pre-specified manifold. This is especially useful for mechanical systems and suggests that the I&I approach may be seen as a more relaxed version of the IDA-PBC approach (Kotyczka and Sarras, 2012).

Besides the adaptive control of port-controlled Hamiltonian systems, researchers have also introduced a different type of stabilization method called the Casimir method. Through energy-shaping, a generalization of the Casimir method for Hamiltonian systems, they have explored the stabilization and adaptive stabilization issues of time-varying PCH (Guo and Cheng, 2006). When dealing with parameter perturbations in port-controlled Hamiltonian systems (PCH), similarly according to (Dirksz and Scherpen, 2010), they propose using an adaptive controller in conjunction with canonical transformation theory. This integration with the adaptive controller expands the PCH framework's applicability to a plethora of port-controlled Hamiltonian systems. Under external disturbances and parameter uncertainties, (Sun and Wang, 2013) propose an adaptive feedback framework that guarantees asymptotic stability and the L2 disturbance attenuation for the closed-loop system of a class of time-delay PCH, where the criteria for the delay time are dependent on the asymptotic stability. Statistical analysis of simulation results validated the effectiveness of the proposed method in (Dirksz and Scherpen, 2010). Parametric uncertainties of the same class of time-delay nonlinear PCH which are studied here, but this time the adaptive H controller is used as mentioned in (Wang et al ,2014). The proposed method obtains necessary conditions for designing an adaptive controller that ensures the closed-loop system's asymptotic stability and the attenuation of L2 disturbances.

Since an I&I based adaptive IDA-PBC control for a port-controlled Hamiltonian system is not yet explored in the literature, we aim to do so in this study by combining the IDA-PBC control with this method. Let's look at some adaptive research for nonlinear systems in general that is based on I&I.

The I&I adaptive controller, in contrast to the vast majority of proposed adaptive controllers in the literature, does not rely on the cancellation of the terms in the Lyapunov function derivative. It is the goal of these frameworks, known as the classical adaptive control methods, that rely on the cancellation of the terms, to reduce the impact of disturbances by enforcing matching conditions that restrict or limit the scope of the disturbances. On the other hand, the I&I adaptive controller's use of the robustness perspective can lessen the bad effects of the uncertain parameters. (i.e., by generating cascaded structures). As many examples have shown, adding a proportional term to the integral action of the parameter estimator in the control law can add extra zero dynamics that make the design more stable (Ortega et al , 2013). Several studies established I&I parameter estimators like those mentioned above to apply the I&I methodology in the design of adaptive controllers (Liu et al, 2010).

III. PRELIMINARIES

A. Introduction

This chapter provides and restates some important preliminary findings that are used to construct the main findings of this study. Moreover, continuous time adaptive control system is also mentioned with its equations.

B. Boost Converter

One type of DC-to-DC power converter is the boost converter, also known as a step-up converter or simply a "step-up converter." This type of converter increases voltage at the output but decreases current at the input (load). This type of switched-mode power supply (SMPS) includes a diode and a transistor in addition to a capacitor, an inductor, or both as energy storage components. Capacitor (and inductor) filters are typically added to the converter's output (load-side filter) and input (source-side filter) to smooth out the voltage (supply-side filter).

Batteries, solar panels, rectifiers, and DC generators are all viable options for supplying DC current to the boost converter. DC-to-DC conversion refers to the process of transforming one direct current (DC) voltage to another DC voltage. A boost converter is a type of direct current to direct current converter whose output voltage is higher than its input. Since it increases the voltage from the source, a boost converter is also known as a step-up converter. Therefore, the output current is less than the input current due to the conservation of power (P=VI) (Sharma et al, 2016).

When the current through an inductor is altered, the inductor's magnetic field either strengthens or weakens, and this property is the primary force behind the boost converter's operation. The output voltage of a boost converter is always greater than the input voltage. Figure 3.1 is a schematic representation of a boost power stage.

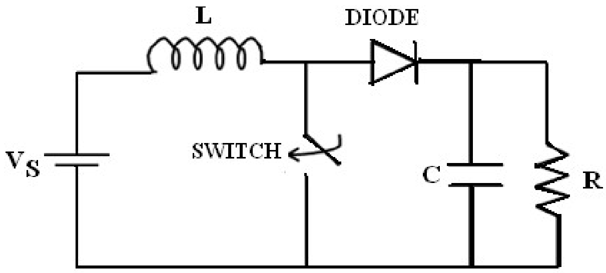

Figure 3.1 Schematic of boost convertor

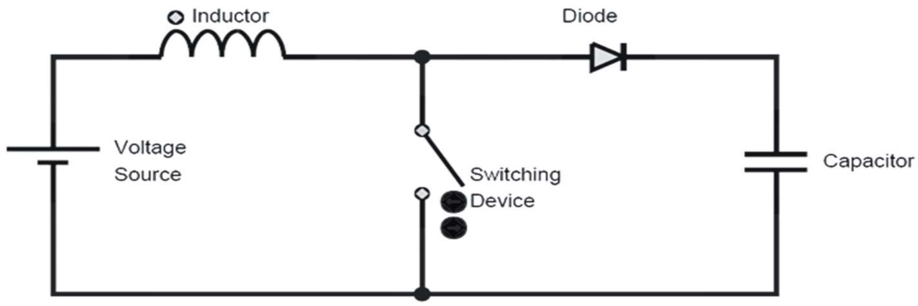

Figure 3.2 Depending on the position

i) If the switch is in its closed (on) position, current will flow clockwise through the inductor, creating a magnetic field that will store energy. The inductor's positive polarity is on its left side.

ii) In the off position (high impedance), less current flows through the switch. In order to keep the current going to the load, the magnetic field will lose some of its energy. This means the polarity will be switched (meaning the left side of the inductor will become negative). Therefore, the capacitor will be charged via diode D at a higher voltage due to the series connection of two sources.

If the switch is cycled rapidly enough, the inductor won't have enough time to fully discharge between charging stages, so the load will always see a higher voltage than the input source alone when the switch is opened. Parallel to the load, a capacitor is charged to this total voltage while the switch is open. The capacitor stores voltage and energy until the switch is closed, at which point the right side is shorted out from the left, allowing the capacitor to supply the load. While this is happening, the capacitor is kept from discharging through the switch thanks to the blocking diode. A fast enough reopening of the switch is required to avoid excessive discharge of the capacitor.

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C. Discrete-Time Settings

To be more specific, a discrete-time signal is a list of numbers that represent specific timestamps. The signal's samples are the values associated with the time instants at which the signal is defined.

Discrete time treats time itself as a discrete variable, with values of variables being viewed as occurring at discrete, separate "points in time" or, equivalently, as remaining constant throughout each non-zero region of time ("time period"). Thus, as one period of time ends and another begins, the value of a variable that is not time-related abruptly changes. This interpretation of time is analogous to a digital clock that displays 10:37 for a short period of time before skipping to 10:38, etc. Each dependent variable is counted only once per time period. It is possible to take only a finite number of measurements between any two given times. Commonly, measurements are taken at even-numbered times in a row.

Quantitative events over time can be represented by "discrete" or "discrete time" signals. A discrete-time signal is not a function of a continuous argument, but it may have been derived from a continuous-time signal through sampling. A sampling rate is associated with a discrete-time signal whenever that signal is obtained by repeatedly taking samples from a sequence at regular intervals. Although there are a few possible categories to place discrete-time signals into, they all fall into one of two broad categories (Zlatanov,2016).

i) This is done by continuously or intermittently grabbing readings from an analog input. Samplin is the name for this procedure.
ii) The weekly peak value of a specific economic indicator is a good example of a process that is discrete by its very nature and can be observed in this way.

D. Adaptive control

When the parameters of the system being controlled change over time or are initially unknown, the controller must employ a method of control known as "adaptive control." During flight, for instance, an airplane loses mass due to fuel consumption, so it requires a control law that can adjust to these variables. Whereas robust control guarantees that the control law need not be changed if the changes are within given bounds, adaptive control is concerned with the control law changing itself, which requires no a priori information about the bounds on these uncertain or time-varying parameters (Chengyu and Yunjun,2012).

Parameter estimation, a subfield of system identification, forms the backbone of adaptive control. Recursive least squares and gradient descent are two common estimation techniques. Real-time adjustments to estimates can be made using both of these methods, thanks to the update laws they provide (i.e., as the system operates). These update laws and convergence criteria are derived using Lyapunov stability (typically persistent excitation; relaxation of this condition are studied in Concurrent Learning adaptive control). It is common practice to employ projection and normalization in order to make estimation algorithms more bulletproof.

E. Hamiltonian System

The origins of the Hamiltonian approach can be traced back to analytical mechanics, where it was developed from the principle of least action and ultimately led to the Hamiltonian equations of motion via the Euler-Lagrange equations and the Legendre transform. Conversely, the network approach is a central tenet of mathematical systems theory and has its origins in electrical engineering. The network perspective is currently dominating the modeling and simulation of (complex) physical engineering systems, while the majority of past analysis of physical systems has been conducted within a Lagrangian and Hamiltonian framework. Both perspectives are brought together in the framework of port-Hamiltonian systems by associating the geometric structure given by a (pseudo-) Poisson structure or, more generally, a Dirac structure with the interconnection structure of the network model. In addition, port-Hamiltonian systems are open dynamical systems that communicate with their external environment via ports (Van Der Schaft, 2014).

1. Classical Equation of Port- Hamiltonian System: These are the standard Hamiltonian equations for a mechanical system which we discussed are from [34]:

$$\dot{q} = \frac{\partial \dot{H}(q,p)}{\partial p} \tag{3.1a}$$

$$\dot{p} = -\frac{\partial \dot{H}(q,p)}{dq} + F \tag{3.1b}$$

where the Hamiltonian $H(q,p)$ represents the system's total energy, $q = (q_1, \ldots\ldots q_k)^T$ are the generalized configuration coordinates for a mechanical system with k degrees of freedom, p = 0, and q = 1. $p = (p_1, \ldots\ldots p_k)^T$ is the vector of generalized momenta, while F is the vector of generalized external forces. Phase space is the state space of (3.1) with local coordinates (q,p).

Immediately, the following energy balance can be derived as in (Van Der Schaft, 2014):

$$\frac{dH}{dt} = \frac{\partial^T}{\partial q}(q,p)\dot{q} + \frac{\partial^T}{\partial p}(q,p)\dot{p} = \frac{\partial^T}{\partial p}(q,p)F = q^{\dot{T}}F \tag{3.2}$$

expressing that the increase in system energy is equal to the amount of work supplied (conservation of energy). This motivates defining the system's output as $e = \dot{q}$. (The vector of generalized velocities) equation (3.1) is typically presented in the following format **:**

$$\dot{q} = \frac{\partial \dot{H}(q,p)}{\partial p}, \ (q,p) = \left(q_{1,} \dots \dots q_{k,} p_{1,} \dots . . p_k\right), \tag{3.3}$$

$$\dot{p} = -\frac{\partial \ H(q,p)}{dq} + \dot{B}(q)f, \qquad f \in R^m, \tag{3.4}$$

$$e = B^T(q)\frac{\partial H}{\partial p}(q,p) \ \ (= B(q)(\dot{q})), \quad e \ \in R^m, \tag{3.5}$$

with $B(q)f$ representing the forces that result from the input $f \in R^m$. In case $m < k$, we refer to a system as being underactuated. Similarly, to (3.2), the energy balance is obtained as mentioned in (Van Der Schaft, 2014)**.**

$$\frac{dH}{dt}\left(q(t), p(t)\right) = e^T(t)f(t), \tag{3.6}$$

A further generalization is to consider local-coordinate-described systems as in :

$$\dot{x} = J(x)\frac{dH}{dx}(x) + g(x)f, \quad x \in \boldsymbol{X}, f \in R^m, \tag{3.7}$$

$$e = g^T(x)\frac{dH}{dx}(x) \qquad e \ \in R^m, \tag{3.8}$$

whereas $J(x)$ is a nxn matrix with entries that depends on (x) and is assumed to be skew-symmetric, so $J(x) = -J^T(x)$, and $x = (x_1, \dots .. x_k)^T$ are local coordinates for an n-dimensional state space manifold X . (Not necessarily even dimensional as above). Energy balance $\frac{dH}{dt}(x(t)) = e^T(t)f(t)$ can be easily reconstructed thanks to the skew symmetry of J. Given the structure matrix $J(x)$, the input matrix $g(x)$, and the Hamiltonian H, refer to (3.8) as a port-Hamiltonian system.

In such cases, we can determine "canonical coordinates" using Darboux's theorem because the structure matrix J also satisfies an integrability condition (the Jacobi-identity). To be more precise, according to (Van Der Schaft, 2014), J is the structure matrix of a Poisson distribution on $\boldsymbol{X}$ **.**

2. Networking of Hamiltonian system by port- based technique**:**

In this section, a general structure of how port-Hamiltonian systems emerge directly from port-based network models of physical systems, adopting a different perspective is shown in figure below as in (Van Der Schaft, 2014).

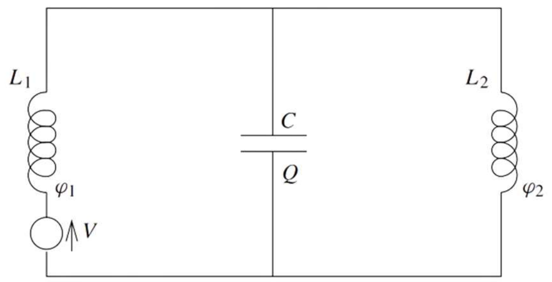

Figure 3.3 General LC circuit

Network models of complex physical systems typically view the system as the interconnection of energy-storing elements via basic interconnection (balance) laws like Newton's third law or Kirchhoff's laws; power-conserving elements like transformers, kinematic pairs, and ideal constraints; and energy-dissipating elements .Port-Hamiltonian systems theory begins with defining the Hamiltonian as the total energy stored in the system and formalizing the basic interconnection laws alongside the power-conserving elements by a geometric structure. The following elementary case already exemplifies .

3. The Hamiltonian systems with inputs, states, and outputs:

When the flow and effort variables of the resistive, control, and interaction ports are decomposed into conjugated input-output pairs, we have a special case of port-Hamiltonian systems known as input-state-output port-Hamiltonian systems, in which the variables in the state space are not constrained by algebra. PCH systems, also known as port-controlled Hamiltonian systems, are a generalization of Hamiltonian systems that can be expressed as (Van Der Schaft, 2014; Pang S et al , 2018):

$$\dot{x} = [J(x) - R(x)]\frac{\partial H}{\partial x} + g(x)u \tag{3.9a}$$

$$y = g^T(x)\frac{\partial H}{\partial x}(x) \tag{3.9b}$$

$J(x)$ is a $n\ x\ n$ matrix whose entries depend smoothly on x and whose skew-symmetry is assumed (Pang S et al , 2018):

$$J(x) = -J^T(u) \tag{3.10}$$

$R(x) = R^T(x)\ 0$ represents the system's dissipation. Due to the R matrix, the form of PCH system described above is sometimes referred to as PCH with dissipation. If $R = 0$ (i.e., there is no dissipation), then the skew-symmetric nature of J permits us to recover the energy-balance relation $H = u^T\ (t)y(t)$ by demonstrating that the system (3.9) is lossless if $H \geq 0$ and $R = 0$.

Physical system network models that treat the system as an interconnection of energy-storing elements inevitably lead to port-controlled Hamiltonian realizations. Passivity-based controls can be built on the basis of the physical properties of this type of system, which occurs in biological, chemical, electrical, and mechanical systems. Several examples can be used to demonstrate the variety of possible contexts.

If we assume about an LC-circuit that has a controller. Then according to [35] consisting of two inductors, with magnetic energies $H_1(\emptyset_1)$ and $H_2(\emptyset_2)$, and links $\emptyset_1$ and $\emptyset_2$ in the magnetic flux. Plus, an electrical capacitor storing $H_3(Q)$ (Q being the charge). Assuming a linear relationship between the elements $H_1(\emptyset_1) = \frac{1}{2L_1}\emptyset_1$,

$H_2(\emptyset_2) = \frac{1}{2L_2}\emptyset_2$, and $H_3(\emptyset_3) = \frac{1}{2L_3}Q^2$, Consider a voltage source to be denoted by u. The following equations for the state variables are obtained by applying Kirchoff's laws (Pang S et al , 2018):

$$\begin{bmatrix} \dot{Q} \\ \dot{\emptyset}_1 \\ \dot{\emptyset}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial H}{\partial Q} \\ \frac{\partial H}{\partial \emptyset_1} \\ \frac{\partial H}{\partial \emptyset_2} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} u \tag{3.11}$$

And

$$y = \frac{\partial H}{\partial \emptyset_1} \tag{3.12}$$

Equation (3.12) represents inductor current. $H_1(\emptyset_1) + H_2(\emptyset_2) + H_3(Q) = H(\emptyset_1, \emptyset_2, Q)$ meaning the sum of all potential energy in the circuit and $J = \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$ is skew-symmetric matric which relies on the connections between its components for its structure, allowing any circuit to be written as a port-controlled Hamiltonian system.

4. Control through the interconnection of port Hamiltonian systems:

The fundamental feature of port-Hamiltonian systems is that any number of such systems can be connected in a power-efficient manner, yielding yet another port-Hamiltonian system**.**

In this study, we introduce a PBC method for the dc on-board distribution system based on interconnection and damping assignment (IDA). In this study of thesis, a boost converter and with adaptive control technique are implemented and studied to provide for the wide range of electrical loads. IDA-PBC does not separate the control strategy into outer-loop and inner-loop like other control methods do. Because of this, a more effective control strategy can be used to maintain the system's steadiness. The control law is imperfect because it is derived from a subset of the PCH model's equations. All equations are satisfied, and the passivity proof is complete when the

PCH form is used in the dc-dc converter system, which considers the total energy in the energy function. As a result, the control law the equations in the closed-loop system and incorporate all of that information. It is of great interest to learn how to connect all the equations and determine the unique control law. The PCH structure's control law also depends on the interconnection and damping matrices we select. The interconnection matrix has a relatively open structure, and the damping matrix should always be positive. As a result, the interconnection matrix is a promising option for constructing the PCH system's internal links. In order to complete this task, an adaptive interconnection matrix is created in this paper. Tuning the dynamic property is also addressed by addressing the virtual damping assignment technique.

F. Passivity Based Control

Synthesizing stabilizing controllers using passivity-based control (PBC) is a common practice. The following characteristics of passive systems contribute to the method's widespread acceptance:

i. The passivity of many different kinds of systems (especially mechanical systems) is guaranteed by an energy conservation principle that is satisfied by the energy function. As a first step in the design of stable passivating controls, selecting a storage function that makes sense for these systems is essential.
ii. As long as the passivated system satisfies a detectability condition, stabilization of the origin is straightforward via output feedback in passive systems.
iii. If two passive systems are connected via a feedback mechanism, then both systems will remain passive, as proven by the passivity theorem. This offers some degree of robustness to unmodeled passive dynamics while providing a modular approach to building large-scale passive networked systems.

Despite its advantages, passive control has had to overcome a number of obstacles in its early stages. When it came to feedback passivation, initially only degree-one systems with negligible phase-zero dynamics were considered.

Backstepping for strict feedback systems and forwarding for strict feedforward systems are examples of recursive design procedures that can be used to get around these problems. Yet, in order to control the passive plant using any of these design methods, information about a suitable storage function is required. While the sum of kinetic and potential energy makes sense as a storage function for mechanical systems, it is less clear cut in electronic and biological systems. To overcome this obstacle, researchers have zeroed in on Hamiltonian structures in their systems of interest. This interest in passivity-based control is further justified by the fact that it has been used to model a number of interesting and important applications.

To a large extent, the passive property of many physical systems can be understood in terms of the dissipation and transformation of energy. The ability to quantify and qualify the energy balance of a system when stimulated by external inputs to generate some output is an inherent Input-Output property. So, passivity is related to the property of stability in an input-output way. That is, we say a system is stable if it has a limited "input energy" and a limited "output energy" as a result. In contrast, Lyapunov stability is concerned with a system's internal stability, or how "far" the current state is from an ideal one. To put it another way, the degree to which a system deviates from an ideal performance.

By controlling a closed loop system so that it does not actively interact with its environment, we say that the system is passively controlled. Since this is still a developing area of study, we can only provide a high-level overview of the key ideas here. The Euler-Lagrange (EL) systems and their passivity-based control are also discussed, as are other passive physical systems. In order to grasp the passivity concept and PBC, we must abandon the idea of the state of a system and instead view it as a device that engages in mutually beneficial exchange with its surroundings by means of the transformation of inputs into outputs. Passive systems, from an energetic point of view, are those that cannot store more energy than is supplied by some "source," with the difference between the two being the dissipated energy. Negative feedback interconnection does not affect the passivity of a system, which is a fundamental property of passive systems. Simply put, a passive system is the result of the feedback connection between two passive systems. Therefore, the closed loop will be input-output stable if the total energy balance is positive, meaning that the energy generated by one subsystem is dissipated by the other. Passivity-based control relies on this characteristic (PBC).

All of the passivity-based control strategies outlined above count on the existence of a priori knowledge of a storage function. Since there are multiple potential solutions, it is not always easy to determine this storage function from the $x = f(x) + g(x)u$ description of the system. The storage function, however, is often recognizable from energy considerations when we return to the physics behind the model. Passivity-based methods of control have this as one of their many advantages. With the help of first principle modeling information, PBC techniques can extract and then reshape the system's total energy. Methods for implementing energy concepts directly into passivity-based control are discussed further below.

First, we'll imagine a system coupled to the outside world via port power variables $u \text{ and } y$, the product of which has a power unit. $u \text{ and } y$ stand for current and voltage, respectively, in electrical circuits. These port power variables are analogous to mechanical systems' force and velocity. Only systems that fulfill an energy balance relation are considered in chapter 10 of Passivity Based Control.

$$H(x(t)) - H\big(x(0)\big) = \int_0^T u^T(s)y(s)ds - d(t) \tag{3.12}$$

where H is a function of the total energy and $d(t)$ is a dissipation term that is not negative.

To solve this stabilization problem, we will choose the control action $u = (x) + v$ and the output z such that the reformulated system with the new input v and output z satisfies a desired energy balancing equation of the form as in .

$$H_d\big(x(t)\big) - H_d\big(x(0)\big) = \int_0^t v^T(s)z(s)ds - d_d(t) \tag{3.13}$$

where H_d is a target total energy function with a minimum at the target operating point x and a dissipation rate of d_d, where dd is the rate at which the target function converges to the target value $d_d(t)$. Keep in mind that this tactic picks the new control and output to reshape the energy function in a way that guarantees passivity, and so we can stabilize by picking the right feedback control v.

Mechanical systems are an excellent example of a type of system for which this method is well suited. Allow us to assume that the energy function H of our unregulated system satisfies the dissipation relation given by equation (3.12). Allow me to assume that we can locate a function $\alpha(x)$ such that in chapter 10 of Passivity Based Control.

$$-\int_0^t \alpha^T\big(x(s)\big)y(s)ds = H_a\big(x(t)\big) + k \tag{3.14}$$

for a purpose $H_a(x)$ so that the desired energy function is satisfied.

$$H_d(x) = H(x) + H_a(x) \tag{3.15}$$

at the point of optimal equilibrium x^*, Given the inert nature of this transformed nonlinear system, we can use a straightforward output feedback law to maintain the desired steady-state value of x^*. Sometimes referred to as energy-shaping or energy-balancing, this concept involves choosing to reshape the energy function in a way that guarantees stabilizability about a desired setpoint α .

Let us apply this energy-balancing strategy to a form-based passive system :

$$\dot{x} = f(x) + g(x)u \tag{3.16a}$$

$$y = h(x) \tag{3.16b}$$

Passivity from $u\ to\ y$ is equivalent to the existence of a nonnegative function $H; R^n \to R$ (i.e., the storage function) that satisfies the relations from our previous discussion :

$$\left[\frac{dH(x)}{dx}\right]^T f(x) \leq 0, h(x)\left[\frac{dH(x)}{dx}g(x)\right]^T \tag{3.17}$$

Consider the passive system described by equation (3.16) with storage function $V(x)$. Let $H_a(x)$ be a function such that $H_d(x) = H(x) + H_a(x)$ has a minimum at x^*, the equilibrium points of interest. If a vector function $\alpha(x)$ that satisfies the partial differential equation exists , then.

$$\left[\frac{dH_a(x)}{dx}\right]^T \big(f(x) + g(x)\alpha(x)\big) = h^T(x)\alpha(x) \tag{3.18}$$

subsequently, the control input $u = \alpha(x) + v$ transforms the initial system into the equation (3.16) passive.

G. IDA-PBC Control

For the (asymptotic) stabilization of nonlinear systems, a new controller design methodology known as interconnection and damping assignment passivity-based control has been developed; this method forges a Hamiltonian structure with a desired energy function, which qualifies as Lyapunov function for the desired equilibrium, rather than relying on, sometimes unnatural and technique-driven, linearization or decoupling procedures. The control law can be found by solving a system of partial differential equations that characterize the assignable energy functions. We discussed a controller design method in the thesis called interconnection and damping assignment passivity-based control (IDA-PBC), which uses the physically motivated principles of energy shaping and damping injection to achieve stabilization for underactuated mechanical systems. The closed-loop system is given a Hamiltonian structure by IDA-PBC. Let us consider the PCH system in (3.9) where the storage function H is constant and the desired equilibrium point x^* is a constant. The goal is to determine a setpoint $u = (x) + v$ for the closed-loop dynamics such that the system satisfies the energy-balancing relation as stated in [35].

$$H_d\big(x(t)\big) - H_d\big(x(0)\big) = \int_0^t v^T(s)z(s)ds - d_d(t)$$

where $H_d(x)$ is the total energy we want, with a hard lower bound at x^*, z is a new passive output, and $d_d(t)$ is the dissipation term we've chosen to have equal to zero. By setting $v = 0$, the passivation-solving control stabilizes x^* using the Lyapunov function $H_d(x)$.

This procedure is called IDA-PBC which are further explained and used to construct our controller in chapter IV.

Theorem of IDA-PBC is usually given by in chapter 10 of Passivity Based Control:

$$\begin{aligned}\left[J\big(x,\alpha(x)\big) + J_a(x) - (R(x) + R_a(x))\right]K(x) \\ = [-J_a(x) - R_a(x)]\frac{\partial H}{\partial x}(x) + g(x,\alpha(x))\end{aligned} \tag{3.19}$$

J_d and R_d maintain their structure , i.e.

$$J_d(x) = J\big(x,\alpha(x)\big) + J_a(x) = -J_d^T(x) \tag{3.20}$$

$$R_d(x) = R(x) + R_a(x) = R_d^T(x) \geq 0 \tag{3.21}$$

Integrability of the underlying PDE is guaranteed if:

$$\frac{\partial K}{\partial x}(x) = \left[\frac{\partial K}{\partial x}(x)\right]^T \tag{3.22}$$

The equilibrium has been achieved i.e.:

$$K(x^*) = -\frac{\partial H}{\partial x}(x^*) \tag{3.23}$$

We can guarantee that x^* is Lyapunov stable, i.e., the Jacobian of $K(x)$ at x^* meets the bound in according to chapter 10 of Passivity Based Control:

$$\frac{\partial K}{\partial x}(x^*) > -\frac{\partial^2 H}{\partial x^2}(x^2) \tag{3.24}$$

The closed loop system with $u = \alpha(x)$ will be a PCH system with dissipation and a total energy function H_d under these conditions :

$$H_d(x) = H(x) + H_a(x) \tag{3.25}$$

Along

$$\frac{\partial H_a}{\partial x}(x) = K(x) \tag{3.26}$$

Even more, the closed-loop equilibrium at x^* will be locally stable. In order for it to be asymptotically stable, x^*must be the largest invariant set in the set of $x \in R^n$ such that:

$$\left[\frac{\partial H_d}{\partial x}\right]^T R_d(x) \frac{\partial H_d}{\partial x}(x) = 0 \tag{3.27}$$

If and only if the integrability condition in equation (3.22) holds, then for every given the solution of equation (3.19) is a gradient of the form (3.26). If we plug these values into equation (3.25), we find that the closed-loop system is a PCH system with a constant total energy (3.25). Here, we show that the desired equilibrium is stable under (3.23) and (3.24).

Building stabilizing controllers using passivity -based control is an effective and useful technique. By redefining both the system's output and its inputs (via a feedback transformation), this technique turns a previously active system into a passive one. Once the system has been passivated, equilibrium can be maintained by means of a straightforward output feedback law. The equilibrium is asymptotically stable if and only if the passivated system has a detectable zero state. However, the range of systems that can benefit from this feedback passivation technique is constrained by the need for feedback transformations of this kind. The passivated system must be in minimum phase and have a relative degree of one for this to work. When this isn't the case, we'll need to resort to more advanced recursive techniques like backtracking, forwarding, or a combination of the two to get around the problem. One more potential flaw with these techniques is that they necessitate familiarity with a storage function for the passivated system. In general, obtaining such storage functions may be challenging unless we can take advantage of first principle modeling of the system. Systems that can be implemented as port-controlled Hamiltonian systems are able to do this. Stabilizing controllers can be built in a methodical fashion with the help of the system's Hamiltonian and knowledge of its interconnection and dissipations structures.

H. Immersion And Invariance (I&I) Method

Non-linear systems can be stabilized with the help of the controller design technique known as immersion and invariance (I&I). By introducing a target dynamical system, as in the I&I approach, the desired behavior of the controlled system can be captured. To ensure that the controlled system asymptotically behaves like the target system, a suitable stabilizing control law is developed. To be more specific, the I&I methodology is predicated on the creation of a manifold in the plant state-space that can be made invariant and desirable via feedback control.

i) This closed-loop dynamics matches the desired dynamics on the manifold.

ii) system state away from the manifold, in the opposite direction that the control law would normally steer it.

Take into account the following discrete-time system (Yalçın and Sümer, 2015; Alkrunz and Yalçın, 2021):

$$x_{k+1} = f(x_k) + g(x_k)u_k \tag{3.28}$$

If the conditions listed below hold for the closed-loop system, then the equilibrium point x^* given in (3.28) is a (globally) asymptotically stable equilibrium.

$$x_{k+1} = f(x_k) + g(x_k)\psi(x_k, \emptyset(x_k)) \tag{3.29}$$

Every possible path the system could take,

$$z_k = \emptyset(x_k) \tag{3.30}$$

and

$$x_{k+1} = f(x_k) + g(x_k)\psi(x_k, z_k) \tag{3.31}$$

If all are bounded and satisfy, $k \geq 0$ then according to [39]:

$$\lim_{k \to \infty} z_k = 0 \tag{3.32}$$

According to the adaptive control based on the immersion and invariance approach is intended to meet the conditions of I&I by incorporating a new term into the classical certainty equivalent control and a law for updating the parameters.

Let us assume that there exists a parameterized function $\psi\ (x_k, \theta)$ at $\theta \in R_q$, such that for some unknown $\theta^{\ *} \in R_q$, the system given in (3.28) is stabilized when

$$x_{k+1} = f(x_k) + g(x_k)\psi(x_k, \theta^*) \tag{3.33}$$

has an equilibrium that is globally asymptotically stable $x_k = x_k{}^*$,

$$x_{k+1} = f(x_k) + g(x_k)\psi(x_k, \theta_k^{est}) \tag{3.34}$$

and

$$\hat{\theta}_{k+1} = \alpha(x_k, \theta_k^{est}) \tag{3.35}$$

$$\theta_k^{est} = l(x_k, \hat{\theta}_k) \tag{3.37}$$

As its already mentioned that $\theta_k^{est} = \hat{\theta}_k + \beta(x_k)$ where $\hat{\theta}_k$ and $\beta(x_k)$ are basically update law and control term , it is possible to stabilize I&I with the desired dynamics also called target dynamics as in (Alkrunz and Yalçın, 2021) :

$$\xi_{k+1} = f * (\xi_k). \tag{3.38}$$

IV. MAIN RESULTS

A. Introduction:

In this chapter we discussed the port Hamiltonian system in discrete time adaptive control IDA-PBC with I &I, initially the circuit of the system is also shown in fig [4.1]. The adaptive control is constructed according to the requirements of the system.

Our system is manufactured in a way it can be modified according to Load. That's why I & I estimator is used. The error dynamics of I & I system is Lyapunov asymptotically stable because general structure for free design function it is presented in such a way. Also update rule was selected for designing the I &I estimator.

In rest of the chapter, calculations of our system formulation of our system is mentioned in details with all the equations. Section B briefly includes all the equation of our structure in port Hamiltonian IDA-PBC used for designing in discrete-time. In section C equations related to I&I system with respect to our IDA-PBC adaptive control in discrete time is written in detail.

B. System formulation

The topological structure of the boost converter with constant power load is shown in figure 4.1.

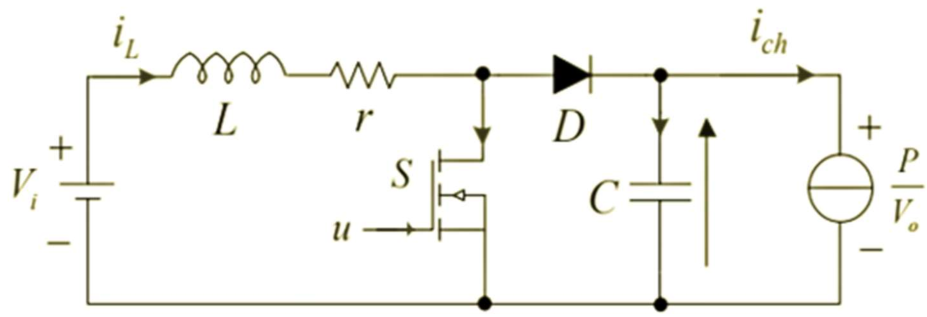

Figure 4.1: Circuit diagram

The total energy stored in the boost convertor is represented as the Hamiltonian function in the continuous-time setting (Pang et al, 2018) is:

$$H\,(x) = \frac{1}{2}\,Lx_1^2 + \frac{1}{2}\,Cx_2^2 \tag{4.1}$$

with $x = [\,x_1 \; x_2]^T = [\,i_L \; v_0]^T$ is the state variables, L is the inductor value and C is the capacitor value.

Gradient of the aforementioned Hamiltonian function is derived as:

$$\nabla H(x) = \begin{bmatrix} \nabla_{x_1} H \\ \nabla_{x_2} H \end{bmatrix} = \begin{bmatrix} Lx_1 \\ Cx_2 \end{bmatrix} \tag{4.2}$$

Let us formulate the dynamics of the uncertain boost-convertor as PCH model in discrete-time as:

$$x^+ - x = (T[J - R]\overline{\nabla} H)(\bar{x}) + T\,g(\bar{x})\,\mathrm{u} + T\delta(\bar{x}, \theta) \tag{4.3}$$

where, $\bar{x} = \frac{3x^+ - x^-}{2}$ as proposed in [38, 39], $\overline{\nabla} H(\bar{x}) \in R^2$ is gradient of the Hamiltonian function in discrete time , T is the sampling time, $u \in R$ is the control vector, $g(\bar{x}) \in R^2$ is the input vector, $\delta(\bar{x}, \theta) \in R^2$ is considered as the disturbances term (Ortega et al, 2002) described with respect to the state variables and the unknown parameter θ. Besides, $J = -J^T \in R^2$ and $R = R^T \geq 0 \in R^2$ are the interconnection matrix and dissipation matrix respectively. Namely,

$$J = \begin{bmatrix} 0 & -\frac{1}{LC} \\ \frac{1}{LC} & 0 \end{bmatrix}, \quad R = \begin{bmatrix} \frac{r}{L^2} & 0 \\ 0 & 0 \end{bmatrix} \tag{4.4}$$

Here in this study, it is considered that the boost converter supplying an unknown constant power load which is a challenging issue and hence:

$$\theta = P \in R \tag{4.5}$$

where P is considered as the unknown constant power load to be estimated. By considering the equations (4.1) to (4.5), the dynamics of the uncertain discrete- time boost converter described by port-controlled Hamiltonian system in (4.3) could be re-expressed as:

$$x^{+} - x = T\begin{bmatrix} \frac{-r}{L^2} & \frac{-1}{LC} \\ \frac{1}{LC} & 0 \end{bmatrix}\begin{bmatrix} L\bar{x}_1 \\ C\bar{x}_2 \end{bmatrix} + T\begin{bmatrix} \frac{\bar{x}_2}{L} \\ \frac{-\bar{x}_1}{C} \end{bmatrix} u + T\begin{bmatrix} \frac{v_{in}}{L} \\ \frac{-\theta}{C\bar{x}_2} \end{bmatrix} \tag{4.6}$$

Besides, the desired Hamiltonian function that represents the desired total energy in the boost converter is defined in continuous time setting as :

$$H_d(x) = \frac{1}{2} L\,(x_1 - x_1^*)^2 + \frac{1}{2} C(x_2 - x_2^*)^2 \tag{4.7}$$

Where x_i^* is the desired equilibrium point, namely $x^* = [\,i_d \;\; V_d\,]^T$, V_d is the desired output voltage and i_d is calculated by

$$i_d = \frac{V_{in}}{2r}[1 - \sqrt{1 - \frac{P}{P_{max}}}] \tag{4.8}$$

$$P_{max} = \frac{V_{in}^2}{4r} \tag{4.9}$$

The desired interconnection matrix and the dissipation matrix in the closed-loop PCH is expressed as :

$$J_d\,(x) = \begin{bmatrix} 0 & -\frac{1}{LC} - K(x, x^*) \\ \frac{1}{LC} + K(x, x^*) & 0 \end{bmatrix}, \quad R_d = \begin{bmatrix} \frac{r_1}{L^2} & 0 \\ 0 & \frac{r_2}{C^2} \end{bmatrix} \tag{4.10}$$

where $r_i > 0$ are constant arbitrary values and $K(x, x^*)$ is a time varying coefficient that changes with time according to the system's states and equilibrium point as illustrated in (4.14). Thus, the desired boost converter system in discrete-time is:

$$x^{+} - x = T[J_d\,(\bar{x}) - R_d\,]\bar{\nabla} H_d(\bar{x}) \tag{4.11}$$

where $\bar{x} = \frac{3x^{+}-x^{-}}{2}$ as proposed in system (Yalçın and Sümer, 2015; Alkrunz and Yalçın, 2021). Then, the above equations in (4.10) and (4.11) that express the dynamics of the desired system in discrete-time is re-written as:

$$x^{+} - x = T\begin{bmatrix} -\frac{r_1}{L^2} & -\frac{1}{LC} - K(\bar{x}, x^{*}) \\ \frac{1}{LC} + K(\bar{x}, x^{*}) & -\frac{r_2}{C^2} \end{bmatrix}\begin{bmatrix} L(\bar{x}_1 - x_1^{*}) \\ C(\bar{x}_2 - x_2^{*}) \end{bmatrix} \tag{4.12}$$

C. Design of discrete-time Adaptive IDA-PBC Controller

By considering the uncertain boost converter in (4.6) and the desired system in (4.12) where the right-hand sides of (4.6) and (4.12) are matched, then:

$$\begin{bmatrix} \frac{-r_1}{L^2} & \frac{-1}{LC} - K \\ \frac{1}{LC} + K & \frac{-r_2}{C^2} \end{bmatrix}\begin{bmatrix} L(\bar{x}_1 - x_1^{*}) \\ C(\bar{x}_2 - x_2^{*}) \end{bmatrix} = \begin{bmatrix} \frac{-r}{L^2} & \frac{-1}{LC} \\ \frac{1}{LC} & 0 \end{bmatrix}\begin{bmatrix} L\bar{x}_1 \\ C\bar{x}_2 \end{bmatrix} + \begin{bmatrix} \frac{V_0}{L} \\ \frac{\bar{x}_1}{C} \end{bmatrix} u + \begin{bmatrix} \frac{v_{in}}{L} \\ \frac{-\theta}{C\bar{x}_2} \end{bmatrix} \tag{4.13}$$

By simplifying the above equation, we obtain:

$$-r_1(\bar{x}_1 - i_d) - (1 + KLC)(\bar{x}_2 - v_d) = v_{in} - r\bar{x}_1 - (1-u)\bar{x}_2 \tag{4.14}$$

$$-r_2(\bar{x}_2 - v_d) + (1 + KLC)(\bar{x}_1 - i_d) = (1-u)\bar{x}_1 - \frac{\theta}{\bar{x}_2} \tag{4.15}$$

where $K_x = KLC$ and it is derived as:

$$K_x = \frac{r_1(\bar{x}_1 - i_d)\bar{x}_1 + r_2(\bar{x}_2 - V_d)\bar{x}_2 - \theta - r\bar{x}_1{}^2 + v_{in}\bar{x}_1}{\bar{x}_1 V_d - \bar{x}_1 i_d} - 1 \tag{4.16}$$

By considering (14), (15) and (16) and by replacing θ with θ^{est}, then the adaptive control law can be obtained as:

$$u(\bar{x}_1, \theta_{est}) = 1 - \frac{\theta^{est}}{\bar{x}_1\bar{x}_2} + \frac{r_2(\bar{x}_1 - V_d) - (\bar{x}_1 - i_d)(K_x + 1)}{\bar{x}_1} \tag{4.17}$$

D. Design of parameter estimator using I&I technology

In this section, the design of I&I based estimator is addressed in discrete-time setting system (Alkrunz and Yalçın, 2021). Let us recall the uncertain system formulation of the boost converter in (4.6):

$$\begin{bmatrix} x_1^+ \\ x_2^+ \end{bmatrix} - \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = T \begin{bmatrix} \frac{-r}{L^2} & \frac{-1}{LC} \\ \frac{1}{LC} & 0 \end{bmatrix} \begin{bmatrix} L\bar{x}_1 \\ C\bar{x}_2 \end{bmatrix} + T \begin{bmatrix} \frac{\bar{x}_2}{L} \\ \frac{-\bar{x}_1}{C} \end{bmatrix} u + T \begin{bmatrix} \frac{v_{in}}{L} \\ \frac{-\theta}{C\bar{x}_2} \end{bmatrix} \tag{4.18}$$

If we write the dynamics of the system's states separately, then:

$$x_1^+ = \frac{-T\,r}{L}\bar{x}_1 - \frac{T}{L}\bar{x}_2 + \frac{T}{L}\bar{x}_2 u + \frac{T v_{in}}{L} + x_1 \tag{4.19}$$

$$x_2^+ = \frac{T}{C}\bar{x}_1 - \frac{T}{C}\bar{x}_1 u - \frac{T\theta}{C\bar{x}_2} + x_2 \tag{4.20}$$

Let us define the parameter estimation error as:

$$z = \theta_{est} - \theta = \underbrace{\hat{\theta} + \beta(x_2^-)x_2}_{\theta_{est}} - \theta \tag{4.21}$$

$$z^+ = \hat{\theta}^+ + \beta(x_2)x_2^+ - \theta \tag{4.22}$$

where $\beta(x)$ is a free design function to be selected such that the estimator is asymptotic Lyapunov stable. By taking the difference equation of (4.21) and (4.22), then:

$$z^+ - z = \hat{\theta}^+ - \hat{\theta} - \beta(x_2^-)x_2 + \beta(x_2)x_2^+ \tag{4.23}$$

By replacing x_2^+ in (4.23) by (4.20), then we have:

$$z^+ - z = \hat{\theta}^+ - \hat{\theta} - \beta(x_2^-)x_2 + \beta(x_2)\frac{T}{C}\left[\bar{x}_1 - \bar{x}_1 u - \frac{\theta}{\bar{x}_2} + \frac{C}{T}x_2\right] \tag{4.24}$$

Or, the above equation (4.24) can be expressed as:

$$z^+ - z = \hat{\theta}^+ - \hat{\theta} - \beta(x_2^-)x_2 + \beta(x_2)\frac{T}{C}\left[\bar{x}_1 - \bar{x}_1 u + \frac{C}{T}x_2\right] - \beta(x_2)\frac{T}{C\bar{x}_2}\theta \tag{4.25}$$

By selecting the update law as:

$$\hat{\theta}^{+} = \hat{\theta} + \beta(x_2^{-})x_2 - \beta(x_2)\frac{T}{C}\left[\bar{x}_1 - \bar{x}_1 u + \frac{C}{T}x_2\right] + \beta(x_2)\frac{T}{C\bar{x}_2}\theta_{est} \quad (4.26)$$

gives the dynamics of the estimation error as:

$$z^{+} - z = \beta(x_2)\frac{T}{C\bar{x}_2}\left(\underbrace{\theta_{est} - \theta}_{z}\right) = \beta(x_2)\frac{T}{C\bar{x}_2}z \quad (4.27)$$

$$z^{+} = \left[1 + \beta(x_2)\frac{T}{C\bar{x}_2}\right]z \quad (4.28)$$

Let us select the free design function $\beta(x_2)$ as

$$\beta(x_2) = \frac{-\alpha C}{T}\bar{x}_2 \quad (4.29)$$

Then, the dynamics of the estimation error be as follows:

$$z^{+} = [\,1 - \alpha\,]z \quad (4.30)$$

where α is a constant free parameter to be selected as $0 < \alpha < 1$ to guarantee the asymptotic stability of the estimator.

Proof:

By considering the dynamics of the uncertain discrete-time boost converter described in (4.6), by defining the estimator dynamics as in (4.21) and (4.22), by selecting the parameter update rule as in (4.26), and by selecting the free parameter function $\beta(x)$ as in (4.29), then:

$$z^{+} = \left[1 + \beta(x_2)\frac{T}{C\bar{x}_2}\right]z = [\,1 - \alpha\,]z = \rho z \quad (4.31)$$

where $\rho = (1 - \alpha)$ and $0 < \alpha < 1$, then ρ satisfies $0 < \rho < 1$.

Let us select the Lyapunov candidate function as:

$$V_z = z^2 \quad (4.32)$$

Then, the time difference of (4.32) is:

$$\Delta V_z = V_{z^+} - V_z = \rho^2 z^2 - z^2 = z^2 \left(\underbrace{\rho^2}_{0<\rho<1} - 1 \right) < 0 \tag{4.33}$$

Thus, asymptotic stability of the estimator is proved.

E. Circuit Diagrams in MATLAB- SIMULINK:

The main circuit that was constructed was mentioned and its subsystem is also shown.

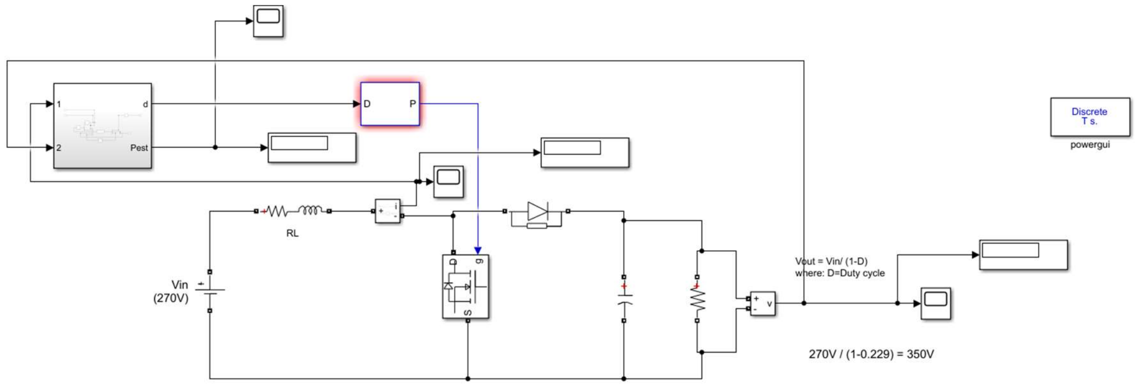

Figure 4.2 Main system

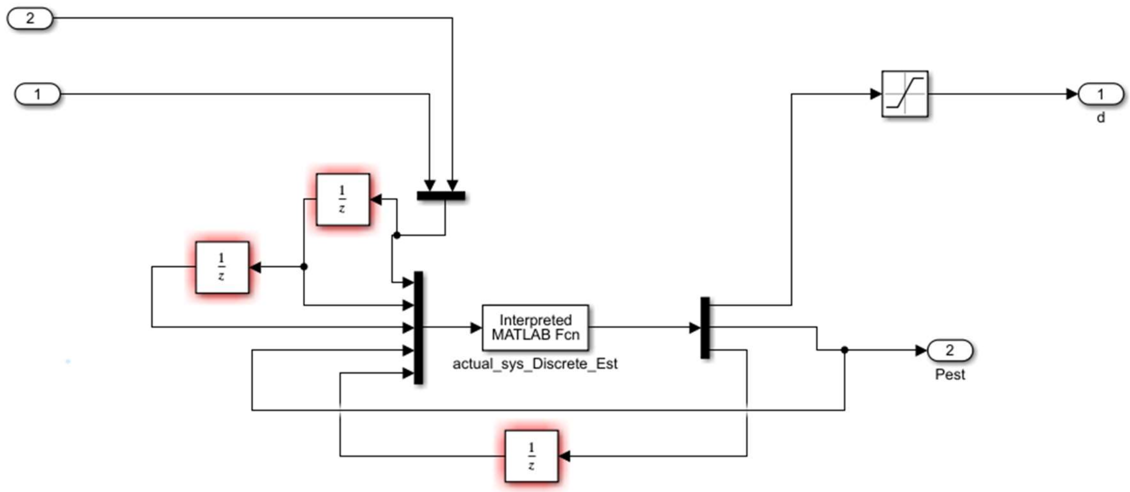

Figure 4.3 Sub-System of main system

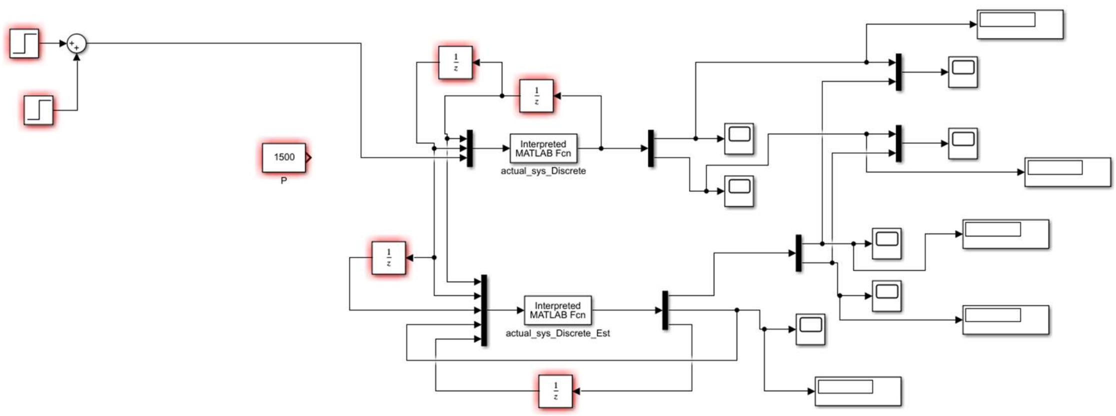

Figure 4.4 Actual system of discrete and estimation

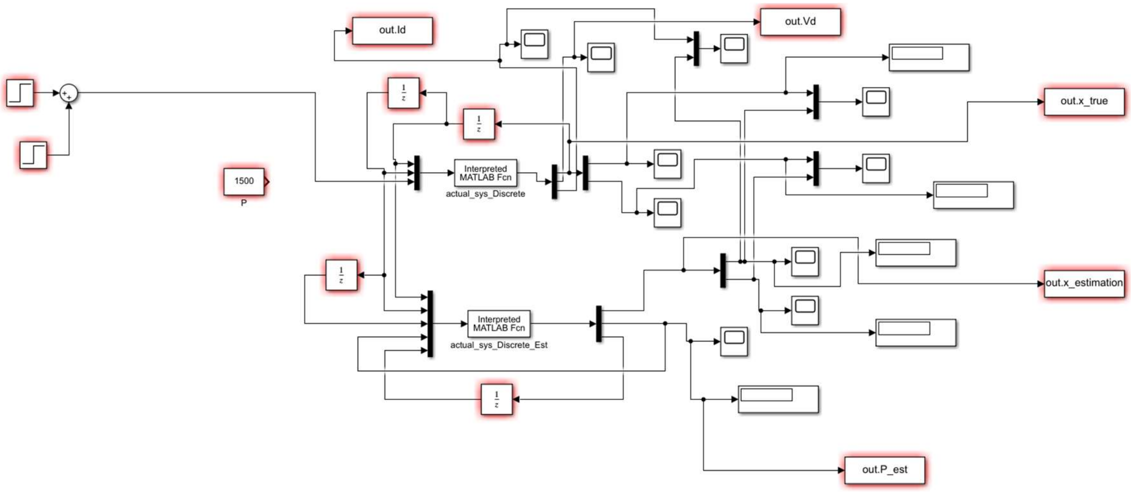

Figure 4.5 Discrete estimation compare.

V. SIMULATIONS:

A. Simulations and Results

In this section, the results of numerical simulations are presented to verify the effectiveness of the proposed adaptive IDA-PBC control under large-scale variations of the constant power load. The unknown constant power load is estimated via the presented I&I-based estimator and the estimated value of the load power is inserted into the control rule. The simulations are performed in MATLAB/SIMULINK with switching frequency of 20kHz, sampling frequency of 2MHz, and the converter parameters as given below.

Table 5.1 Parameters Using in Boost Converter

Parameter	**Symbol**	**Value**
Input Voltage	V_{in}	270V
Output Voltage	V_o	350V
Inductance	L	$805\mu H$
Capacitance	C	$460\ \mu F$
Inductor Resistance	r	0.07Ω
Switching Frequency	f_s	20kHz

The parameters of the desired energy function is assumed as: $r_1 = 7$ and $r_2 = 0$. The parameter of the free design function is assumed as: $\alpha = 0.001$. The simulations are performed under sampling time, $T = 5e - 7$. The initial conditions are selected as: $x(0) = [0 \quad 50]^T$ and $\theta_{est}(0) = 0.01$.

In order to show effectiveness and robustness of the proposed adaptive IDA-PBC controller, we applied a step change to the constant power load. Namely, the load power is changed from 1.5kW to 3kW and the performance of the estimator and the closed-loop system is presented below.

The simulation results are shown in the Figures 2 and 3. In Figure 2, the closed-loop of the system dynamics $x = [i_L \quad V_0]^T$ are shown for different two cases in comparison to the desired closed-loop dynamics $x_d = [i_d \quad V_d]^T$ when the constant power load changes from 1.5KW to 3KW. The black color responds to the desired response $x_d = [i_d \quad V_d]^T$, the blue color responds to the case when the controller knows the true value of the power load, while the green color responds to the case when the controller does not know the true value of the power load where the proposed adaptive controller uses the estimated value of the unknown constant power load. As you see from the performance that the proposed adaptive controller with estimation shows its productivity and successfully preserves the desired closed-loop dynamics.

Figure 3 shows the estimation of the constant power load when it is step changed from 1.5KW to 3KW. As it is clear from the figure that the estimator successfully converges the true values of the unknown power load.

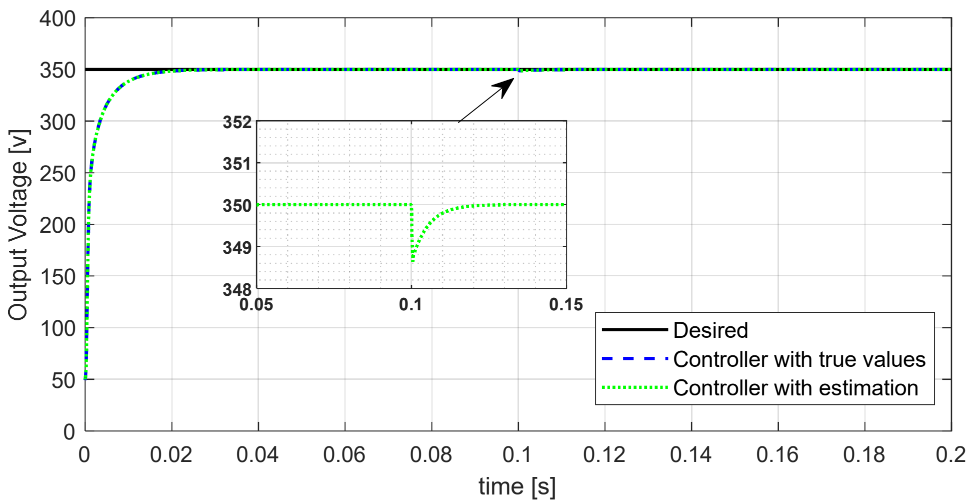

Figure 5.1 Estimation output voltage / time

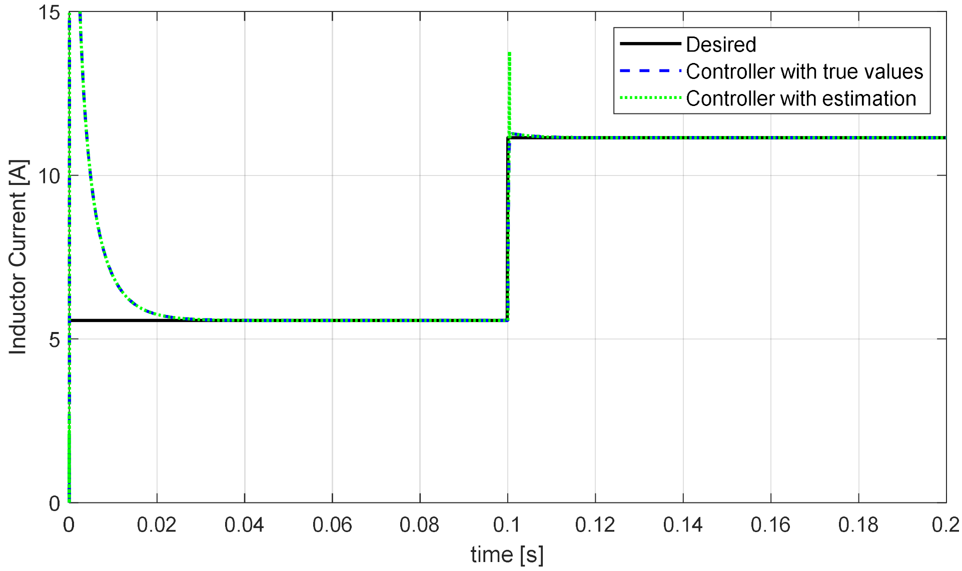

Figure 5.2 Output voltage and inductor current dynamics corresponding to the adaptive IDA-PBC controller and the controller with true values.

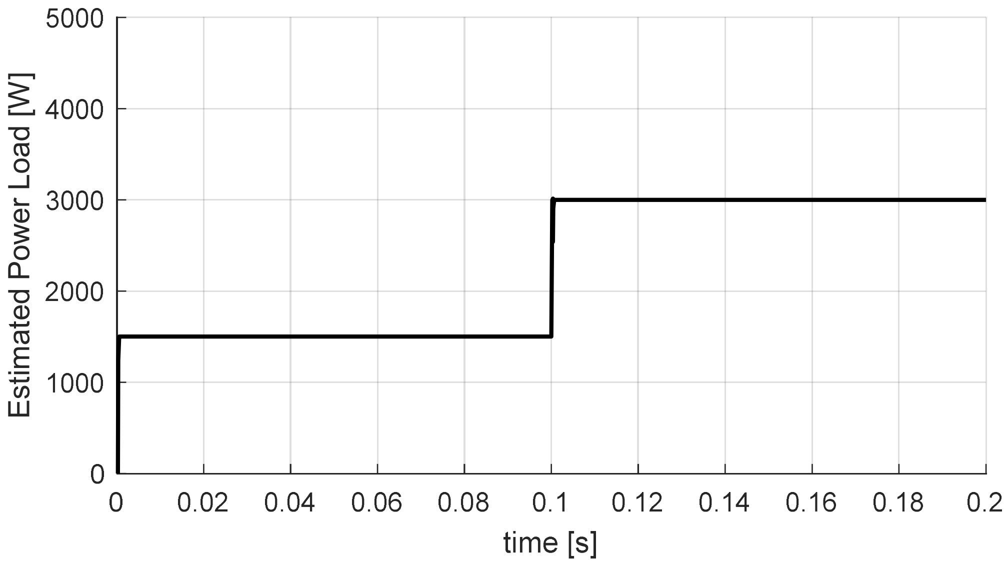

Figure 5.3: The dynamic of the estimated parameter

VI. CONCLUSION

This thesis presents a discrete-time adaptive IDA-PBC controller for the dc-dc boost converter to regulate the output voltage. This thesis considers unknown constant power load where the power load is estimated using I&I-based estimator, which guarantees its asymptotic stability, and the estimated value of the constant power load is inserted to the adaptive controller supplying an automatic tuning mechanism. The proposed adaptive controller is compared to the desired values and also compared to the controller when the constant power load is known. The simulation results show that the proposed adaptive controller successfully preserve the desired dynamics under large-scale variations in the constant power load.

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APPENDICES

A. Actual discrete system for theta

```
function [out]=actual_sys_discrete_theta(inputs)
%iL = x1    vo = x2
x1 = inputs(1);
x2 = inputs(2);
xe1 = inputs(3);
xe2 = inputs(4);
P = inputs(5);
%theta = inputs(6);
x1d = (3*x1 - xe1)/2;
x2d = (3*x2 - xe2)/2;
if x1d<0.001 && x1d>=0
   x1d=0.001;
end
if x2d<0.001 && x2d>=0
   x2d=0.001;
end
r = 0.07;
```

```
L = 805e-6;
C = 460e-6;
%P = 1500;
vi = 270;
vd = 350;
% T = 0.00001;
T = 5e-7;

r1 = 7;
r2 = 0;
Pmax = (vi^2)/(4*r);
id = (vi/(2*r))*(1 - sqrt(1-(P/Pmax)));
ich = P/x2d;
J = [0 -1/(L*C);1/(L*C) 0];
R = [r/(L*L) 0;0 0];
% R = 0;
g = [x2d/L;-x1d/C];
zeta = [vi/L;-ich/C];
gradH = [L*x1d;C*x2d];
kk = (r1*(x1d-id)*x1d + r2*(x2d-vd)*x2d - x2d*ich - (x1d^2)*r + vi*x1d)/(vd*x1d -
x2d*id);
k = kk - 1;
K = k/(L*C);
Jd = [0 (-1/(L*C))-K;(1/(L*C))+K 0];
Rd = [r1/(L*L) 0;0 r2/(C*C)];
gradHd = [L*(x1d-id);C*(x2d-vd)];
d = 1 - (ich/x1d) + (r2*(x2d-vd)-kk*(x1d-id))/(x1d);
% d = inv(transpose(g)*g)*transpose(g)*((Jd-Rd)*gradHd - (J-R)*(gradH +
gradH*theta) - zeta);
x = [x1;x2];
```

```
x_plus = T*[-r/(L*L) -1/(L*C);1/(L*C) 0]*[L*x1d;C*x2d]+ T*[x2d/L;-x1d/C]*d + T*zeta + x;
out= [x_plus;vd;id];
end
```

B. Actual discrete system for estimation

```
function [out]=actual_sys_discrete_Est(inputs)
%iL = x1    vo = x2
x1 = inputs(1);
x2 = inputs(2);
xe1 = inputs(3);
xe2 = inputs(4);
xee1 = inputs(5);
xee2 = inputs(6);
P_est = inputs(7);
theta_hat = inputs(8);
x1d = (3*x1 - xe1)/2;
x2d = (3*x2 - xe2)/2;
x1d_e = (3*xe1 - xee1)/2;
x2d_e = (3*xe2 - xee2)/2;
if x1d<0.001 && x1d>=0
   x1d=0.001;
end
if x2d<0.001 && x2d>=0
   x2d=0.001;
end
r = 0.07;
L = 805e-6;
C = 460e-6;
%P = 1500;
```

```
vi = 270;
vd = 350;
% T = 0.00001;
T = 5e-7;
r1 = 7;
r2 = 0;
Pmax = (vi^2)/(4*r);
id = (vi/(2*r))*(1 - sqrt(1-(P_est/Pmax)));
ich = P_est/x2d;
J = [0 -1/(L*C);1/(L*C) 0];
R = [r/(L*L) 0;0 0];
% R = 0;
g = [x2d/L;-x1d/C];
zeta = [vi/L;-ich/C];
gradH = [L*x1d;C*x2d];
gradH_e = [L*x1d_e;C*x2d_e];
kk = (r1*(x1d-id)*x1d + r2*(x2d-vd)*x2d - x2d*ich - (x1d^2)*r + vi*x1d)/(vd*x1d - x2d*id);
k = kk - 1;
K = k/(L*C);
Jd = [0 (-1/(L*C))-K;(1/(L*C))+K 0];
Rd = [r1/(L*L) 0;0 r2/(C*C)];
gradHd = [L*(x1d-id);C*(x2d-vd)];
d = 1 - (ich/x1d) + (r2*(x2d-vd)-kk*(x1d-id))/(x1d);
x = [x1;x2];
alpha = 0.01;
Beta_x = -alpha*C*x2d/T;
Beta_x_e = -alpha*C*x2d_e/T;
P_est = theta_hat + Beta_x_e*x2;
% d = inv(transpose(g)*g)*transpose(g)*((Jd-Rd)*gradHd - (J-R)*(gradH + gradH*theta_est) - zeta);
```

```
theta_hat_plus = theta_hat + Beta_x_e*x2 - Beta_x*T*(1/C)*(x1d - x1d*d +
(C/T)*x2) + Beta_x*T*(1/(C*x2d))*P_est;

x_plus = T*[-r/(L*L) -1/(L*C);1/(L*C) 0]*[L*x1d;C*x2d] + T*[x2d/L;-x1d/C]*d +
T*zeta + x;

out= [x_plus;P_est;theta_hat_plus];

end
```

RESUME

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