Design and Implementation of a PI-Controlled Lithium Ion Battery Charger with Protection and Monitoring

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ABSTRACT

The importance of power electronics has been growing in recent decades and nowadays it is playing an undeniable important role in our everyday life. One of the most common application of power electronics is switching mode power supply. Those chargers for mobile phones and laptops, power supply for desktop computers, and uninterruptable power supplies are few examples of such converters. In this thesis work, a design and implementation of a PI controller for a switching power supply, that is specifically a Lithium-Ion battery charger, is presented. A brief review of rechargeable batteries and DC-DC converter is provided. Different control techniques for charging the Lithium-Ion battery is studied and constant-current/constant-voltage interpretation is employed in this study. Different topologies for DC-DC power conversion are compared and a half-bridge converter is designed and implemented as a prototype. A comprehensive description of protective mechanism and safety systems is provided. Moreover, a brief description for all the components that are used in this thesis is presented. The design of the control loop and PI compensator are investigated in details. The results of the stability analysis in form of step response and Bode plot are presented in simulations and experimental tests. In the conclusion it is indicated that the proposed digital controller can effectively eliminate the steady-state error with an excellent gain margin and phase margin improvements.

Keywords: Battery Charger, Half-bridge converter, PI controller, Digital Controller.

ÖZ

Güç elektroniğinin önemi son yıllarda artmakta ve günlük yaşamımızda yadsınamaz önemli bir rol oynamaktadır. Güç elektroniğinin en yaygın uygulamalarından biri anahtarlamalı güç kaynağıdır. Cep telefonları ve dizüstü bilgisayarlar için olan şarj cihazları, masaüstü bilgisayarlar için güç kaynağı ve kesintisiz güç kaynakları, bu tür dönüştürücülerin birkaç örneğidir. Bu tez çalışmasında, anahtarlamalı bir güç kaynağı için bir PI denetleyicinin, özellikle bir Lityum-İyon pil şarj cihazına uygun tasarımı ve uygulaması sunulmuştur. İlk olarak, şarj edilebilir piller ve DC-DC dönüştürücü hakkında kısa bir inceleme sağlanmıştır. Daha sonra, lityum-İyon pilin şarj edilmesi için farklı kontrol teknikleri çalışılmış ve bu çalışmada sabit akım / sabit voltaj yorumlaması kullanılmıştır. DC-DC güç dönüşümü için farklı topolojiler karşılaştırılmışve bir yarım köprü dönüştürücü bir prototip olarak tasarlanıp uygulanmıştır. Buna ek olarak, bu tezde bulunan koruyucu mekanizma ve güvenlik sistemlerinin ve kullanılan tüm bileşenlerin kısa bir açıklaması sunulmaktadır. Kontrol döngüsü ve PI kompansatörünün tasarımı ayrıntılı olarak incelenmiştir. Stabilite analizinin adım tepkisi ve Bode grafiği şeklindeki sonuçları simülasyonlarda ve deneysel testlerde sunulmuştur. Sonuç olarak, önerilen dijital denetleyicinin kararlı durum hatasını mükemmel bir kazanç marjı ve faz marjı iyileştirmeleri ile etkili bir şekilde ortadan kaldırabileceği belirtilmiştir.

Anahtar Kelimeler: Pil Şarj Cihazı, Yarım köprü dönüştürücü, PI denetleyici, Dijital Denetleyici

To my wife

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I would like to express my sincere gratitude to my supervisor, Asst. Prof. Dr. Davut Solyali, who has devoted countless of hours on this thesis with his advocate and encouragement. I also wish to thank him for his guidance and great patience throughout the whole process of the thesis. It was not possible to finish this piece of work without the support and help of my supervisor and it is my honor to appreciate it.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Ampere
AC	Alternative Current
AC-DC	Alternative Current to Direct Current
ADC	Analogue to Digital Converter
Ah	Ampere Hour
BJT	Bipolar Junction Transistor
BMS	Battery Management System
C	Capacitance
CAGR	Compound Annual Growth Rate
CC-CV	Constant-Current/Constant Voltage
CMC	Current-Mode Control
CO_2	Carbon-Dioxide
DC	Direct Current
DC-DC	Direct Current to Direct Current
DPWM	Digital Pulse Width Modulator
DSP	Digital Signal Processor
EMI	Electromagnetic Interference
EV	Electric Vehicle
FIR	Finite Impulse Response
H(s)	Continuous Transfer Function
H(Z)	Discrete Transfer Function
Hz	Hertz
IC	Integrated Circuit

I_{fc}	Final Current Value
IGBT	Insulated Gate Bipolar Transistors
IIR	Infinite Impulse Response
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
L	Inductance
LiB	Lithium Ion Battery
Li-Ion	Lithium Ion
LLC	Inductance-Inductance-Capacitance
MCU	Microcontroller Unit
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
NTC	Negative Coefficient Temperature
Op-Amp	Operational Amplifier
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation
R	Resistance
r_C	Capacitor Series Resistance
r_L	Series Resistance with Inductance
SAE	Society of Automotive Engineers
SMPS	Switch-Mode Power Supply
SoC	State of Charge
T_S	Sample Time
UPS	Uninterruptable Power Supply
V	Voltage
V_{max}	Maximum Voltage

VMC	Voltage-Mode Control
V_{nom}	Nominal Voltage

Chapter 1

INTRODUCTION

The use of battery energy is getting more significant due to the growing battery utilization of portable electronic devices, renewable energy sources, electric vehicles, and so on. Nowadays, rechargeable battery has been widely used in various kind of electronic device, such as portable devices, uninterrupted power supply (UPS) system, electrical vehicle, etc [1, 2, 3, 4].

Therefore, battery charger plays a very important role in recharging batteries efficiently and prolonging the battery life. Typically, the constant current constant voltage (CC-CV) charging method is the most popular charging technique due to its simple-design, low cost and safe operation. Traditional chargers are controlled by analog controller that can regulate charge voltage and also perform current control. However, in analog controller, compensation parameters are composed of resistor and capacitors, where the components are highly dependent on temperature variation and with aging issues [5, 6, 7].

For digital control, the compensation parameters are implemented digitally, therefore, temperature and aging issues can be mitigated. Moreover, it has other advantages including implementing complex control methods, robustness to noise, programmable compensator, short-time to market, and on-the-fly parameter tuning. Therefore, in this thesis, a digital controlled charger is implemented to charge the batteries.

Digital controllers are increasingly used especially in complex systems, including power electronics systems, because of their advantages including the ability to perform sophisticated and enhanced control schemes, low power consumption, reliability, reconfiguration flexibility, elimination of component tolerances and ageing, and ease of integration and interface with other digital systems. Of course, there are still some disadvantages/challenges in using digital controllers for analog systems such as DC-DC converters in power electronics including the required high resolution from the digital controller to satisfy the converter tight regulation requirements and the required high speed to satisfy the converter dynamic requirements, which results in cost increase. Fortunately, the digital controllers industry is rapidly advancing, allowing the availability of faster and higher resolutions digital controllers at a lower cost. Therefore, it can be expected that digital controllers will be increasingly used in the future [8, 9].

Designing a digitally controlled and compensated converter system encounters selection and optimization of several blocks including digital feedback compensator, Analog-to-Digital Converter (ADC), Digital Pulse Width Modulator (DPWM), additional digital control algorithms such as dead time control, over current/over voltage protection, and current sharing, and of course the design of the converter power stage itself. In this study, detailed design, simulation, and experimental results of a fully digitally controlled isolated half-bridge converter are presented [10].

The charging characteristics have three stages. The first stage is constant current charging. The second one is constant voltage charging. The third one is floating charge. To perform constant current charging, traditional charging control requires current sensor to feedback the current information. There are various kinds of current sensing techniques, the most commonly used methods include shunt resistor, Hall sensor, and current transformer. However, these three methods will cause additional power loss, cost, and component count to the system. For constant voltage charge and floating charge, the control is realized by output voltage feedback and temperature compensation.

In this study, a digital controlled Switch-mode Power Supply (SMPS) system with the proposed battery charging technique is presented. The proposed charging method can perform constant current constant voltage charging. Safety mechanism such as over voltage protection, inrush current protection and over current detection are designed and implemented in both hardware design and control design.

The SMPS is implemented as half-bridge power converter that is required to charge a battery pack including 10 by 10 Lithium-Ion (Li-Ion) cells from Panasonic NCR18650B. The battery pack and the SMPS are parts of a greater project referred to Efficiency Challenge Electric Vehicle that is held by TÜBİTAK organization each year [11]. TÜBİTAK is short for The Scientific and Technological Research Council of Turkey that is the leading agency for management, funding and conduct of research in Turkey. It was established in 1963 with a mission to advance science and technology, conduct research and support Turkish researchers. The Council is an autonomous institution and is governed by a Scientific Board whose members are selected from prominent scholars from universities, industry and research institutions. According to TÜBİTAK Efficiency Challenge rule book, a series of regulations and rules must be considered for each unit charger and battery pack of each electric vehicle [12]. For example, the continuous charging current of the battery pack must not exceed 10 A. The charging schemes and protective mechanism is required to charge a battery pack for higher power system such as Electric Vehicles (EVs). These concerns needs accurate understanding of rechargeable batteries behavior. Furthermore, after modeling and presenting an equivalent circuit for a Li-Ion battery, it is required to implement the most practical charger for it. Currently, many advance chargers are connected with a Battery Management System (BMS). With a proper communicating between BMS and battery charger, not only operator and battery safety stay intact, but also it extend the life cycle of the battery.

In order to meet all the requirements mentioned above, a precise design with all the protection mechanism is presented in this thesis. The proposed battery charger is able to fully function as an off-line Half-bridge DC-DC converter. It produces the output current and voltage with minimum ripple during the charging. The thesis objective is as follow:

- To design and implement the control mechanism for a half-bridge prototype battery charger
- To develop the battery charger with CC-CV charging technique for 10x10 NCR18650 battery cells
- To determine the most proper DC-DC converter topology for the proposed battery charger
- To design and implement the protection mechanism for the battery charger

In chapter two a brief description of previous works and typical charging method for charging Li-Ion batteries ia presented. The importance of a reliable and efficient battery charger is explained in details. Different suitable topologies for this purpose are mentioned coherently, with a full explanation on their advantages and drawbacks in chapter two and three.

In chapter three, a brief description for control theory and control methods for CC-CV charging scheme are presented. Moreover, analogue control methods, transfer function, and Laplace transform of analogue systems are fully investigated. After comparing all the suitable power converter topologies for the desired purpose, a half-bridge DC-DC converter is used to implement the prototype for the desired battery charger.

The thesis outlines are as follows:

- Investigating the characteristic of the rechargeable batteries specifically Lithium-Ion batteries
- Exploring the charging schemes for a Lithium-Ion battery
- Emphasizing the importance of a proper charging technique
- Addressing the available converter topologies
- Analyzing the circuit of a Half-bridge power converter
- Deriving a model for the Li-Ion battery
- Extracting the transfer function of the battery charger
- Describing the analogue and digital control techniques
- Extracting the transfer function of the battery charger
- Proposing flowchart for charging the battery pack
- Investigating the proposed microcontroller to obtain the best values for PI controller
- Simulating the models, testing the prototype and concluding the results

Chapter 2

LITERATURE REVIEW

In this chapter, main characteristics of a Lithium-Ion(Li-Ion) battery during charging and discharging are discussed. Furthermore, a brief description of past works that have been done on Li-Ion battery chargers and switching-mode power supplies (SMPS) will be presented. Moreover, different topologies of power converters are investigated. In order to understand which topologies are the more suitable in different scenarios, the advantages and drawbacks of them are compared. Related control techniques from most typical to most recent methods are inspected in details.

2.1 Rechargeable Batteries

In past few decades, the rapid growth rate of portable electronic devices including mobile phones, laptop and tablet computers, has established enormous demand in compact and lightweight batteries. In order to lower the costs for users, it is more practical to use rechargeable battery cells in such devices [13]. Additionally, automobile industry is shifting towards Electric Vehicles (EVs) and hybrid vehicles with an accelerating speed rate due to climate change concerns and stricter environmental regulations on reduction emission of Carbon-Dioxide (CO2) [14, 15]. Therefore, it is estimated the global electric vehicle market will reach $1,212.1 billion by 2027, expanding at Compound Annual Growth Rate (CAGR) of 38.1% over the forecast period [16]. EVs will not entirely remove the emission of greenhouse gases, however, they are capable to reduce daily tailpipe emissions [13]. Consequently, it is absolutely necessary to address the supreme importance of battery technology and its effective applications.

2.1.1 Basic Operation of Rechargeable Batteries

In a rechargeable battery, the chemical process that results to power generation includes oxidation process or redox between its working elements [17]. These elements includes the anode, cathode, and the electrolyte that support the common medium for achieving the purpose as shown in figure 1. The result of this process is producing the negative charges at the anode terminal. Furthermore, it forces the electric potential to become negative. At start the system in inherently neutral, because the same amount of positive charges gather near cathode terminal. Regarding the mechanism, positive charges tend to collect towards cathode terminal and it produce the positive potential [18].

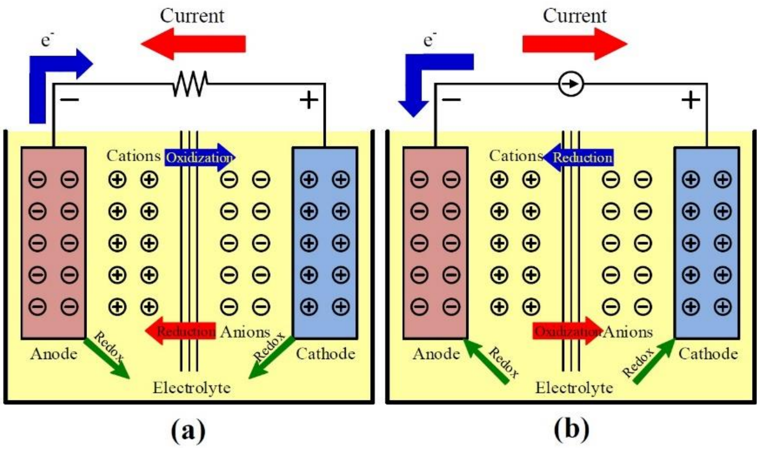

Figure 1. A typical rechargeable battery cell indicating the (a) discharge and (b) charging process.

As it is shown in the figure 1 (a), as a load is connected to the battery, the charges flow from the anode terminal to reaches to the cathode terminal. The battery inherently tend to stay in a steady state condition and this process produces an unbalance state. Furthermore, the charges flow through load and arrive to the other terminal to make the charges of the battery balance at all times. In theory, the new steady state should sustain the voltage across the battery to the same as in the open circuit conditions. However, due to the redox process, the voltage across the battery is always lower the open circuit voltage of the battery. Additionally, as discharging continues, the battery voltage drops until the battery is fully empty [19].

During charging conditions, charge is injected into the battery as indicated in figure 1 (b). If the battery can absorb the charge and store it, it counts as rechargeable battery or secondary cell. In contrast, if the redox process is permanent, the charge flow dissipates in the cell as heat and the battery will explode eventually.

The state of charge (SoC), the capacity (C), the nominal voltage (V_{nom}), and the rated maximum voltage (V_{max}) are the four main parameters used to describe a battery. SoC describes the battery status and is represented in percentage. The zero percent indicates that the battery is fully depleted and hundred percent shows that the battery is at its full level. The capacity outlines the maximum charge a battery can supply to a load when it is fully charge to its complete empty condition. Despite the fact that the capacity represents charge, it is usually measured in amp-hours (Ah) rather than Coulomb. Generally, charging and discharging current of a battery defined by the capacity rather than amps. The nominal voltage is named as the battery`s average voltage as it is discharged with a continuous current from a fully-charged state to a fully –depleted state, while the rated maximum voltage defines the maximum voltage the battery can generates when it is fully-charged [20].

2.1.2 Li-Ion Batteries

Currently, among all different kind of battery cells, in majority of related applications, Li-Ion batteries are dominance. Two main factors that make Li-Ion battery a desirable product are its high-energy storage and power density [17]. These popular batteries can provide higher voltages by adding them in series and producing higher energy with connecting in parallel. Figure 2 shows the comparison between different rechargeable batteries technologies.

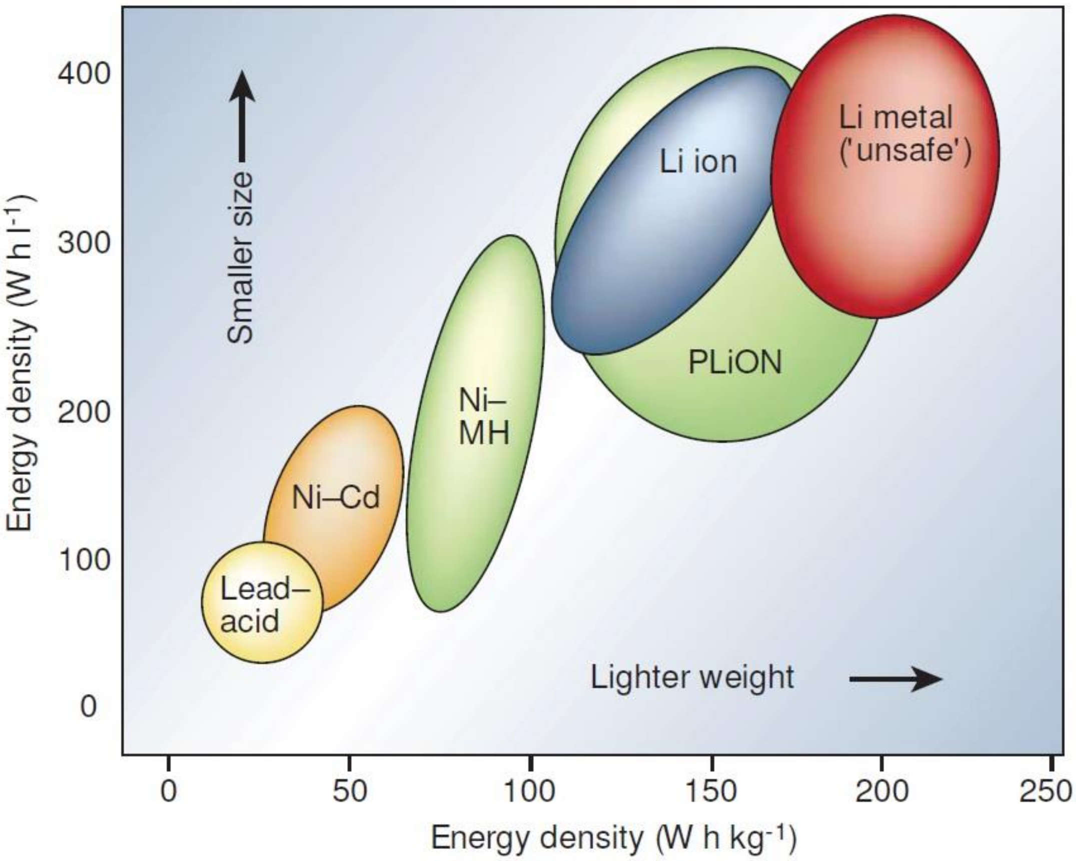

Figure 2. Diagram comparing the rechargeable battery technologies as a function of volumetric and specific energy densities [16].

Despite the fact that Li-Ion have many advantages and flexibilities, they are very sensitive to charging and discharging procedures and conditions such as overcharge and deep discharge. If such a condition continues unattended, it will result in damaging the battery, shortening its life expectancy and in some cases, it even will cause hazardous situations with possible explosion and fire. Therefore, portable applications such as smartphones, tablets, smartwatches, laptop and etc. have to monitor safety condition of the Li-Ion battery and regulate the flow rate of charge or discharge of each cells. A proper Battery Management System (BMS) can fully control the State of Charge (SoC), temperature, voltage and energy capacity of a Li-Ion battery pack. A practical BMS with a well-designed battery charger are required for each Li-Ion battery pack to maintain its life expectancy and manage its safety conditions.

2.2 Battery Charger

Battery charger is a device that is responsible for charging rechargeable batteries such as Li-Ion battery. The role of a battery charger is very important and it must work properly. By properly, it means a well-designed battery charger must either has a background knowledge of the parameters of the charging battery, by a pre-setup data or input data, or it can detect the parameters of the battery with or without the help of the BMS. More advance battery chargers include a BMS part and an SMPS section. These two parts can operate independently, however, for the best performance they must communicate correctly. Charging a battery contains the charging algorithm and the procedure that of implemented and monitored with analogue or digital devices, and the circuit implementation of the algorithm.

2.2.1 Battery Charging Schemes

The process that a battery is charged, referred to as the charging scheme. For charging Li-Ion batteries, several charging techniques have been developed based on their charging time, cell temperature rise, charging efficiency, and cycle life [21]. The two most popular charging methods for charging a rechargeable batteries include pulse charging and Constant-Current Constant-Voltage method (CC-CV) [22]. In this thesis, for charging a given Li-Ion battery pack, the CC-CV control-method is investigated.

2.2.2 The Constant-Current Constant-Voltage (CC-CV) Schemes

The constant-current constant-voltage charging method is the most commonly accepted method for charging Li-Ion batteries [23, 24, 25], where the battery is initially charged with a constant-current method at a range usually between 0.5 C to 1 C that is specified in the datasheet of the battery. For charging a Li-Ion battery pack, it is recommended to use BMS and balancing techniques to equalize all the cells in the pack [26, 27, 28]. Assuming a good BMS and balancing, the CC mode of charging continues until each cell of the Li-Ion battery pack that reaches to 4.2 V (Here for NCR18650B). Consequently, charging proceeds in the CV mode in order to limit the overvoltage stress on the cells. Corresponding to 0.5 C charging, the typical period for a cell to become fully charged from fully-depleted state is about 3.5 h. Although, this time can be much longer if charging is finished below 0.5 C. For example, due to the limited power available from the supply or increasing the cycle life of the Li-Ion battery pack home charging of EVs can take up to 8 h.

In some cases, the CC-CV scheme primarily includes three stages as shown in figure 3. The first phase, stated as the trickle-charge phase, which mainly concerns to test whether the battery is working accordingly or if it is damaged. .This process can be addressed by checking the voltage of the battery when injecting a very low current to the battery. Typically, the current level at this stage is not more than one tenth of the full charging current of the battery (1 C) in order to avoid extra heating if the battery is damaged. Furthermore, if the battery passes this test successfully corresponding to the defined values of the battery parameters, the second charging phase will start. If the system cannot determine the safety status of the battery or it identifies that the battery has been damaged, the whole charging process stops. During the second phase, denoted as the constant current phase, the level of the charging current applied to the battery is increased to a predefined value or the final current value (I_{fc}). During this stage, the voltage level of the battery must be inspected carefully. Until the battery voltage reaches to its rated final level, which approximately is corresponding to 70% battery capacity, the charging procedure is operating in constant current mode. In order to reach 100% capacity, operating in constant current mode corresponds to increasing heat and temperature of the battery more than maximum rated values. Consequently, at this moment the constant-current phase must be terminated.

The third phase correspond to the constant voltage phase and it concerns about keeping the voltage at a constant level. In this phase the battery charger is required to operate in CV mode and constantly checks how much current is flowing to the battery. At this moment, the battery defines how much current it can absorb to continue the charging process. The current level of the battery starts to drop gradually in this phase, and it reaches to approximately 2% of 1C when is fully charged. Then, the constant-voltage phase is terminated and the battery considered fully charged. It is worth mentioning that CC-CV chargers can also include additional phases other than three main phases described previously.

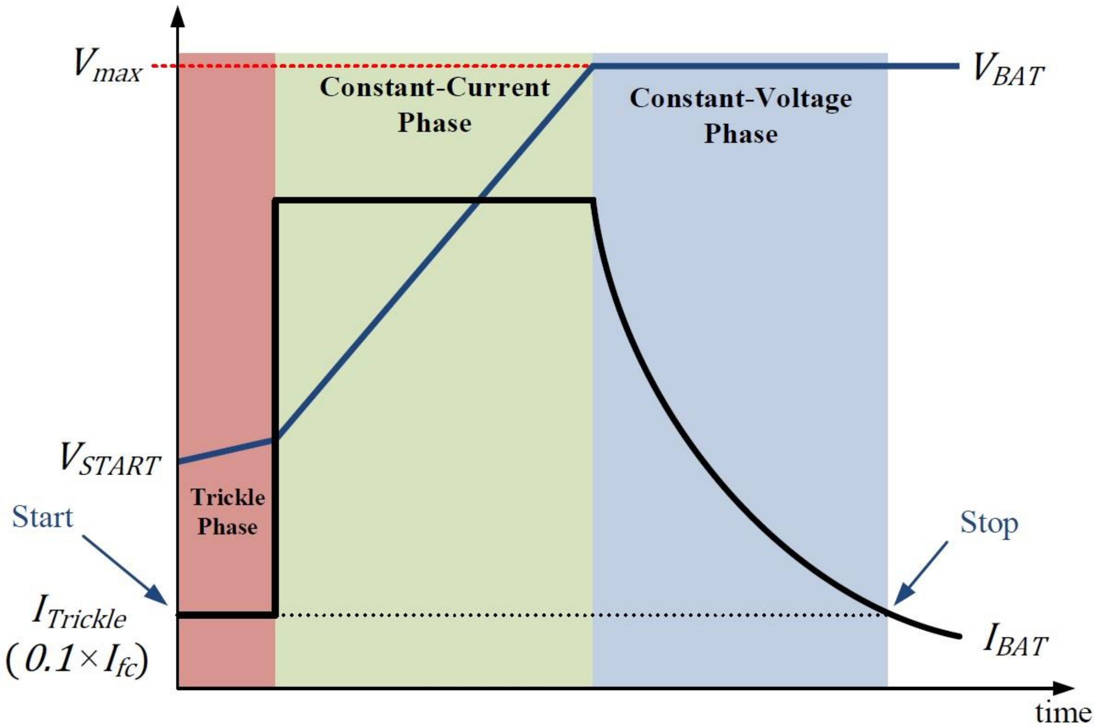

Figure 3. The CC-CV charging scheme showing the three main phases.

In some applications, at the end of the three phases, battery chargers designers add another stage referred to as top-off phase. As the battery is connected to the charger and it is fully charged, in a period of time it loses some of its capacity due to the leakage or loading current. One solution to keep the battery at full-charged stage all the time is to observe the voltage across the battery and when it falls behind a defined value, start charging it in CV mode. Additionally, for testing whether if the battery is connected to the charger correctly or not, in some implementations, a very small test current is applied to the battery to check it [29]. This phase is referred as the short-circuit phase and it must be done before trickle-charge phase. For those batteries that has higher sensitivity to the voltage or current levels during charging like Li-Ion batteries, CC-CV charging plan is very desirable due to its accuracy and efficiency.

Generally, the implementation of CC-CV scheme is more complicated than pulse charges. An example model is shown in figure 4 that can be implemented using simple linear current and voltage sources, that due to the similar behavior of power transistor in voltage-mode control (VMC) and current-mode control (CMC), the size of the power circuit can be reduced further [30]. Although linear implementations advantages from a very straightforward circuit design and control technique, they suffer from poor efficiency. As a result, they dissipate more power in form of heat and are limited by maximum current they can produce. In figure 4 a simple circuit diagram of CC-CV charger is demonstrated. In this case, the VMC and CMC are implemented utilizing a common buck converter topology [29].

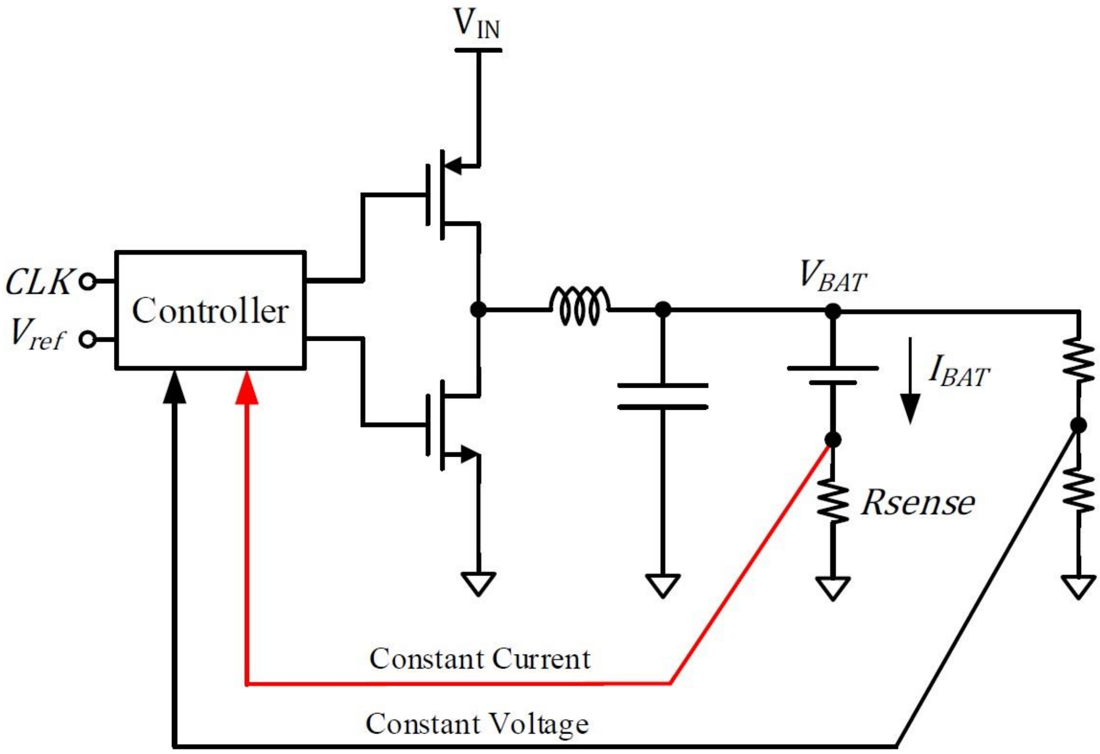

Figure 4. A simple buck converter, capable of sensing voltage and current of the battery.

2.2.3 Battery Capacity Measurement

An important role of battery chargers is capacity measurement of the battery, which is required to estimate the *SoC* of the battery and how much charge is left is it [31]. For battery capacity measurement or fuel gauging, several techniques can be used. One is measuring the battery internal impedance [32]. Other typical methods include inspecting the battery terminal voltage and internal impedance [33], practical explanation of discharge curves, e.g. coupe de fouet technique [34]. Although, coulomb counting is the most common technique in portable devices to measure *SoC* of the battery. The principles of this method based on knowing the initiate value of *SoC*, the capacity of the battery. The remaining charge of the battery can be estimated after measuring how much is consumed previously [35, 36]. In this study, a combination of voltage and impedance measurement of the battery with a different algorithm will be investigated.

2.2.4 Battery Charger For Li-Ion Battery Pack

In many applications, it is required to harness the electrical energy of the battery in a higher voltage and capacity level of a single one. In order to increase the voltage level of a stack of multi cells, one cell must be added in series with them. For increasing the total energy or capacity level, batteries can be added in parallel. Although, the process of charging multi cells connected in series requires more considerations than charging a single battery. According to figure 5 (a), where multiple batteries are charged in constant current mode. Because of the different time constant of each cell during charging, it reacts differently to the charging current. As a result, the required time for each cell to reach its maximum voltage varies. In one hand, if the charging process does not terminate at this point and the charger keeps charging the batteries, it will damage the batteries that already reached to their maximum voltage value by pumping excessive charge to them and increasing their temperature. Eventually, if this process occurs many times, depends on the battery characteristics, it can change the chemical reactions inside the battery and permanently damage the battery. In another hand, if the charger stops when one cell reaches its maximum voltage level, it is not guaranteed that other cells reach to their maximum point as well. One way to solve this difficulty is to use cell-balancing and cell-monitoring as indicated in figure 5 (b) [37]. In this method, BMS monitors the voltage of each individual cell. For instance, in a passive balancing, whenever the voltage level reaches to a certain level, BMS close the charging path of the related cell and send a command signal to the corresponding discharging circuit. The circuit with the help of couple resistor and transistor dissipate the extra charge of the battery. In this interpretation, the charging process can continue until all cells reach their rated maximum voltage without endangering the safety of each independent cell. Passive and active balancing are two most common approaches for balancing a Li-Ion battery pack that is a part of BMS [38, 39].

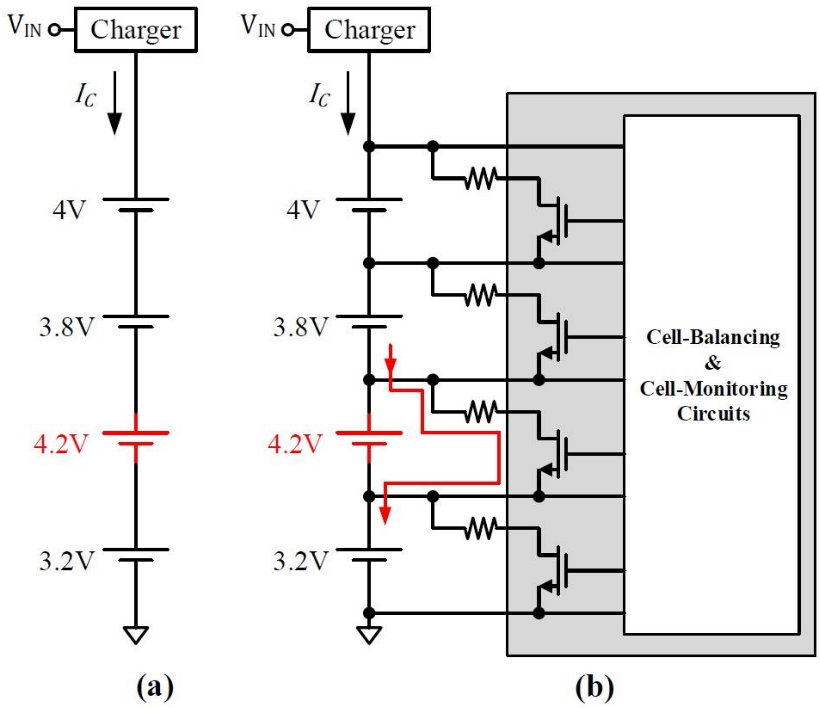

Figure 5. (a) Charging a series stack of batteries with different time constants, (b) Cell-balancing and monitoring for routing the charging current.

2.3 Medium Power AC/DC and DC/DC Converters

Power converters, including rectifiers (AC to DC), inverters (DC to AC), step-down and step-up regulators (DC to DC), and linear regulators are forging a huge part of power electronics applications. Intrinsically, a power electronic equipment consist of a power segment and a control segment. The power section, function as the transfer of energy from the source to the load, contains power electronic switches, electric chokes, transformers, capacitors, fuses, and sometimes resistors. In order to adapt the main supply and the character of the load, a mixture of these components is used to achieve different converter circuits. In these type of converters, it is essential to minimize the energy loss. Therefore, the semiconductor components of the converter are primarily operating in the pulse mode. They may be either controllable such as transistors, thyristors or noncontrollable like diodes. The control block of the apparatus manages the regulating of the components, specially the switching elements. This type of regulation can be achieved based on the information that can be gathered from power section. In most of the time, the critical information are output voltage, load current or current/voltage of a specific component such as a transistor. The control section can operatively consist of a complicated installation of either analogue or digital primary elements assemblies [41, 42].

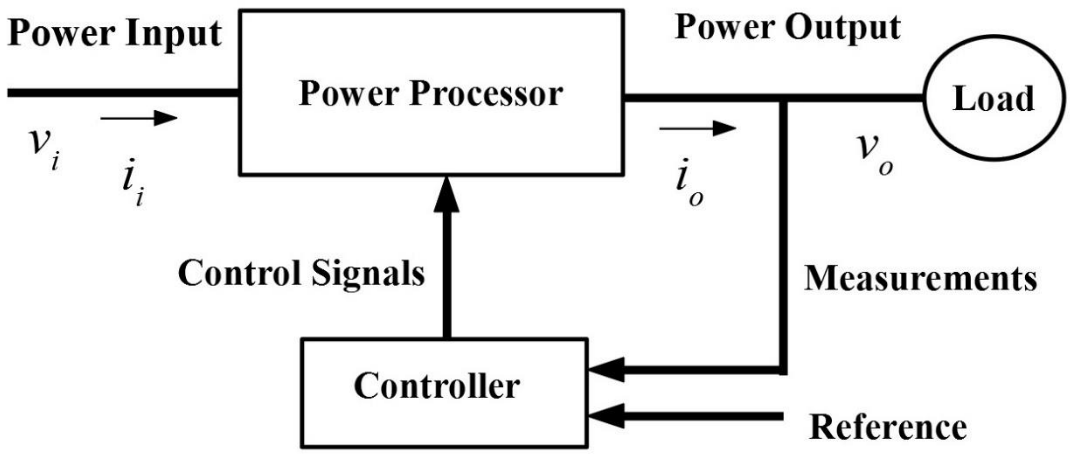

Figure 6. Block diagram of a power electronic system.

As discussed previously, one of the major section in electronic circuits in investigating control and conversion of electrical energy is power electronics. The technology is an essential part of our energy infrastructure, and is a key topic for a vast variety of electricity applications. It is a significant progress tool in managing efficient, accessible energy conversion. In majority of cases, the power electronics design must perform with minimum to almost zero loss in a complete reliable system. The goal to have a system with high efficiency and reliability is only possible with assisting of energy storage devices and switching techniques in electronic circuits.

Generally, in a power electronic system, there are three types of challenges, how to implement the "Hardware" task, algorithm how the "Software" task operates, and the "Interface" task to remove unwanted distortion. The "Hardware" task involves the selection of proper semiconductor switches and the supplementary elements that drive and protect them. In the "Software" task, the challenge is how well the written algorithm and code are operating to achieve the desired conversion. All functional decisions are implemented by adapting switch timing. The "Interface" task concerns about providing the filters or intermediate storage required to meet application needs by including energy storage elements. On contrary to other filters structures, here only simple lossless filters are required.

Compared to a few years ago, improvements in modern semiconductor devices have been significant. Thus, in one hand, power capabilities and ease of control have been increased profoundly. In other hand, costs of finished products have been reduced sharply. These new devices have achieved to new converters that are affordable in a huge number of applications. Additionally, with help of these new devices, implementing of new topologies for power electronics applications are possible now. In order to truly appreciate the potential of these new topologies and applications, it is necessary to investigate the characteristics of available power devices.

In most cases, to facilitate the analysis of converter topologies, power semiconductor devices are considered as ideal switches. The advantage of this approach is that the details of the device operation will completely reveal the basic operation of the circuit. Thus, it is much easier to analyze the power circuit and understand the important characteristics of a converter.

Several types of semiconductor devices with complete controllability feature that most often used in power electronics circuits include bipolar junction transistors (BJTs), metal-oxide-semiconductor field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and gate turn off (GTO) thyristors. In recent years, these mentioned devices have been faced a huge growth in advancement and improvement.

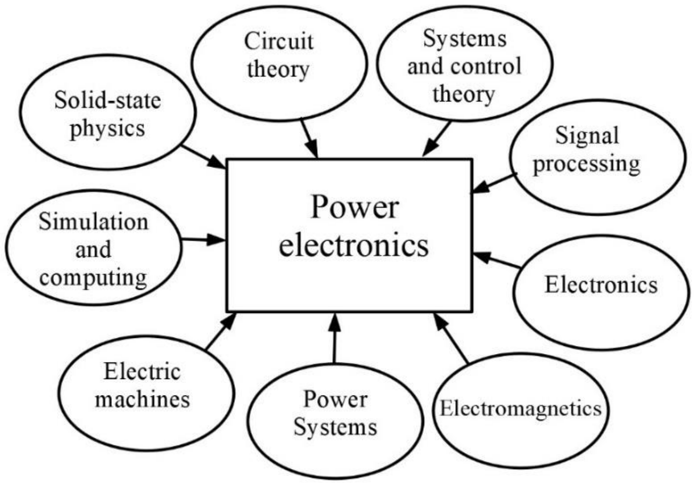

Figure 7. Multidisciplinary nature of power electronics.

Application of power electronics are expanding enormously. Nowadays, producing practical computers, cell phones, cars, airplanes, industrial processes, and a great more numbers of everyday products is unrealizable without utilizing power electronics. Power electronics is essential for alternative energy systems such as wind generators, solar power, fuel cells and others to operate. Technology progressions such as hybrid vehicles, laptop computers, microwave ovens, plasma displays, and hundreds of other innovations were not achievable until progress in power electronics (Figure 7). Although no one can predict the future, power electronics will be at the heart of fundamental energy innovations definitely [45].

As mentioned previously, in recent years the importance of rechargeable batteries in EVs and other portable applications has been growing worldwide. EVs due to their higher efficiency in energy conversion, regenerative braking mechanism, least local emissions, and less acoustic noise and vibrations, as compared to internal combustion engine. One of the notable advantages of EVs compared to conventional cars with combustion engines is that, they operate with considerably lower moving parts. Each of these parts have friction and power loss related to them.

Therefore, there are two solutions for recharging of the batteries according to Society of Automotive Engineers (SAE) charging configurations and rating terminology: One is off-board charger and the other one is on-board charger [30]. The most popular on-board framework contains an active-front-end AC/DC converter following with an isolated DC/DC converter. Initially, an AC/DC converter or rectifier converts AC power to DC power to sustain the middle DC bus. Afterwards, the isolated DC/DC converter will recharge the Li-Ion battery pack of the EV.

2.3.1 Linear Regulator vs Switch-Mode Regulator

DC to DC converters and DC to AC inverters deliver natural interfaces with DC energy sources such as solar cells, thermoelectric generators, fuel cell UPS (Uninterruptible Power Supply). In AC to DC converter, there have been increasing calls for "direct-off-line" switching-mode supply because it takes its power input directly from the ac power lines, without using the rather large low-frequency (60 to50 Hz) isolation transformer that is usually found in linear power supplies. Moreover, industrial motor drives, electrical vehicle power and drive system, robotic technology, inverter systems for renewable energy generation applications, off-line power systems for computers, communication equipment, etc are some examples of commercial applications of power electronics. Many people predict that power electronics will have a huge impact on industrial automation, energy conservation, utility systems, transportation, and environmental protection in twenty-first century.

In fact, application of power electronics covers a range of less than one watt in battery operated portable equipment to more than a few 1,000 W in technologies such as motor drives, rectifier and inverters that interact DC transmission line to the AC utility power system. In consideration of that efficiency in all power processing application is playing an undeniably important role, the key element is switching converter. Because it is not possible to achieve high energy efficiency with linear electronics where the semiconductor devices are operated in their active (linear) region, in switching converters, the semiconductor devices such as transistors and thyristors work as switched mode. Simply when a switch works in the off state, its current is near to zero, and when it functions in on state, its voltage drop is very small. In both cases, its power dissipation is low. For instance, if the switching device is ideal, the power dissipation is also zero. Changing in frequency can easily affect efficiency considering that real devices absorb some power when transition between on and off states and vice versa. To summarize, by utilizing new switching devices, modern control techniques, new circuit topologies and new ways of manufacturing, one can sufficiently improve efficiency of a switched mode power supply.

2.3.2 General Tendency in Modern Power Supplies

There are two different inclination towards electronic power supplies that are one of the most important parts of power electronic circuits. One of them is exploiting microprocessors, memory chips, and other advanced digital circuits in order to increase performance and efficiency at very low voltage. In these types of power supplies, the purpose is to feed the low voltage load efficiently with minimum tolerance in voltage output. To understand the issue, assume the load supposed to receive 100 A current with a magnitude of 1 V voltage. It is quite challenging to regulate the voltage within a few nanoseconds through noises and disturbances.

In the other hand, the growing rate of portable devises with rechargeable batteries is enormous. The two main incentives to manufacture commercial power supplies for these devices and many other consumer products are increasing efficiency and lowering the costs. Current challenge to encounter is losses in low-cost power supplies. For example, in low-end power supplies and battery chargers, the power electronic apparatuses drain energy even when their load is off. Therefore, one who designs these kind of power supplies must appreciate these issues and emphasizes on saving energy and minimizing the costs. EnergyStar® program is good example of efficiency standards for a wide range of low-end power supplies that proposes a series of regulations and requirements to help consumers, businesses, and industry save money and protect the environment through the adoption of energy-efficient products and practices.

Prior to 1960s and 1970s, power supplies used to be large and heavy. The main reason was using bulky off-line transformers and rectifiers with the same frequency as ac line frequency. The development of power electronic dc-dc conversion circuits for power supplies occurred due to the restrictions and requirements of aerospace industry and applications for using dc sources. Modern power supplies are designed in such a way that can regulate multiple levels of ac-dc or dc-dc voltages, without utilizing direct transformation. In another word, a switch-mode power supply compared to linear power supplies is significantly lighter and much less expensive. For example, in a personal computer, there are usually multiple different required voltage levels, three different 5 V supplies, a 3.3 V supply, two 12 V supplies, a -12V supply, a 24 V supply, and a separate converter for 1 V delivery to the microprocessor. Moreover, there power supplies for video display or peripheral devices. Merely a switch-mode power supply can pluck for such complicated conditions with reasonable costs.

Tendency towards high reliability, low cost and reducing the size of the semiconductor devices such as MOSFET or IGBT in switch-mode power supply technologies has been reached to its peak. For example, consider a battery charger for a mobile phone that can provide a 5 V power supply, with only 15 cm^3 that might continue to work for more than 1,000,000 h (more than a century). Compared to those old linear power supplies, this achievement is quite remarkable. An interesting quandary in this type of power supply is the comparison between size of the ac line cord to plug it and power supply itself. With help of new innovative concept such as integrating a power supply within a connection cable, this problem will be solved in future.

Increasing demands in the automotive and telecommunications industries as well as in markets for portable equipment motivate device technology for power supplies. The automotive industry is shifting to higher voltage levels to manage expanding electric power demands. In this industry, power conversion systems not only must have high efficiency in performance and cost, but also they need to be strong enough in order to continue to function properly through high vibration and wide temperature range.

To achieve global communication in almost everywhere, complex equipment are required. Throughout much of the world, access to electrical supplies that are reliable and consistent are limited and it requires special effort to tackle this challenge. Although, voltage swings for domestic ac supply is North America are often ±5 around a nominal value, in many developing nations the swing can be ±25 when power is available. Equipment of power electronics in communication applications are required to support these swings. Additionally, they must be able to work with wide range of possible sources. To satisfy the need for the immense size of worldwide markets, there must be flexible-source equipment. To address the problem correctly, small batteries and power electronic equipment must design with maximum performance and minimal energy requirements.

2.3.3 Topologies of Switching-Mode Power Supply

A major step that must be studied carefully before designing a switch-mode power supply is that which basic topology matches for your purpose considering all the constraints that you may have. The term *topology* means the blueprint of the power components within the switch-mode power supply system. With knowing the topology type, one can understand the safety level of the system and the rating input/output power of it. Moreover, this decision clarifies an important issue, the tradeoffs of cost versus performance of the converter [48]. Each topology has its own advantages and drawbacks. One topology may have a lower parts cost, however, it can only provide a limited amount of power due to its inherent design. Another one can work with higher voltage and current at the expense of increasing the costs, and so on. In most of cases, more than one topology will operate for any application, although, only one of the options may offer the best performance at the required cost. To summary the value of each basic topology comparing other ones, the table 1 is given.

Table 1. Comparison between different topologies

Topology	**Power Range (W)**	**V_{in}(dc) Range**	**In/Out Isolation**	**Typical Efficiency (%)**	**Relative Parts Cost**
Buck	0-1000	5-40	No	78	1.0
Boost	0-150	5-40	No	80	1.0
Buck-boost	0-150	5-40	No	80	1.0
Forward	0-150	5-500	Yes	78	1.4
Flyback	0-150	5-500	Yes	80	1.2
Push-pull	100-500	5-500	Yes	75	2.0
Half-Bridge	100-500	50-1000	Yes	75	2.2
Full-bridge	400-2000+	50-1000	Yes	73	2.5

Main decision factors that need to be considered prior to designing a converter can be summarized as follow:

- Transformer isolation necessity
- Maximum input voltage that appears across the primary winding of the transformer or inductor
- Peak current that flows through the power switches
- Maximum operating voltage across the power switches

In some applications such as *board-level* converters, it is not necessary to use a transformer for isolation. These boards are placed in an intermediate level, where the bus voltage of the power systems has already regulated and then distributed throughout the system and each board within the system has its own power supplies. The supplied bus voltage level is at a safe level and it is not considered fatal to the operator of the board or destructive to the board components. It is highly recommended that in most switch-mode power supply applications working with input DC voltage higher than 40 V, a transformer isolation will be considered in the system. Because, compared to level of safety that it adds to the converter, the cost is minimal.

To obtain how much peak current is flowing through the power switches, one way is to calculate the amount of voltage appearing across the primary side of the isolation transformer. Generally, since the switch-mode power supplies tend to have a high efficiency, the input power assumes to be equal to output power. Therefore, for a constant power load, with decreasing the input voltage, the input current will increase automatically.

Voltage spikes are very common within switch-mode power supplies. With increasing the maximum voltage appearing across the power transistor during switching time, the possibility that those voltage spikes exceed safe operation areas of the power switch and damage it will boost. In figure 8, the relationship between output power and DC input voltage where different topologies are usually used in the industry is indicated.

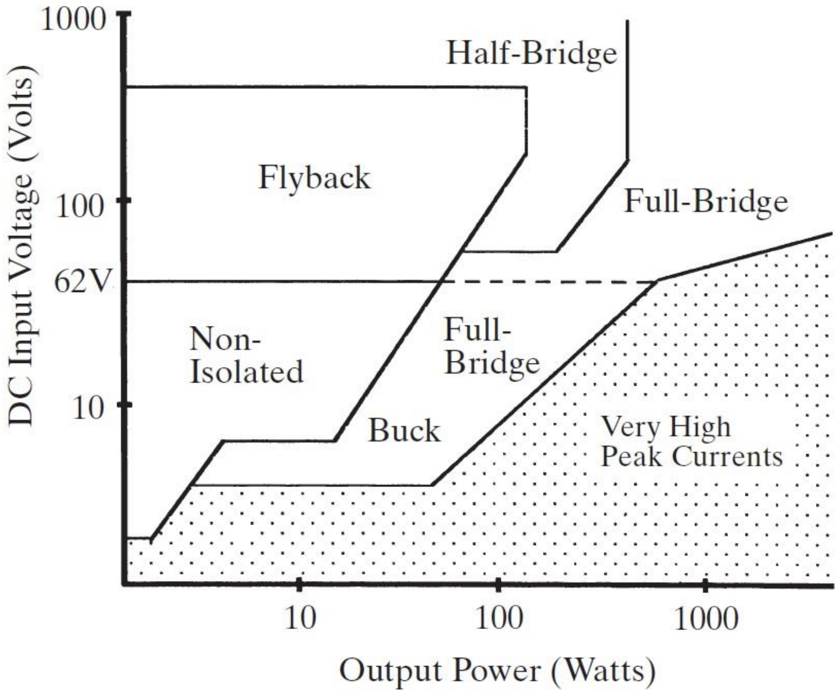

Figure 8. Where various topologies are used.

According to the mode of control of the output voltage, another classification can be derived (figure 9). The self-oscillating converters are simple from the design point of view, but their efficiency factor η is the lowest. They are mainly used for supplying small loads (up to several tens of watts). The widest application today finds DC/DC converters using pulse width modulation (PWM). The output voltage is controlled by varying the ratio of the on and off times of the switch with a constant frequency of switching.

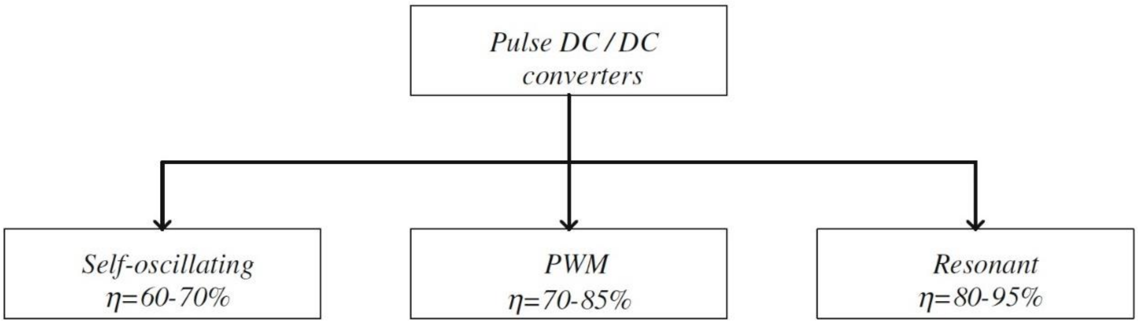

Figure 9. Classification according to the mode of control.

One classification for different kind of DC/DC converters is to sort them based on their galvanic isolation condition (the input and the output are separated by a transformer or an optocoupler). The classification of these two groups is indicated in figure 10, depending on their isolation level. However, all these devices can be divided into four groups: push-pull (symmetric), forward (direct), flyback (indirect), and Ćuk converters [49].

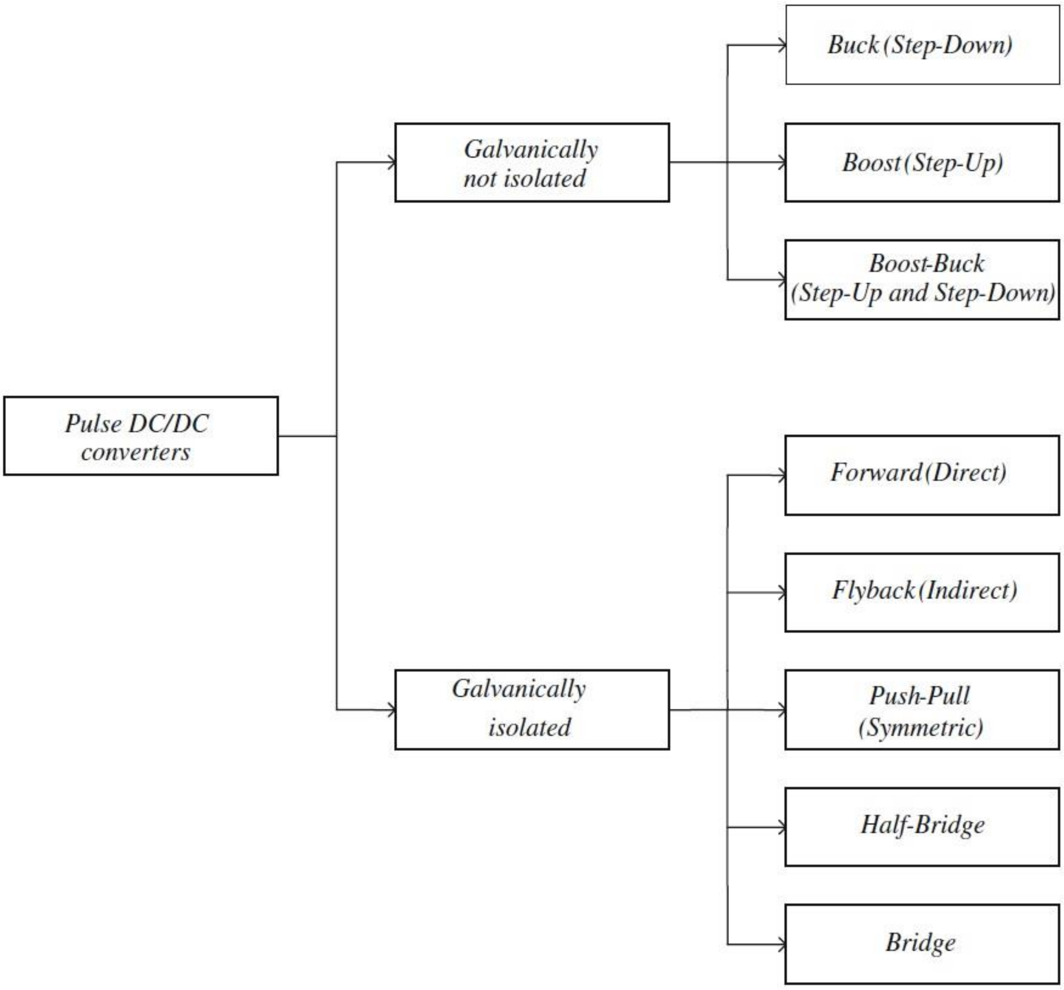

Figure 10. Classification of pulse DC/DC converters based of the isolation condition.

Chapter 3

METHODOLOGY

In this chapter, the process of designing and implementing of the battery charger is investigated. Furthermore, the procedure of components preference, control techniques and protection methods is explored. The main focus is on CC-CV charging and digital control of the converter.

3.1 A Brief Review of Control Systems

Nowadays, control systems are everywhere and they include wide range of applications, from turning a light in the room by your will to pushing the gas pedal to accelerate, from a simple toy for children to a more complex unit in military and aerospace. The latter one usually referred to automatic control systems, that can operates its task without interference of any operator. Automatic control systems classifies as the highly intelligent and complicated to the absurdly simple [50].

3.1.1 Open-loop and Closed-loop Systems

Systems can either run in open-loop or closed-loop conditions. In open-loop systems, a control signal as the input can be linked to the output with a specific relationship. The input signal is independent from the output action. As it is indicated in the figure 11, the output *y* relates to the input *u* by a gain factor *k*. This systems is often referred to as *the plant* in the literature and is noted *H* [51].

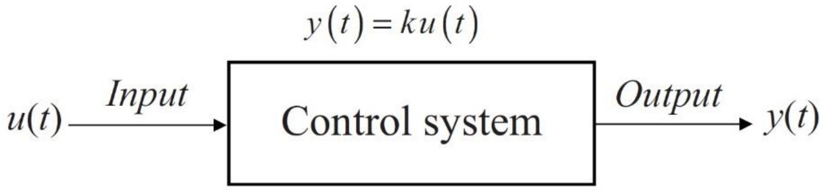

Figure 11. simple representation of a system where the output depends on the input by a factor k.

3.1.2 Closed-loop Control

A closed-loop control system has the ability to measure its own output and then based on that it can decide the best input. Closed-loop control has some strong advantages, however, in some cases it is much difficult to design and implement it. It is a popular method of solving engineering problems because with a polished design the drawbacks can be ignored compared to its powerful advantages. Figure 12 shows a simple closed-loop system that is common in digital control techniques.

An engineer who wishes to design a closed-loop control system, shall face many difficulties. These system, inherently, offer many advantages compared to open-loop system, although, analyzing and designing them need extra knowledge about the behavior and physics of the plant, sensors, actuators and controller.

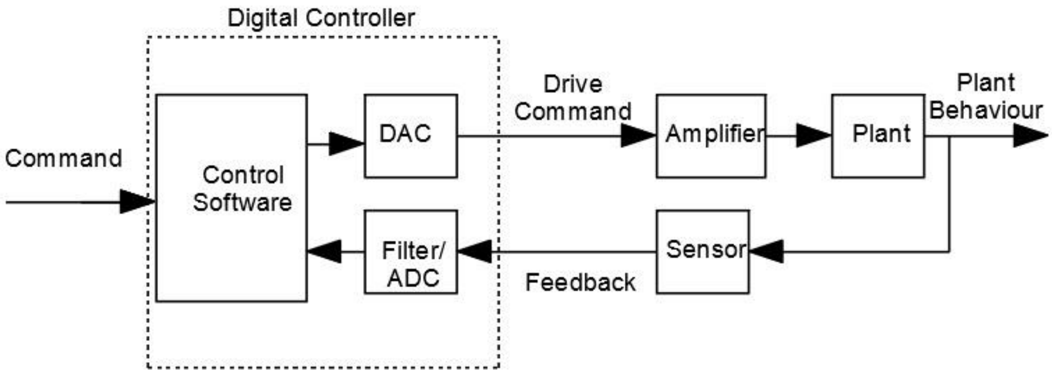

Figure 12. A generic control system.

In order to design a perfect controller for a closed-loop system, accurate and reliable measurement of plant`s output and sensors are required. With a an accurate sensor and well-behaving plant, the controller can follow the error signal and effectively minimize or remove it through external disturbances that perturb the plant`s output. A proper feedback control system can accelerate the transient response of the system, even if the plant can respond robustly to drive but it is slow by its nature. Additionally, with respect to sensor limitation and inevitable gain from feedback loop, controllers are useful [50].

The most considerable drawback of systems with feedback is their instability. A proper system supposed to follow its command signal and stay in the correct position with a negligible tolerance. An incorrect closed-loop control can impose oscillation to a perfectly stable plant and transform it to an unstable system. These instability disadvantages of closed-loop systems can be avoided with a careful design. In the end, considering all difficulties brought by closed-loop systems such as the costs of the controllers, development time, and instability issue, the advantages outweigh the drawbacks. The most important factor to use a feedback control is that, it provides the desired outcome at the reasonable expense.

3.2 Analogue Control

An analogue signal is a signal that is continuous in both time and amplitude. An analogue controller is a circuit that has an analogue desired output signal from an analogue sensor. For instance, an Op-Amp circuit can operate as an analogue regulator. In fact, many different compensators can be implemented by manipulating Op-Amp circuits.

In most cases in order to analyze analogue circuit, the transfer function of the system can be used. The transfer function indicates the behavior of the output signal of a system related to its input signal. Generally, to extract a transfer function for an analogue system, the Laplace transform of the impulse response is exploit. In another word, by applying Laplace transform to the input signal and output signal of the system, the transfer function can be addressed very straightforward (Figure 13).

3.2.1 The Transfer Function of a Continuous-Time System

A control system can be analyzed straightforward based on relationship between its output, y, and its input u. This model of analysis indicates the effect of a certain amount of changes in input signal on output signal over time. To be able to derive mathematical model for a system that can describe it correctly, the usage of differential equations is required. A differential equation uses the notion of derivative, a mathematical tool that measures the rate of change of a function when its input varies by a certain quantity.

3.2.2 Laplace Transform

Generally, a system can be defined by its differential equations. These differential equations can adequately describe the behavior of a system. Since solving linear differential equations gets more difficult based on its order, other alternatives mathematical tools are preferred. The Laplace transform, noted L, is a mathematical tool that converts complex linear differential equations of any order into a simpler set of algebraic expressions. Once the solution of these algebraic equations is found, the expression can be transformed back to the time domain using the inverse Laplace transform, denoted $\mathcal{L}^{-1}$ [52]. Equation (1) is describing the Laplace transform:

$$\mathcal{L}\{x(t)\} = \int_0^\infty x(t)e^{-st}\,dt \qquad (1)$$

In electrical and electronic circuit analysis, the Laplace transform can be utilized to process periodic or non-periodic time-domain functions to map them into a two-dimensional plan, the complex frequency domain. In this domain, the new expressions, now noted U(s) and Y(s), are a function of a complex argument $s = \sigma + j\omega$. The resulting function of *s*, now features an argument (the phase) and a magnitude (the amplitude). Figure 3.3 represents a simple transformation of an analogue system, from time domain to *s* domain:

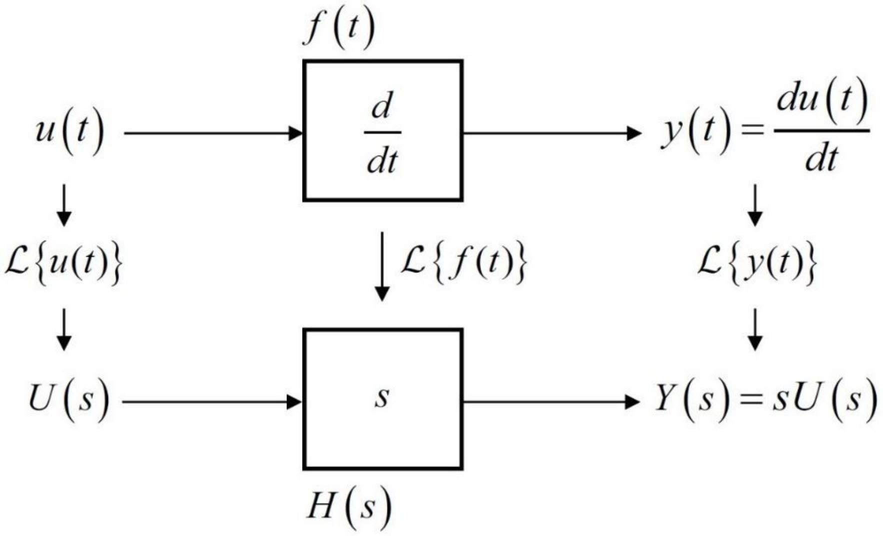

Figure 13. An example of an analogue control circuit.

In order to obtain the transfer function of a system, one way is to transform all the components in the time domain to s-domain. For instance, transfer function of the capacitance *C* can be represented by 1/s*C*, the inductance *L* by s*L* and the resistance stays the same since it is independent of the frequency. A simple transfer function in electronic circuit is indicated in figure 14.

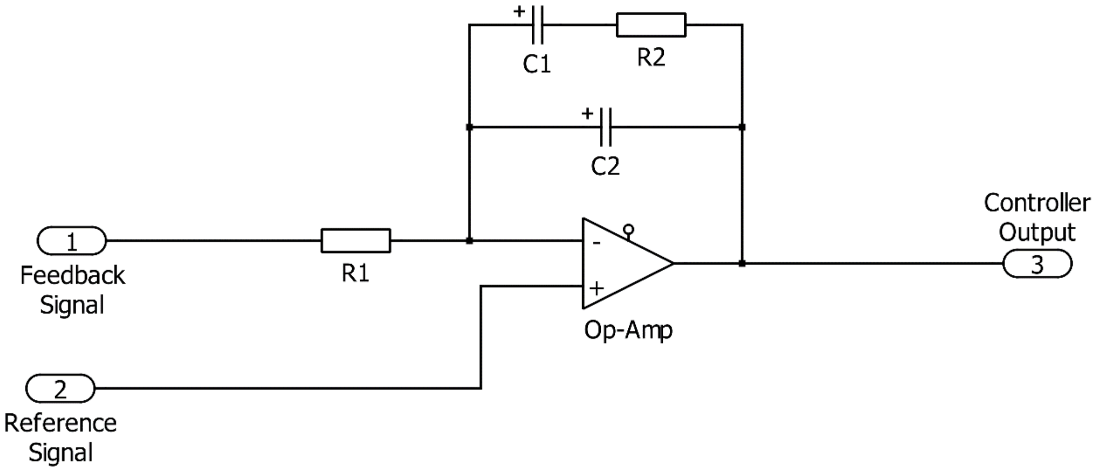

Figure 14. Representation of the transfer function.

3.2.3 Analogue Regulators Types

The most popular regulators for analogue control includes “P” (Proportional), “PI” (Proportional-Integral), “PD” (Proportional-Derivative), “PID (Proportional-Integral-Derivative) regulators. Others common analogue compensators are Lead regulator, Lag regulator, and Lead-Lag regulator. PID controllers are generally being used in closed-loop systems. In a P-type regulator, the output signal is proportional to the input signal. A PI-type has also an integrating part as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t')dt' \tag{2}$$

where *e(t)* is the error signal, *u(t)* is the output signal and K_p and K_i are constants. The main reason for the integrator part is to remove the steady-state error. In a PD-type compensator, the control signal can be approached as follows:

$$u(t) = K_p e(t) + K_d \frac{\partial\{e(t)\}}{\partial t} \tag{3}$$

where K_p and K_d are constants. The purpose of using the derivative part is to improve the stability and transient time of the system. The PID controller is the combination of all three types and can be shown as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t')dt' + K_d \frac{\partial\{e(t)\}}{\partial t} \qquad (4)$$

where K_p , K_i and K_d are constant.

To limit the gain at high frequencies, in most of the cases a first order low-pass filter is also added to the system in cascade with controller. The order of all mentioned regulators are less or equal to 2 [52].

3.2.4 PID Control Action

The performance of the PID regulator can be simulated in terms of the transient error after being excited with a step change as shown in figure 15.

The figure 15 indicates that at time t_1, how control loop error reacts to the step change of the set-point. The contribution of the proportional term is directly connected to the instantaneous loop error. The integral term is responsible for accumulated error history as indicated as shaded area in the lower plot. The derivative term contributes a control error which is proportional to a tangential line to the error curve with respect to the time. In another word, the derivative term defines the rate of change of the error and how fast it is changing with respect to time; and the integral term aims the steady-state error with constantly integrating the past errors prior to current time [53].

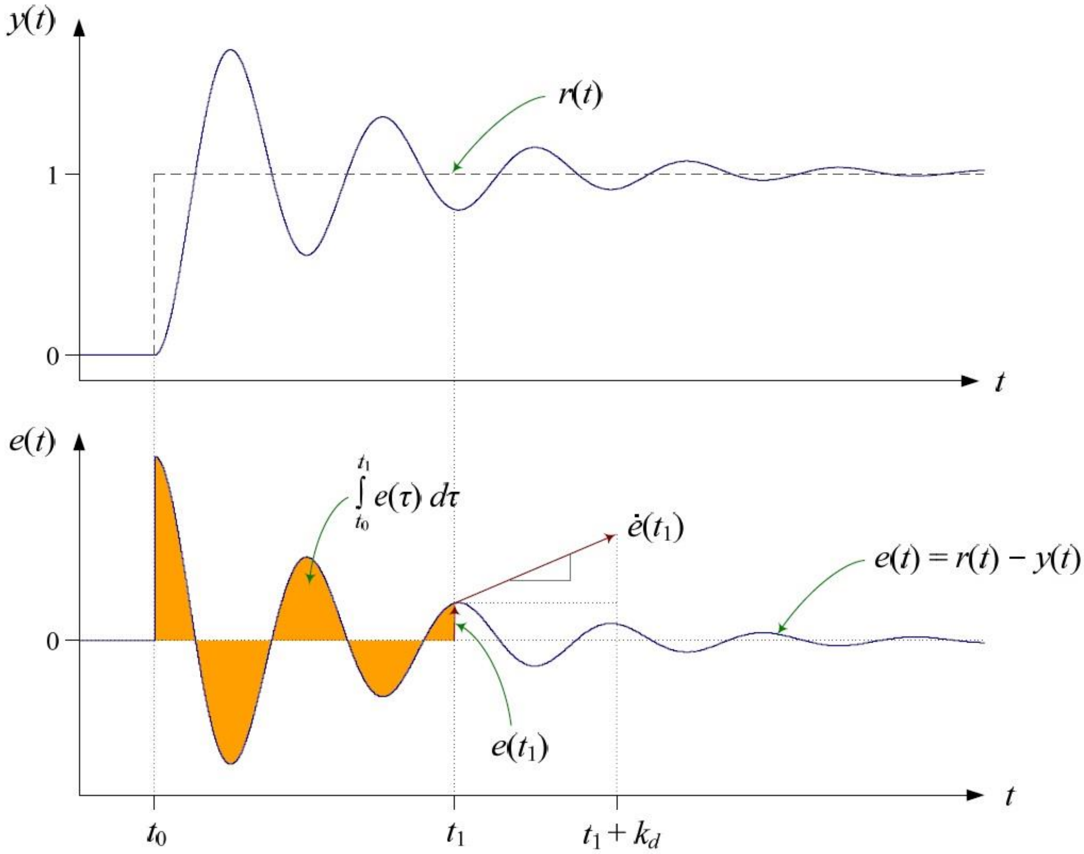

Figure 15. Operation of a PID controller following a step change of set-point.

Figure 16 indicates a step change in a low-power DC-DC converter. The system is excited with 1 V of step set-point. In some cases, finding the constants of PID controller, in other words tuning the PID, is a difficult task. A good PID tuning starts with finding the optimum values for K_p , K_i and K_d constants, which effectively provides a minimum steady state error, rise time and overshoot. One can say, tuning a perfect PID controller for a complex system can be considered as an art work. In many literatures using the Zeigler-Nichols tuning method is proposed. However, due to constraints and limitations of some systems, that method is not feasible. For example, in a power electronics converter, increasing the K_p to reach to the oscillation point is equal to compromise the safety of the operator and components and it can put the components of the converter at risk of heating and burning. There are also some other methods with try and error to find the best balance of the three gain terms.

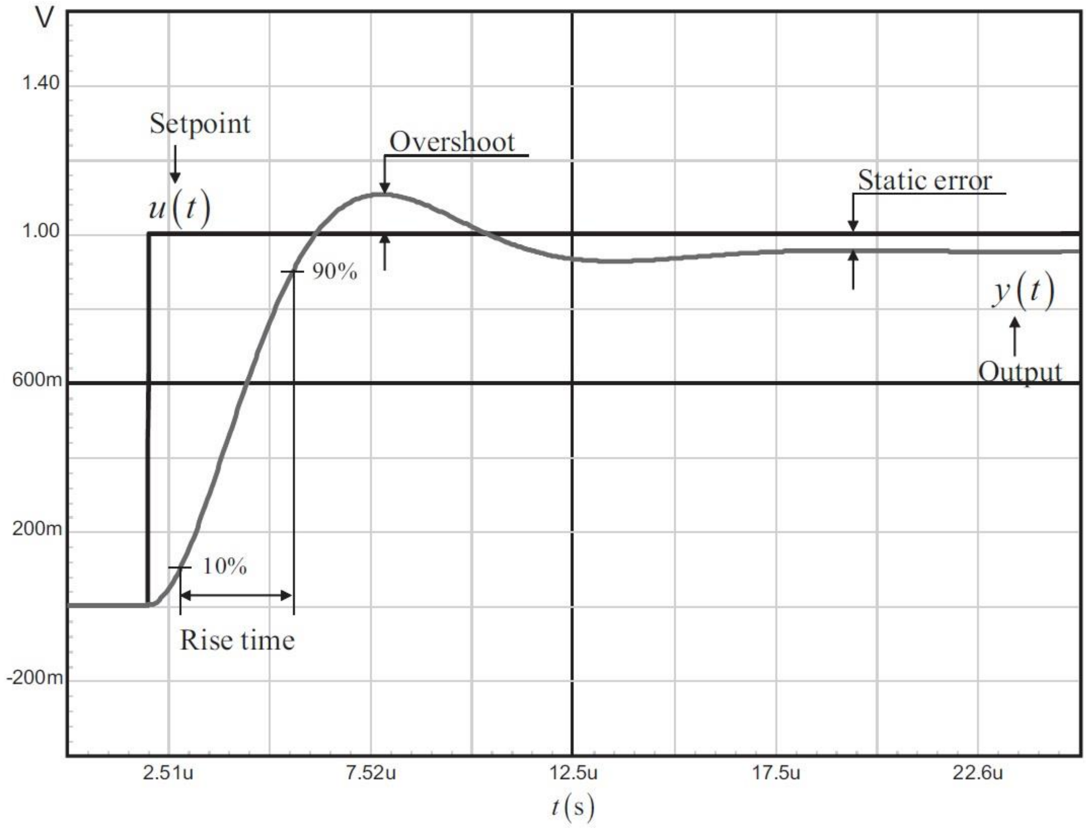

Figure 16. Rise time, overshoot and static error of a control system considering a step response of 1 V.

3.3 Digital Control

A digital signal is referred to a discrete-time signal. In this thesis, a digital control system refers to a system that appreciate a digital controller inside it. Each Digital controller measures the output signal once each cycle and hold it constant until the next cycle. This process called sample-and-hold process and practically it is implementing in each digital controller [44]. .Same as analogue systems, a digital control system has a compensator, however, unlike the analogue controller it is not continuous in time. The real world data acquisition in digital systems can achieved by using Analogue to Digital Converter (ADC) units. Each ADC unit has its own sampling rate and resolution.

Similar to analogue systems, in digital control a transfer function can describe the system. This transfer function called z-transform and is presented as follow:

$$Z\{x[n]\} = \sum_{n=0}^{\infty} x[n]z^{-n} \tag{5}$$

The transfer function of a digital control system corresponds to z-transform of its output excited by an impulse input. A digital control system is stable if all poles of its transfer function are inside the unity circle. Digital filters that are depending on their transfer function include Infinite Impulse Response filter (IIR-filter) and Finite Impulse Response filter (FIR-filter).

3.3.1 FIR-filter

FIR-filter or finite impulse response filters are digital filters that after stimulating by a unit impulse, their output diminish gradually and reaches to zero again [44]. Generally, FIR-filters are implemented as summation of previous input values as indicated in figure 17. Implementing the digital filter in this way have the following advantages and drawbacks:

- Since the poles of the filters are located within the unit circle, the FIR-filters are always stable
- FIR-filters can be designed to have constant phase and group delay
- Round-off errors can be made relatively small since previous output signals are not used in the calculations
- To obtain the desired outcome, FIR-filters require many filter coefficients to converge

$$y[n] = \sum_{k=0}^{N} h_k x[n-k] \tag{6}$$

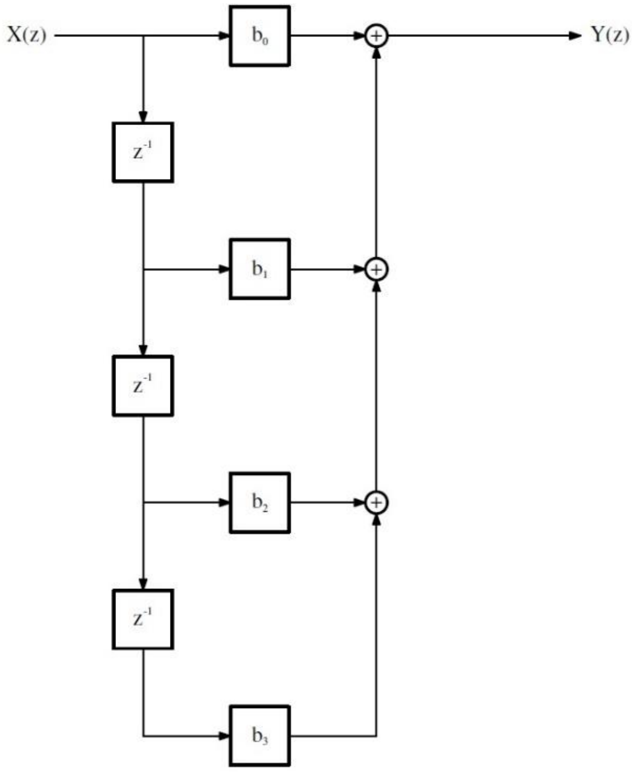

Figure 17. Representation of FIR-filter where X(z) is the input signal and Y(z) is the output signal in the z-domain.

3.3.2 IIR-filter

IIR-filters are digital filters with an infinite impulse response. In another word, if these filter are triggered with an unit impulse, their reactions are not required to converge to zero [44]. This important property provides the integration capability of the system. It means the output of these filter are dependent of previous output as well.

$$y[n] = \frac{1}{a_0}\left(\sum_{k=0}^{N} b_k\, x[n-k] - \sum_{k=1}^{N} a_k\, y[n-k]\right) \tag{7}$$

where a_k and b_k are filter coefficients, N is the order of the filter, $x[.]$ is the input signal and $y[.]$ is the output signal. The filter coefficient a_0 defines the total gain and generally it is 1.

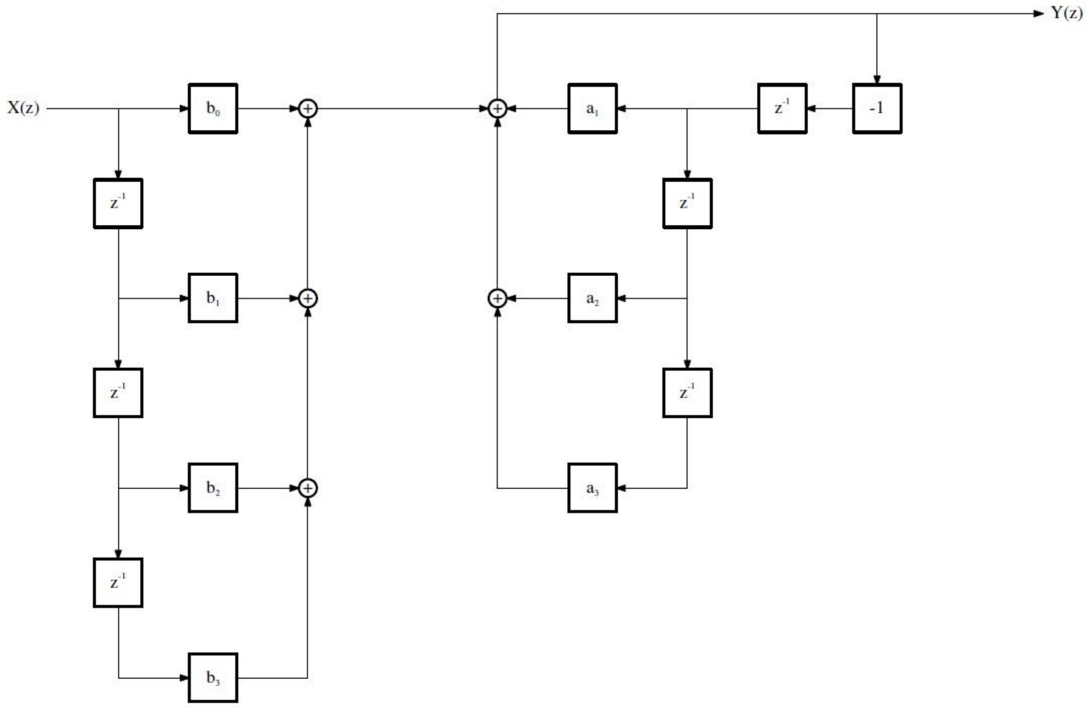

Figure 18. Representation of IIR-filter with a0 set to 1 where X(z) is the input signal and Y(z) is the output signal in the z-domain.

IIR-filter have the following advantages and drawbacks:

- Generally compared to FIR-filters, with IIR-filters less coefficients are required for a desired response
- IIR-filters are better options to approach similar frequency response as analogue filters
- As they may have poles outside of the unity circle, they are less unstable compared to FIR-filters
- Round-off errors can be significant since previous output signals are used

3.4 Digital Control Technique in CC-CV Method

Initially, the voltage-mode and current-mode control methods gained attention with analogue control techniques. Typically, a voltage regulation technique include a single feedback loop, in which the error signal is the difference between reference voltage and feedback. However, in a current mode regulation, two separate loops are required, which one of them is inner loop as indicated in figure 19 [55, 56, 57]. Current mode control technique compared to voltage mode has several advantages as follows:

- Faster transient response time since the order of the converter transfer function is only one
- Better option for converters working in parallel
- Over-current protection capability

The main drawback of current mode control is its inherent instability for duty cycle more than 0.5. It also injects sub-harmonic oscillations to the system at duty cycle higher than 0.5 in all converter topologies. The remedy for instability is to add an artificial ramp to the measured inductor current or the voltage control signal [55].

In past decades, in DC-DC converter control techniques, digital controller has had a substantial development. Compared to analogue control techniques, digital controller has the following advantages:

- It offers a high flexibility in programming, since the control algorithm is translating to the machine language, different control algorithms can be programmed into the same hardware control system. It will be very simple to change the algorithm due to the design requirement once the capability of the digital control is abled
- It provides a powerful interface such as monitoring, protection, prevention and communication capabilities. Moreover, digital controller has the ability to save the data in its memory for further operations
- Multiple power converter can be controlled and managed with only one controller

3.4.1 Voltage Mode Control of DC-DC Converter

As it is indicated in figure 19, the voltage mode regulation manages the error signal by sensing the feedback voltage and compare it with a reference voltage. The error then passes through a controller, for instance a PI controller. The output of the compensator then passes to a comparator or a simple Op-Amp that compare the control signal with a fixed frequency saw-tooth waveform. The corresponding duty cycle, adjust the voltage across the inductor and therefore the inductor current set the output voltage to its reference point.

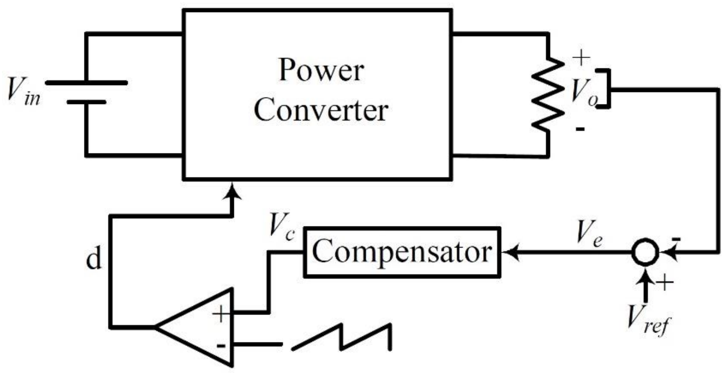

Figure 19. General form of voltage mode regulating.

Voltage mode regulation despite its simplicity in implementation has several disadvantages as follows:

- The main switch suffers from weak reliability
- In parallel power supply mode for a single mode, voltage mode DC-DC converters typically has poor stability and degraded reliability
- For some DC-DC converter topology such as Push-Pull converter, it requires complex and inefficient methods to keep the main transformer operating in linear region
- Transient response time is slower compared to current mode

3.4.2 Current Mode Control of DC-DC Converter

Despite voltage mode regulation, current mode benefits one extra inner loop. In most cases, the current of the inductor is sensing. However, in some cases the current of the switch is monitoring and sensing. As indicated in figure 20, the outer loop control the voltage with same technique that describe and the compensator generates the control signal $i_c(t)$. Afterwards the inductor current is sensed and compared with control signal, the duty cycle is generated. The inductor current is proportional to the signal $i_c(t)$ and gradually the error signal become small.

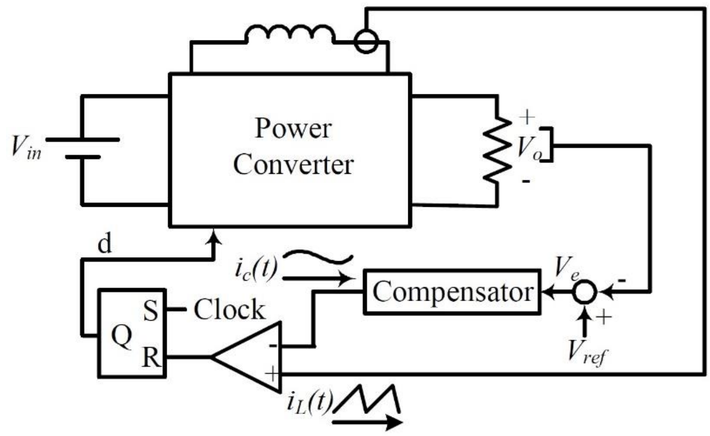

Figure 20. General form of current mode regulating.

Both voltage and current regulating starts with analogue circuitry. Due to its simplicity and low implementation cost, analogue control technique has been popular. Although, analogue control includes important drawbacks including low flexibility, large part count, and sensitivity to environmental influence such as thermal, aging and tolerance.

3.5 Push-Pull DC-DC Converter

This converter belongs to the group of symmetric converters because it utilizes the magnetization curve of the transformer in both quadrants. Practically, a symmetric converter (figure 21) consists of two isolated step-down converters operating in push–pull, often called the countercycle converters. One of the converters consists of transistor T_{r1} and diode D_1 and the other of transistor T_{r2} and diode D_2, including, of course, the corresponding transformer windings. One converter is active alternately to the other so that double power is obtained at the output compared to the basic forward converter. Namely, during one cycle of the control pulses the energy is transferred twice to the output choke L_o via the transformer. The energy accumulated in L_o is transferred to the load when both transistors are off, also twice within one cycle. Therefore, within one cycle a push–pull converter performs twice the action of the forward converter. The transistors are controlled in such a way that they must not be on simultaneously in order to avoid short-circuiting of the transformer.

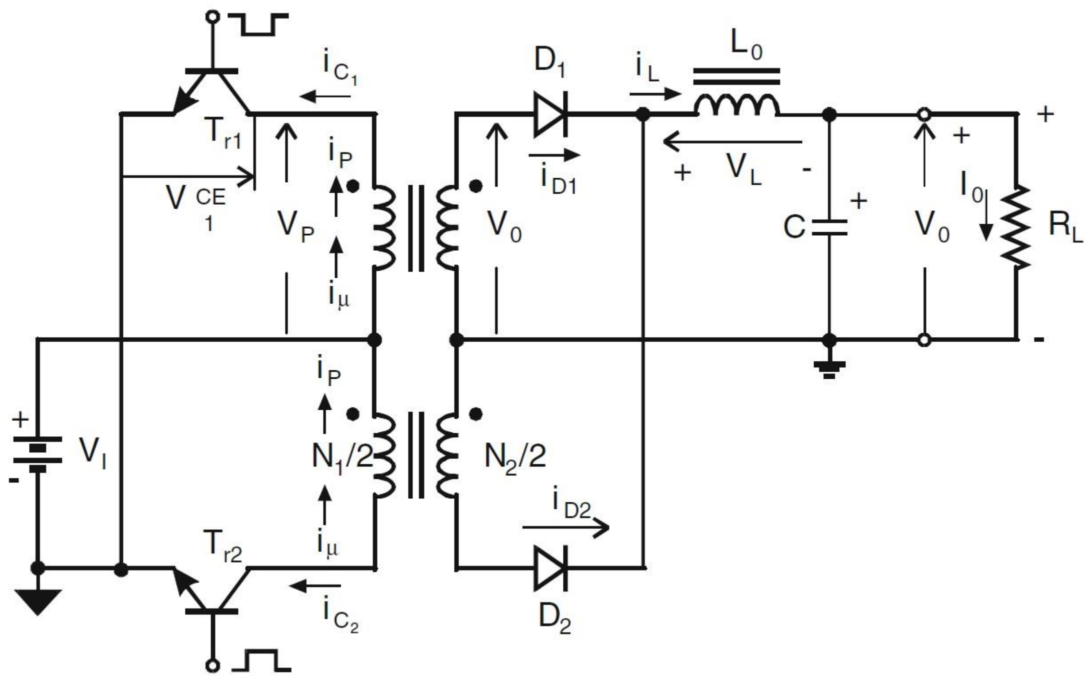

Figure 21. A typical push-pull DC-DC converter.

The push-pull can also be used for output power less than 500 W, however, it suffers from a potentially severe failure mode called core imbalance. This is where the flux within the transformer will operate non-symmetrically about a “zero” balance point. This will cause the transformer to saturate in the direction of one power switch and burn it out within nanoseconds when step changes occur in the load. Pulse-to-pulse current protected voltage-mode control or current-mode control techniques must be used to avoid this problem.

The push-pull converter is adequate for small size and weight regulators. It is also a good option for multiple outputs regulators with low output ripple and nose. Some of the advantages of the push-pull DC-DC converter are outlined as follow:

- Low primary current compare to similar isolated topologies
- Simple low-side gate drive
- Low output current ripple
- Transformer rating required is smaller than the forward converter
- The Push pull converter is of low cost
- Best isolated topology for output power between 50 W and 500 W

Some of most evident drawbacks of the push-pull DC-DC converter are:

- Very high switch stress compare to other isolated topologies (Two times of input voltage)
- Center-tapped transformer is required and impedance of the each of the transformer must be very close to avoid transformer saturation
- Hard switching that increase the switching power loss
- Push-pull switching power supply does not have the possibility of two control switches colluding at the same time as half-bridge and full-bridge switching power supplies
- Push-pull converter is not a suitable option for when the load voltage varies too much, especially when the load is very light or often open

3.6 Full-Bridge DC-DC Converter

Despite a push-pull converter, a full-bridge DC-DC converter stress their transistors to a voltage equal to the DC input voltage not twice this value. Bridge topologies (Full-bridge and Half-bridge) are almost always used where the normal AC input voltage is 220 V or higher.

An additional valuable feature of the bridge topologies is that primary leakage inductance spikes are easily clamped to the DC supply bus and the energy stored in the leakage inductance is returned to the input instead of having to be dissipated in a resistive snubber element.

Both Half-bridge and Full-bridge converters have simpler transformers compared to those of the basic push–pull converter. This can be further simplified if only one primary and one secondary are used as it is indicated in figure 22 . Then a diode rectifier bridge (diodes D_1–D_4) is used in the secondary circuit. When the transistor pair T_{r1} and T_{r3} is on, the core of the transformer is magnetized in one direction, whereas when the pair T_{r2} and T_{r4} is on, it is magnetized in the other direction of the magnetization curve. This creates a variation of the magnetic flux in the core. The AC rectangular voltage that is induced in the secondary then is rectified by the diode bridge.

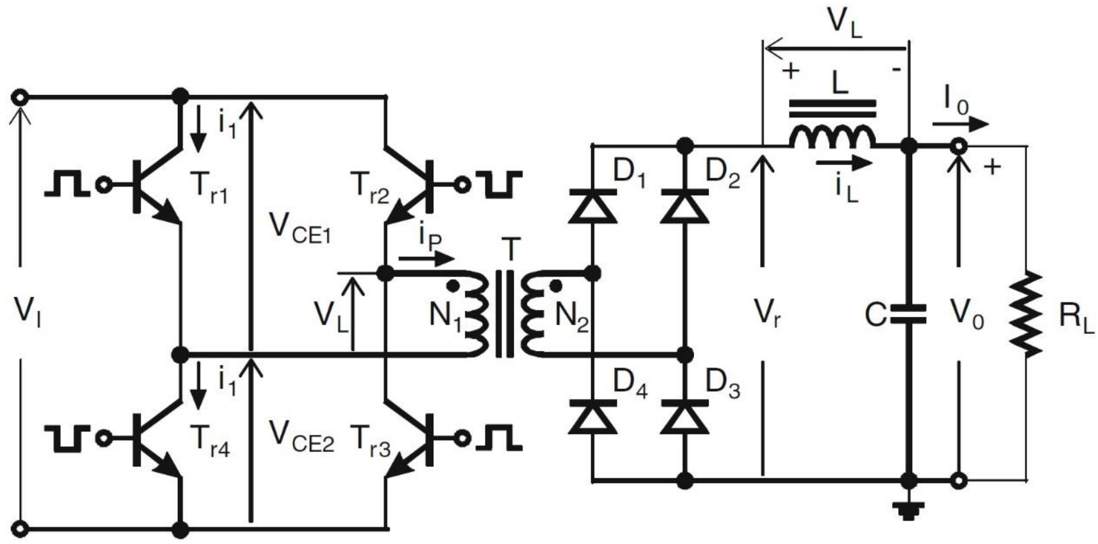

Figure 22. Full-bridge DC-DC converter.

The major advantage of Full-bridge converter is that the voltage impressed across the primary is a square wave of $\pm V_I$, instead of $\pm V_I/2$ for the half bridge. Further, the maximum transistor off-voltage stress is only the maximum DC input voltage—just as for the half bridge. Thus, for transistors of the same peak current and voltage ratings, the full bridge is able to deliver twice the output power of the half bridge. In the full-bridge converter the transformer primary turns must be twice that of the half bridge as the primary winding must sustain twice the voltage. However, to get the same output power as a half bridge from the same DC supply voltage, the peak and RMS currents are half that of the half bridge because the transformer primary supports twice the voltage as the half bridge. With twice the primary turns but half the RMS current, the full-bridge transformer size is identical to that of the half bridge at equal output powers. With a larger transformer, the full bridge can deliver twice the output of the half bridge with transistors of identical voltage and current ratings. Some of the advantages of the full-bridge converter are as follow:

- Better transformer utilization
- Higher efficiency with help of

- Voltage stress of the transistors are limited to V_I
- Higher power output compare to Half-bridge
- Only one filter capacitor is required in output filter

Some of the most important drawbacks of the full-bridge DC-DC converter are:

- Circuit complexity
- Four switching transistors and clamp diodes are required
- Power circuit has two pole small signal characteristics
- Dual, totem pole primary gate drive is required
- Hard switching that increase switching loss

3.7 Half-bridge resonant DC-DC Converter (Resonant LLC)

Over the past 10 years an ever increasing attention has been paid to the resonant converters. It is considered that the future in the design of efficient power supplies belongs to this type of converter. The essential difference of resonant power converters compared to other converter types is that the state of the switch is changed at the zero crossing of the current or voltage. Owing to this the dissipation of the switching elements is very low and the efficiency factor of the resonant converters may be in excess of 90 %. This allows the switching elements to operate up to the frequencies of several MHz, whereas the maximum switching frequency of PWM converters is within the limits of 100–200 kHz. For this reason, the specific power density is more than one order of magnitude higher compared to that of the PWM converters and amounts to several thousands W/dm3. This opens new possibilities in designing compact power supplies which can, together with the standard ICs, constitute a part of the layout of a printed circuit board. In the resonant converter, energy is redistributed within a resonant circuit consisting of a coil and a capacitor. In this process, the energy is proportional to the square of the current through the coil and to the square of the voltage across the capacitor. The output voltage depends on the operating frequency. It is at the highest when the operating and the resonant frequency are equal. In figure 23 and 24 typical half-bridge resonant converters are shown. Figure 23 is without transformer isolation and figure 24 is with transformer isolation.

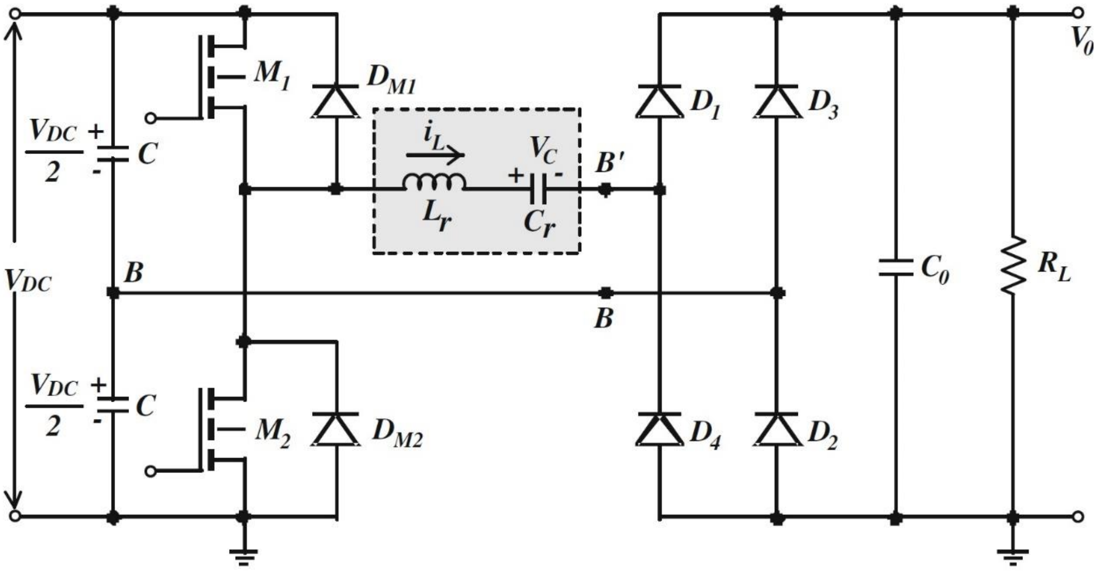

Figure 23. A half-bridge resonant converter without transformer isolation.

Some of the main advantages of the half-bridge LLC resonant converter are as follow:

- Much higher efficiency and lower switching loss due to the zero-crossing voltage and zero-crossing current switching methods
- Smaller size and weight due to the utilizing of higher frequency
- Problem with leakage inductance is minimized
- Higher reliability due to lower heat from switching and automatic current limiting from L_r
- Less electromagnetic interference compare to hard switching mtehods

- When the two magnetic components are implemented with a single core, for instance the leakage inductance as the resonant inductor, one component can be saved

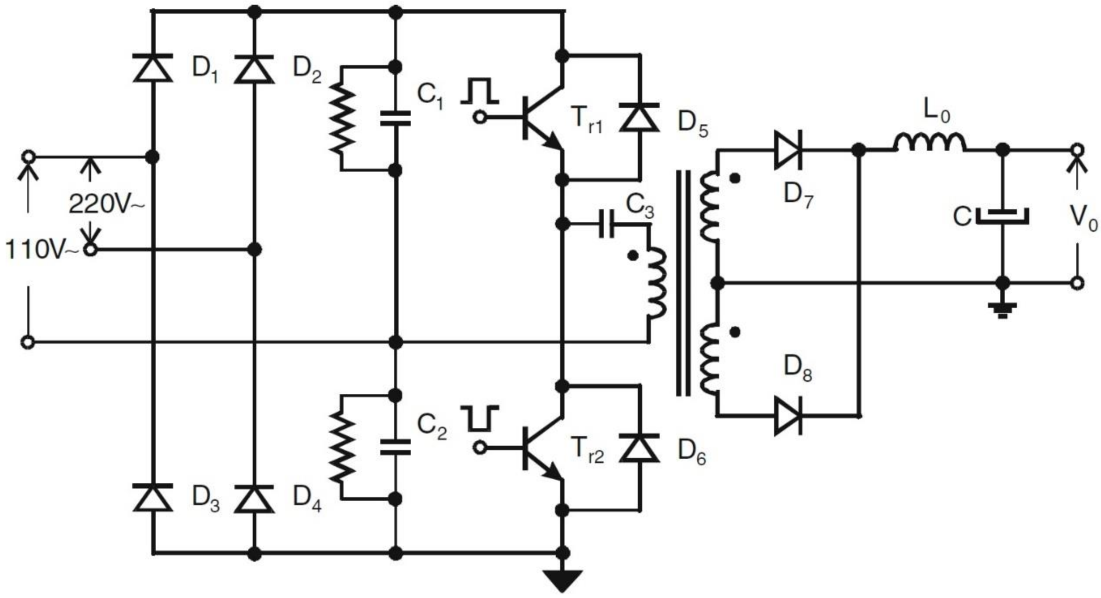

Figure 24. A half-bridge resonant converter with transformer isolation.

The most important drawbacks of the half-bridge LLC resonant converter include following:

- High output current ripple
- Difficult to regulate the output at no load condition
- Quasi-sinusoidal waveforms exhibit higher peak values than equivalent rectangular waveforms
- Significant current may circulate through the resonant network, even at the no load condition
- Requires additional resonant network, L_r and C_r
- Current rating of the switch is three to four times higher than conventional switching regulators

- Complex control method is required for switching devices

3.8 Half-Bridge DC-DC Converter

Half-bridge DC-DC converter is a type of step-down converter. Although, Half-bridge converter has the transformer isolation advantage compared to normal buck converter. Compared to a Full-bridge converter, the voltage stress of the source on each transistor in Half-bridge is half. Moreover, Half-bridge converter benefits of good exploitation of transformer core and recovery of the leakage inductor energy to the input voltage [45]. A Half-bridge converter includes two capacitors that produce a midpoint voltage. The arrangement of the midpoint voltage provides an alternative path for current to flow in transformer. The two switches connect the primary winding of the transformer to the each capacitors. In the figure 25 a Half-bridge converter with center tap transformer is presented. In fact, in a battery charger, AC source supplies the power for the converter. At start the charger unit converts the AC power of the line to a DC level. Then, the Half-bridge converts it to a high frequency square source. The transformer appreciate output source cause by switching MOSFETs as an AC and it acts as a inductor. In the second winding, the output passes through another full-bridge rectifier circuit. In the last section the output LC filter averages the current and removes the voltage`s ripples. For these reasons Half-bridge converter is particularly a suitable candidate for low and medium power energy conversion and for off-line applications in which the converter input voltage exceeds the peak value of line voltage.

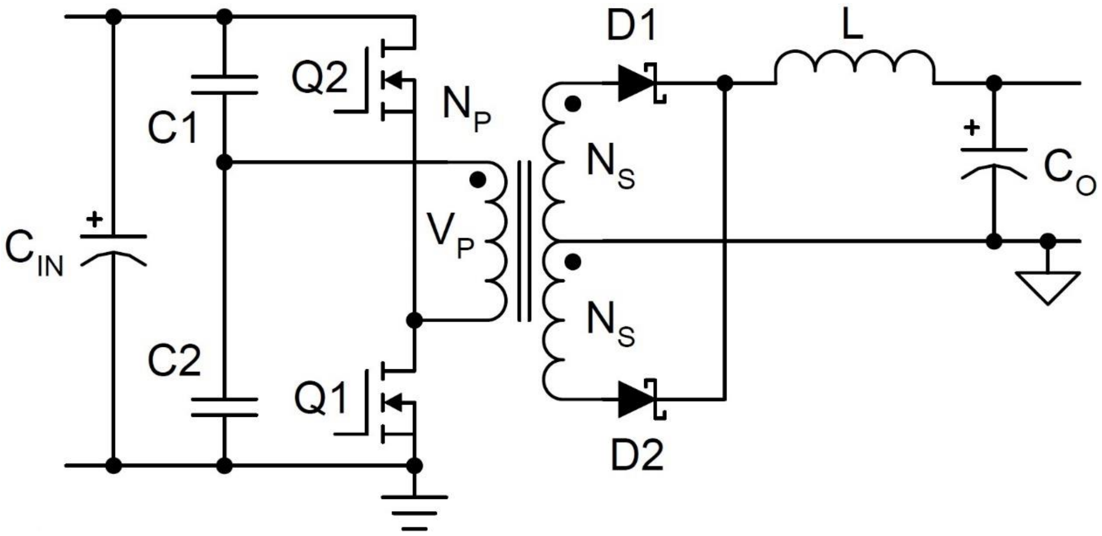

Figure 25. Half-bridge topology with a center-tapped transformer.

Some of the most important advantages of the half-bridge DC-DC converter compared to similar isolated topologies are as follow:

- Higher output power compare to Push-pull converter
- Optimizing transformer utilization by operating in first and third quadrants
- The voltage stress of the transistors are limited to V_I
- No need for a center-tapped transformer
- Best topology for high input voltage in off-line applications up to 500 W
- Higher efficiency due to the better transformer utilization, leakage inductance and magnetization energy

Some of the most important drawbacks of the half-bridge DC-DC converter include:

- High primary current
- Hard switching
- Possible cross conduction between Q1 and Q2
- Power circuit has a double-pole small signal characteristics
- Complex control method for gate drive

In figure 26, the two stages of converter is show. In first stage, the AC input is filtered initially, passes through an NTC resistor to limit the inrush current at start-up. Afterwards, there is another line filter that reduces the Electromagnetic Interference (EMI) due to the switching actions. For overvoltage protection in first stage, a Varistor is used. The purpose of the component in this particular circuit is to protect rest of the board from high voltage fluctuating that may occur. The rest of the stage one includes low-pass filters, full-bridge rectifier and finally two capacitors that are required to produce a mid-point voltage for second stage circuit.

In next stage, there are switches and their control schemes that for simplicity are not shown in the figure completely. The two MOSFETs operate as main switches and produce a +155 V and -155 V alternatively at the first winding of the isolation transformer. In the second winding of the transformer a new voltage is induce that its amplitude is equal to the first winding voltage. Afterwards, the voltage is rectified again and passes through the output filter.

In conclusion, for charging a Li-Ion battery pack consists of ten cells in series multiply ten cells in parallel, a switch-mode power supply with output power around 500 W is required. Based on advantages and drawbacks of the push-pull, the full-bridge, and the half-bridge LLC resonant converters, the best option for an off-line battery charger that can produce 500 W efficiently is the half-bridge converter. Considering the cost of materials and some limitation to provide all the necessary parts, such as a high frequency center-tapped transformer, the half-bridge converter can be the best choice.

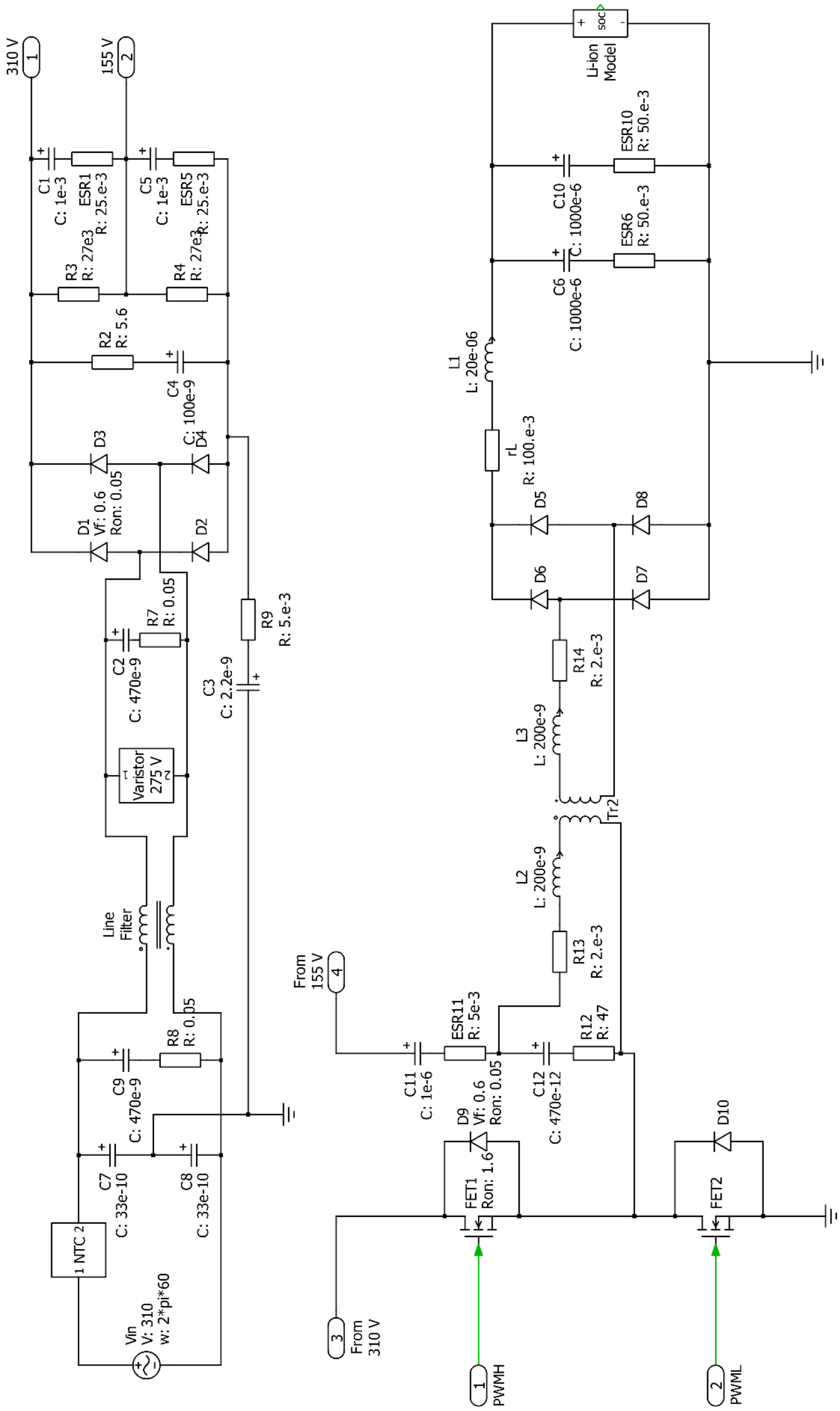

Figure 26. Representation of two stages Half-bridge converter.

3.8.1 Transfer Function of Half-Bridge Converter

In order to obtain the transfer function of Half-bridge, the state-space average method is employed to linearize the equations. First, the state-variable for each circuit state must be identified. Then, assuming the MOSFETs and diodes act as an ideal switches and only second stage of the Half-bridge converter is investigated. Another assumption in this piece of work is that the power converter operates in continuous conduction mode. Two scenarios can be pointed out: one stage is when both transistors are on, and two when they are off.

The purpose of the state-space averaging analysis is to derive a small signal transfer function $\overline{v}_o(s)/\bar{d}(s)$, where v_o and d are small perturbations in the output voltage v_o and the switch duty ratio d, respectively, around their steady-state DC operating values V_o and D. The procedure is as follows [56]:

1. **State-Variable Description for Each Circuit State:**

   There are two circuit states in a switching-mode power converter that is operating in continuous conduction mode, one stage corresponds to time when switch is conducted and the other one when the switch is one. For each state, the inductor current and capacitor voltage are considered as state-variables. To describe the behavior of the system more accurately, the parasitic elements such as resistance of the filter inductor and equivalent series resistance (ESR) of the filter capacitor are included. In following equations the input voltage is indicated with V_d. To represent a variable with its perturbation, a lower case letter is used. For instance, $v_o = V_o + \bar{v}_o$ which is the steady-state DC value plus a small ac perturbation. During each circuit state, the following equations can be derived:

$$\dot{\mathbf{x}} = \mathbf{A_1}\mathbf{x} + \mathbf{B_1}\boldsymbol{v_d} \text{ during } d \text{ with } T_s \quad (8)$$

and

$$\dot{\mathbf{x}} = \mathbf{A_2}\mathbf{x} + \mathbf{B_2}\boldsymbol{v_d} \text{ during } (1-d) \text{ with } T_s \quad (9)$$

where $\mathbf{A}_1$ and $\mathbf{A}_2$ are state matrices and $\mathbf{B}_1$ and $\mathbf{B}_2$ are vectors.

The output v_o in all conversion can be defined with their state variables as follows:

$$v_o = \mathbf{C}_1\mathbf{x} \text{ during } d \text{ with } T_s \quad (10)$$

and

$$v_o = \mathbf{C}_2\mathbf{x} \text{ during } (1-d) \text{ with } T_s \quad (11)$$

where $\mathbf{C}_1$ and $\mathbf{C}_2$ are transposed vectors.

2. **Averaging the State-Variable Description Using the Duty Ratio d:**

In order to obtain an equation to describe the state-variable during a complete period of switching, two corresponding state equations can be calculated based on their switching duty cycle and presented as follows:

$$\dot{\mathbf{x}} = [\mathbf{A_1}d + \mathbf{A_2}(1-d)]\mathbf{x} + [\mathbf{B_1}d + \mathbf{B_2}(1-d)]\boldsymbol{v_d} \quad (12)$$

and

$$v_o = [\mathbf{C}_1 d + \mathbf{C}_2(1-d)]\ \mathbf{x} \quad (13)$$

3. **Introducing Small ac Perturbations and Separation into ac and dc Components:**

Small ac perturbations can be represented with dc steady-state quantities. Therefore, it can be written as follows:

$$\mathbf{x} = \mathbf{X} + \bar{\mathbf{x}} \quad (14)$$

$$v_o = \mathbf{V}_o + \bar{v}_o \quad (15)$$

and

$$d = D + \bar{d} \quad (16)$$

In general, $v_d = \mathbf{V}_d + \bar{v}_d$. Although, in this study the purpose of obtaining the transfer function is to investigate the small changes of output voltage due to the small changes in duty cycle. Therefore, to simplify the analysis it can be indicated as follows:

$$v_d = \mathbf{V}_d \quad (17)$$

4. **Transformation of the ac Equations into s-Domain to Solve for the Transfer Function:**

   With using a Laplace transformation and arranging the equations, the transfer function of the system can be represented as follows:

$$T_p(s) = \frac{\bar{v}_o(s)}{\bar{d}(s)} = \mathbf{C}[s\mathbf{I} - \mathbf{A}]^{-1}\,[(\mathbf{A}_1 - \mathbf{A}_2)\mathbf{X} + (\mathbf{B}_1 - \mathbf{B}_2)V_d] + (\mathbf{C}_1 - \mathbf{C}_2)\mathbf{X} \quad (18)$$

   As it is indicated in figure 27, a Half-bridge converter is simplified to its output filter. The transfer function of the converter can be obtained as follows:

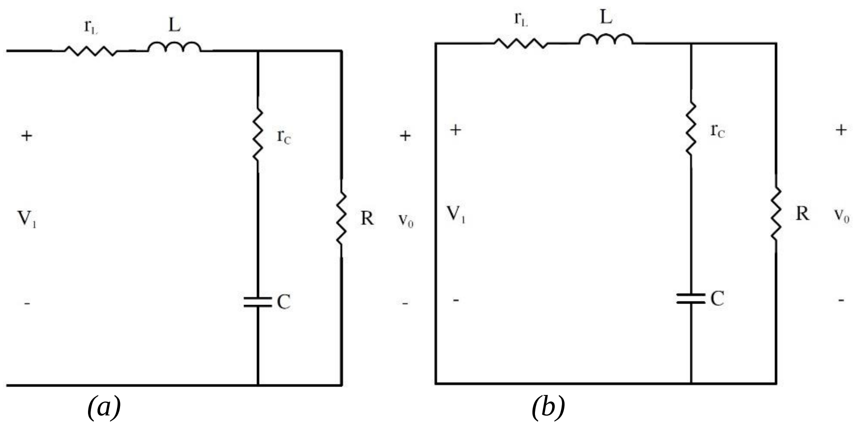

Figure 27. Simplified Half-bridge converter, (a) when the switch is on, (b) when the switch is off.

With one KVL and one KCL, the following equation can be written as follow:

$$-V_1 + L\dot{x}_1 + r_L x_1 + R(x_1 - C\dot{x}_2) = 0 \quad (19)$$

$$-x_2 - Cr_C\dot{x}_2 + R(x_1 - C\dot{x}_2) = 0 \tag{20}$$

In matrix form, these two equations can be shown as:

$$A_1 = A_2 = \begin{bmatrix} -\frac{Rr_C + Rr_L + r_C r_L}{L(R + r_C)} & -\frac{R}{L(R + r_C)} \\ \frac{R}{C(R + r_C)} & -\frac{1}{C(R + r_C)} \end{bmatrix} \tag{21}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{22}$$

$$B_2 = 0 \tag{23}$$

Where N_1 and N_2 are the number of winding turn of the isolation transformer.

And for the output of the system:

$$C_1 = C_2 = \begin{bmatrix} \frac{Rr_C}{R+r_C} & \frac{R}{R+r_C} \end{bmatrix} \tag{24}$$

3.9 Case Study

As mentioned previously, the motivation and purpose of this study is to design and implement a digital PI controller for a prototype battery charger that charges a Lithium-Ion battery pack with CC-CV mode. The battery pack contains ten by ten Panasonic NCR18659B rechargeable Li-Ion batteries. The maximum voltage of the battery pack after a full charge is almost 42 V and its capacity is 33.5 Ah. The battery charger is implemented based on Half-bridge topology because the required power is less than 500 W and it provides a transformer isolation and a good exploitation of transformer core.

For the control part, a digital controller is picked because of its flexibility. Additionally, it provides many different modules inside and it saves board space. With help of a 60 MHz DSP, executing PI loop is much easier and the transport delays of the data through ADC is negligible. Frequency of the switching is set at 100 kHz and the ADC sample time is 2×10^{-5}.

3.9.1 Lithium-Ion Battery Equivalent Circuit

In order to understand the behavior of the Li-Ion battery, an equivalent circuit is proposed in figure 28. This model include different electrical part to describe the behavior of the battery properly. A voltage source that represents the open circuit voltage, parallel RC networks that indicates the delay in voltage response and charging cycle, and a resistor that referred to the internal resistance of the cell [57, 58].

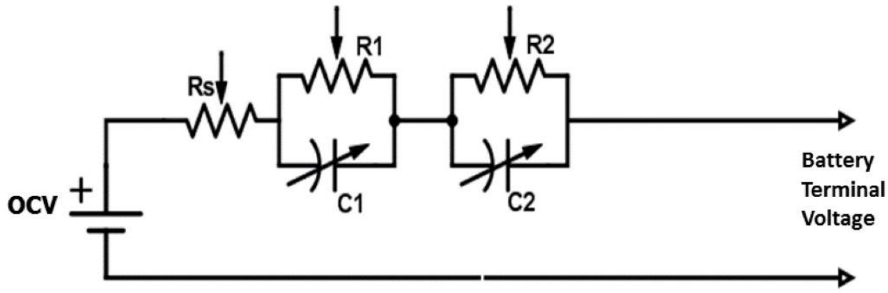

Figure 28. Equivalent circuit of a Li-Ion battery.

Figure 29 shows the equivalent component of the battery pack that is using in the simulations with PLECS software.

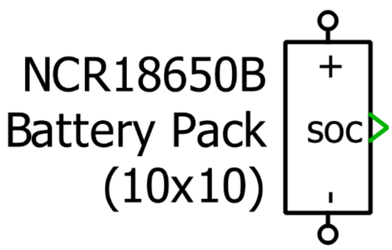

Figure 29. Equivalent circuit block of NCR18650B battery pack in PLECS.

Table 2. Parameters of Li-Ion battery pack model

Initial SOC (%)	Number of Cells in Series	Number of Parallel Branches	Nominal Voltage (V)	Rated Capacity (Ah)	Maximum Capacity (Ah)	Maximum Voltage During Charging (V)
20%	10	10	2.9	3.2	3.35	4.2
Nominal Discharge Current (A)	**Internal Resistance (Ω)**	**Capacity at Nominal Voltage (V)**	**Exponential Zone Voltage (V)**	**Capacity at Exponential Zone (Ah)**	**Low-Pass Filter Time-Constant (sec)**	
3.25	0.25	2.35	3.05	0.35	30	

Table 3. Parameters of switching-mode power supply

V_1	D	L	r_L	C	r_C	R
$V_D/2$	0.4	20μH	100mΩ	2000μF	25mΩ	250mΩ

According to table 2 and 3, the parameters of the Li-Ion battery and the circuit of the SMPS is given. With respect to equations 21, 22, 24, and 18 the open-loop transfer function of the system can be written as follows:

$$T_p(s) = \frac{\bar{v}_o(s)}{\bar{d}(s)} = \frac{220\,s + 4.532\times10^6}{s^2 + 7954\,s + 3.182\times10^7} \tag{25}$$

To understand the behavior of the transfer function and subsequently the system, a step response and bode plot of the transfer function is indicated in figures 30 and 31. As it is shown the steady-state error of the system is huge and it needs considerations.

As it is indicated in figure 30, the closed-loop system is not able to follow the input control signal properly and there is always a steady-state error in the system.

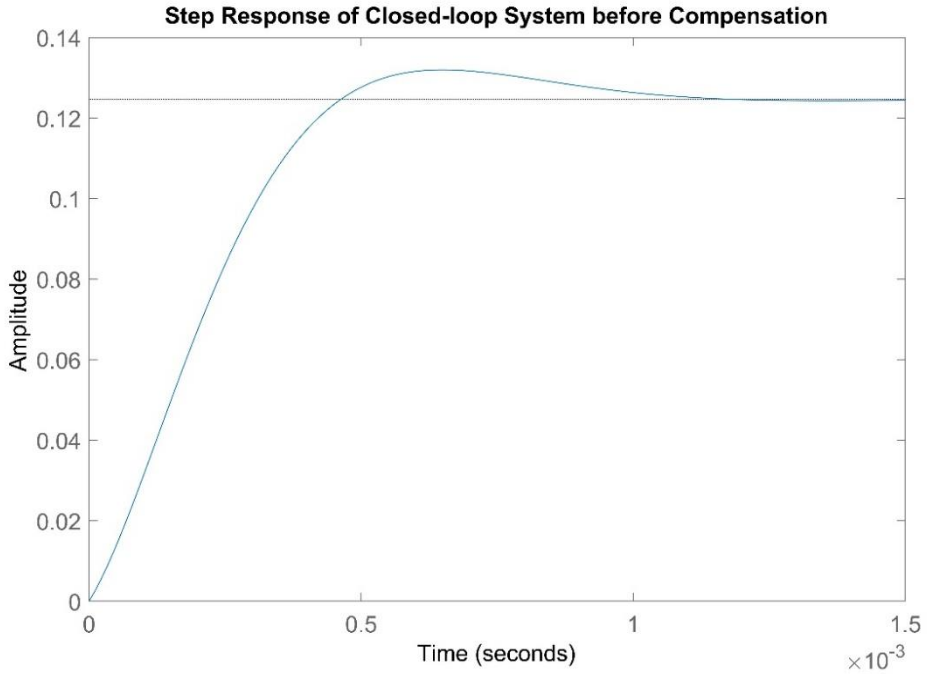

Figure 30. Step response of closed-loop system before compensation.

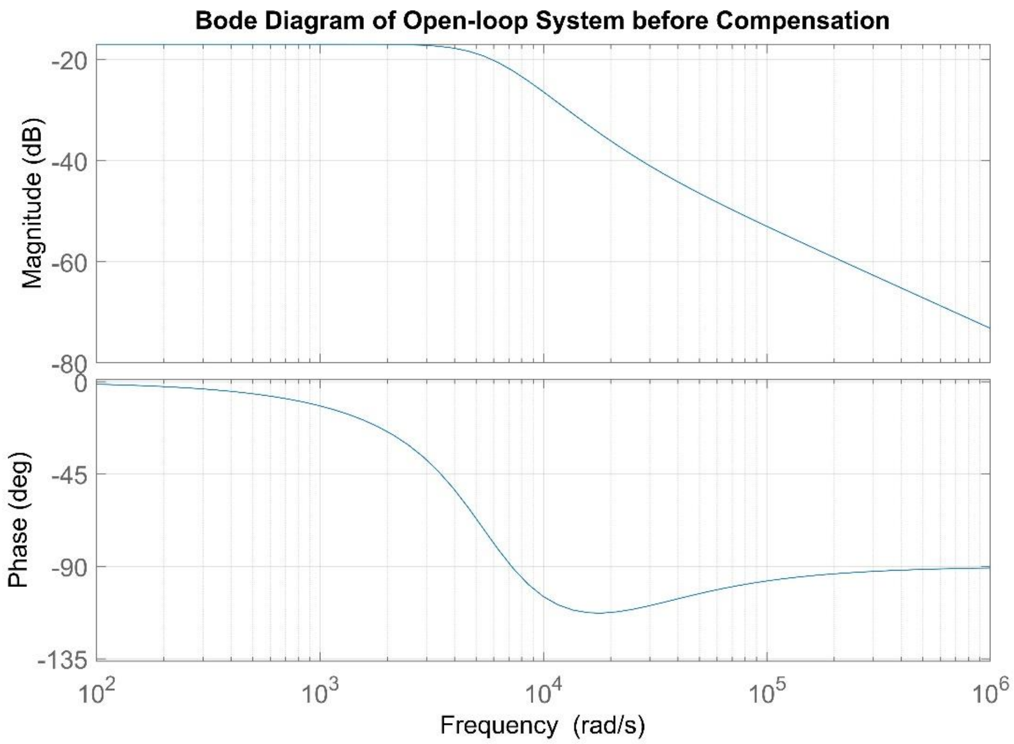

Figure 31. Bode diagram of the open-loop uncompensated system.

In figure 31, as it is shown, the gain margin and phase margin of the system are infinite. It indicated that the system has a proper stability through disturbances and noises.

3.9.2 Controller Design

In this prototype battery charger, utilizing of some ICs and components were the only or few available options that existed. Due to some constraints and shipment limitations in this particular time, the prototype battery charger could not be the perfect one in the market. Although, with these electronic and electrical components, it can operate properly. One limitations that exists is the position of voltage sensor and current sensor. Ideally, the microcontroller (here TMS320F28027D) should be able to read the input voltage and inductor current as well. However, here the MCU can read the output voltage and output current. Therefore, by manipulating controller design and coding some part of the problems can be solved. The MCU is from C2000 series of Texas Instruments. It provides a CPU with 60 M Hz and ADC with 12.bit resolution.

The MCU programming is proposed in C Language. The main reason is that first the IDE or programming software that TI introduced for its products is presented in C and C++ language. Then, the C programming language is inherently flexible and the programmer has access to every single bit of the MCU. However, his capability brings some drawbacks as well. For instance, more difficult debugging procedure in some scenarios, longer learning curve of the programming language, and too much coding for a simple job. The C programming language is the backbone of other modern languages that has a more user friendly interfaces such as Java or C#. In figure 32 a flowchart of MCU tasks is provided.

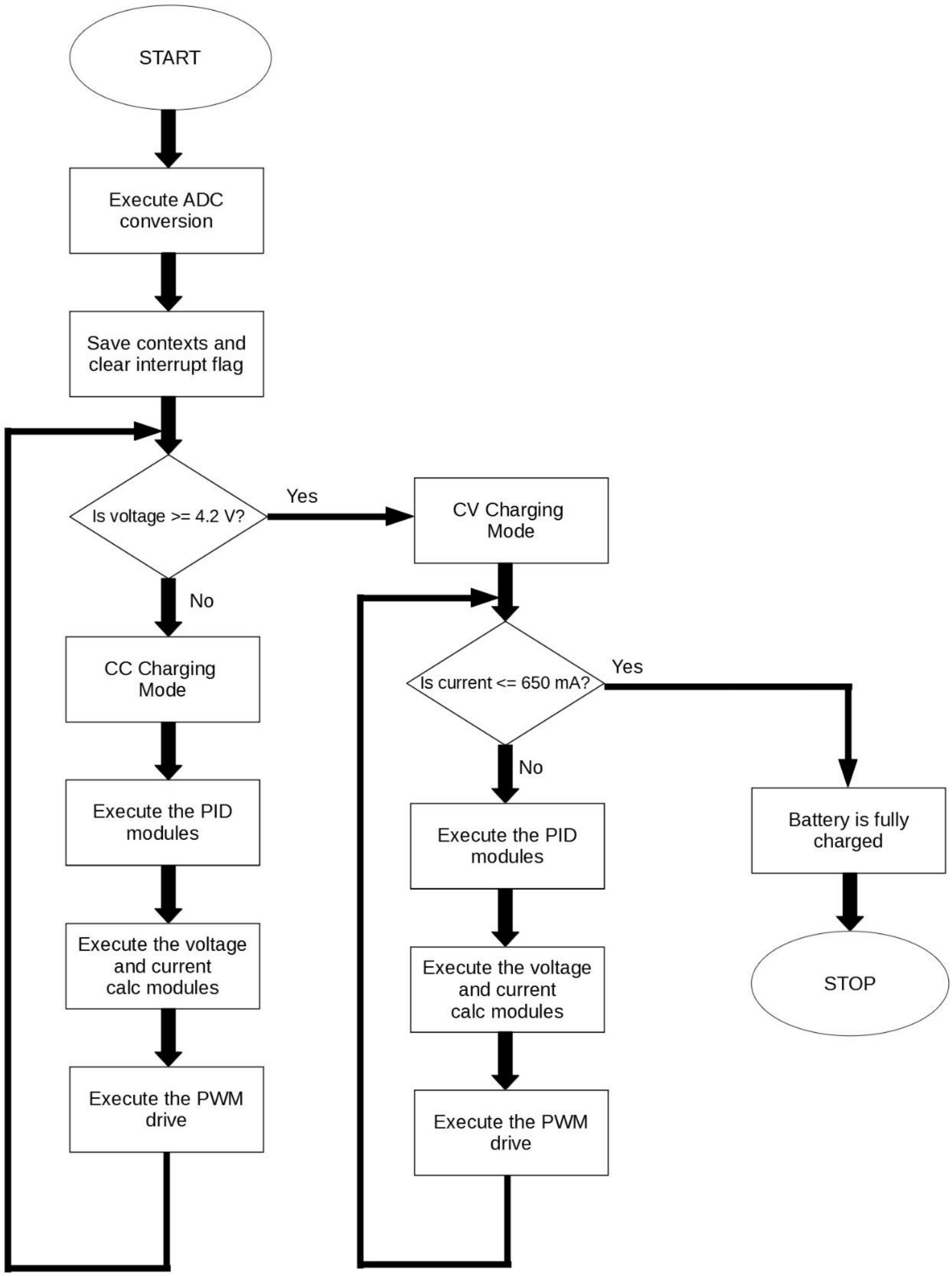

Figure 32. Flowchart of MCU actions.

3.9.2.1 Process Description

Initially, when the battery charger starts, it reads the voltage and current of the battery pack. For voltage sensing, first a voltage divider lower the voltage by factor of 10, then with help of ISO224 as an isolation IC and TLV9002 as Op-Amp the ADC can read the voltage by a factor of 1/15. The voltage can varies from 0 to 50 V in this scheme, however with changing the gain factor to 1/30 or 1/60 the range will increase, however, the resolution will decrease (Figure 33).

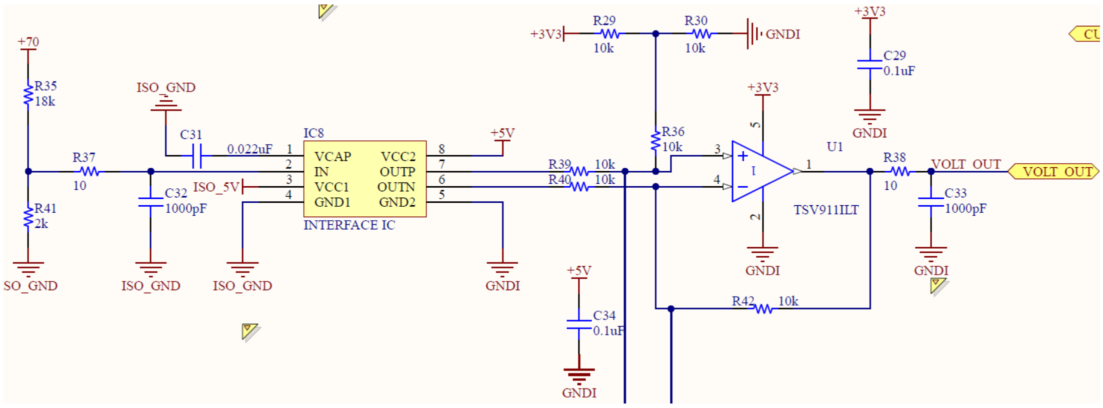

Figure 33. Voltage divider and isolation IC for safe and accurate voltage sensing.

For the current sensing, a current transducer sensor is used. LTS 15-NP, a current sensor from LEM, with right configuration can sense -50 A to +50 A. The output signal of the sensor is a voltage between 0.375 V to 4.625 V. This sensor is robust against noises with proper setting (30).

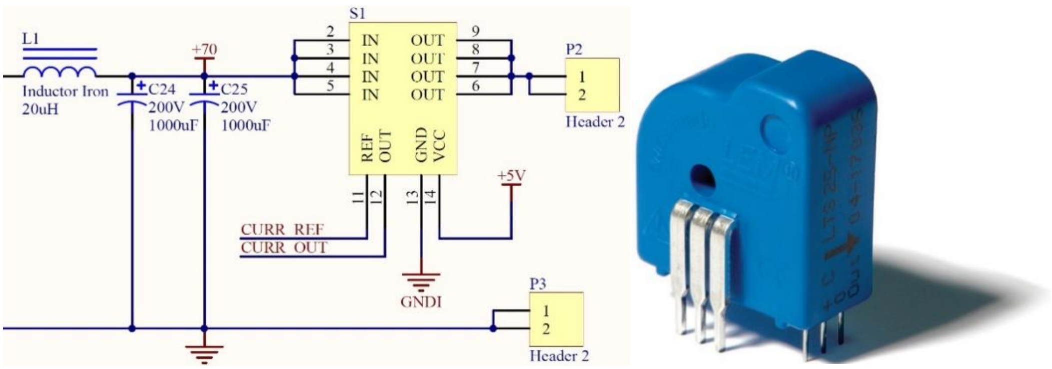

Figure 34. Current transducer sensor, LTS 15-NP.

After reading the voltage and current in each interrupt at frequency of 50 K Hz, the MCU decides which phase the battery pack is at the moment and the output signal sends to the ePWM module for driving the two MOSFETs. For a more accurate simulation model, the blocks for TI C2000 MCUs are employed (figure 35). A dead-band module is also provided inside the ePWM to prevent short circuit.

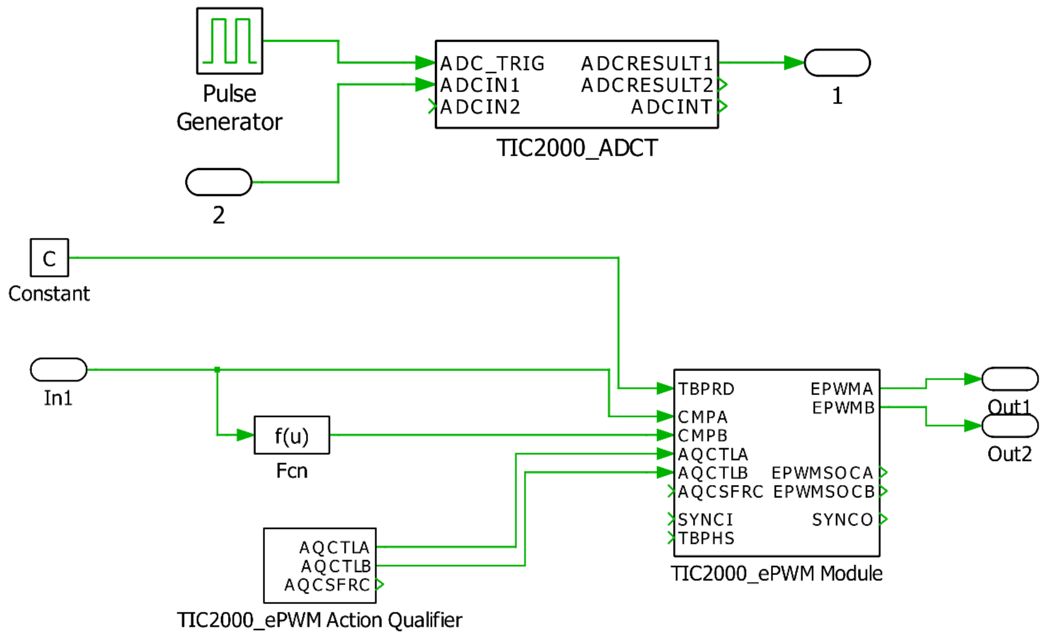

Figure 35. ADC and ePWM modules in PLECS simulation software.

When reading the feedback signal through ADC channel and producing the correct PWM output to compensate the error signal, the PI controller is processing the proper output. The time cycle of each run time of PI controller is about 100 cycles or 165 ns, and it is acceptable delay. The figure 36 indicates the PI controller with anti-windup protection that is implemented in the MCU.

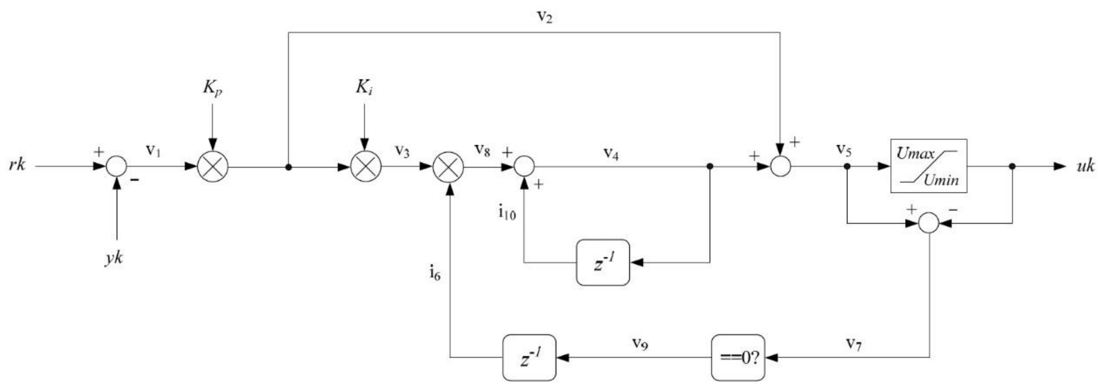

Figure 36. The implementation of PI controller with anti-windup.

According to the figure 36, the equations of the signal processing can be shown as follows:

$$v_1(k) = r(k) - y(k) \tag{26}$$

$$v_2(k) = K_p v_5(k) \tag{27}$$

$$v_3(k) = K_i v_2(k) \tag{28}$$

$$v_8(k) = v_9(k-1) v_3(k) \tag{29}$$

$$v_4 = v_8(k) + v_4(k-1) \tag{30}$$

$$v_5(k) = v_2(k) + v_4(k) \tag{31}$$

$$v_7(k) = u(k) - v_5(k) \tag{32}$$

$$u(k) = \begin{cases} v_5(k) & : u_{min} < v_5(k) < u_{max} \\ u_{max} & : v_5(k) > u_{max} \\ u_{min} & : v_5(k) < u_{min} \end{cases} \tag{33}$$

$$v_9(k) = \begin{cases} 1 & : v_7(k) = 0 \\ 0 & : v_7(k) \neq 0 \end{cases} \tag{34}$$

The output of the PI controller, assuming that it is not saturated can be written as follows:

$$u(\mathrm{k}) = v_1 \, [K_\mathrm{p} + K_\mathrm{p} K_\mathrm{I} \, u(\mathrm{k}-1)] \tag{35}$$

where v_1 is the error signal.

3.9.2.2 Protection Mechanism

In the design of the converter there a few protection mechanism. First in the rectifier stage, there is process that at start current passes through a resistor in order to limit the inrush current that caused by empty-charged capacitors. After 5 seconds, the resistor will bypass by a simple circuit including a transistor and a relays (Figure 37).

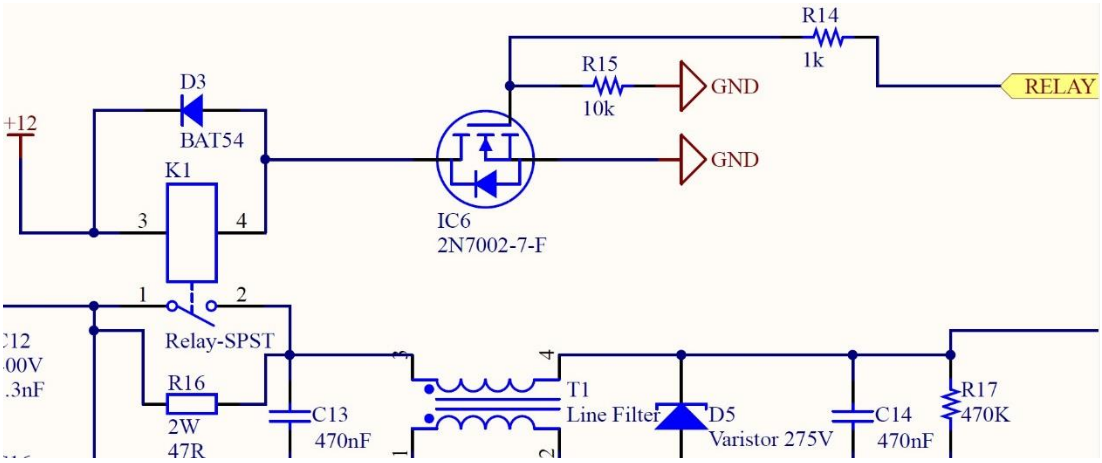

Figure 37. Inrush current limiting with resistor and bypassing by a relay.

After that, a negative coefficient resistor (NTC) is proposed for limiting inrush current. The equivalent circuit of the NTC model is simulated in the figures 38 and 39. Although, the because of inherent nonlinear characteristics of the NTC, it may cause unwanted harmonics in the system.

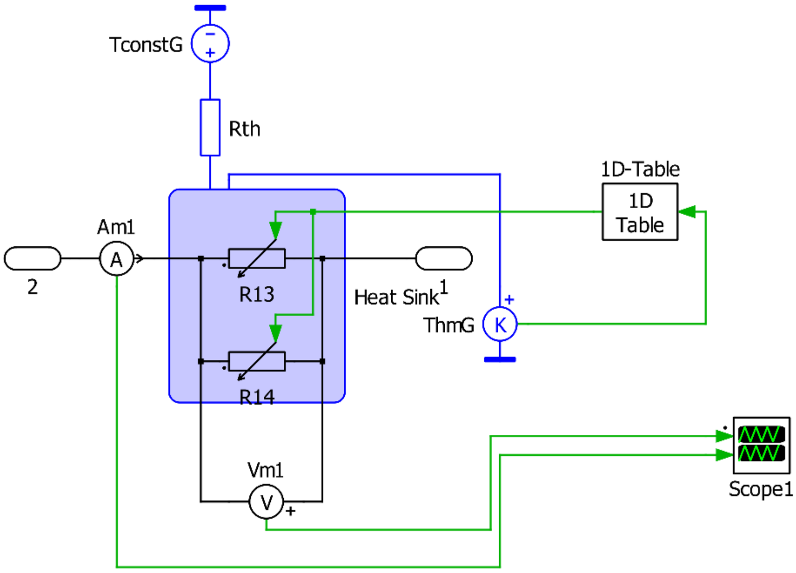

Figure 38. Equivalent circuit of an NTC varistor.

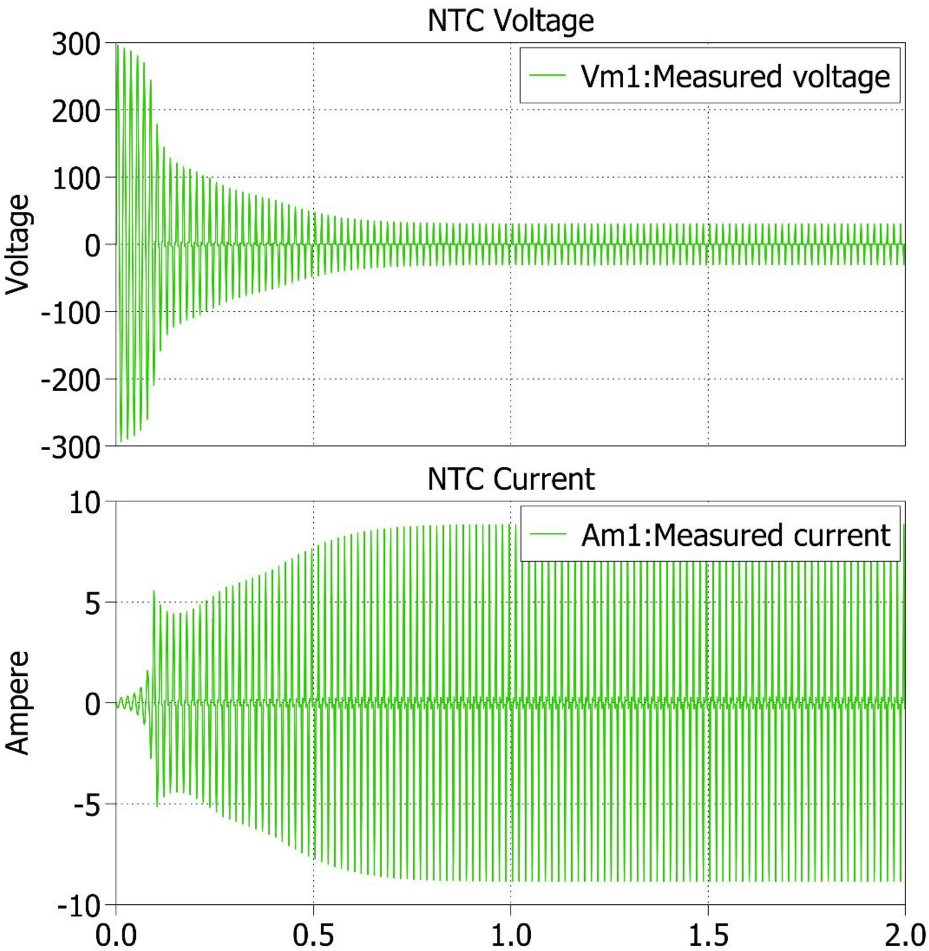

Figure 39. Voltage and current of an NTC at start of the circuit when all the capacitors are empty.

For high voltage protection at input, a Varistor is employed in the first stage of converting AC to DC. The mechanism is in a such way that for supply voltages of less 275 V it acts as an open circuit with a high impedance. However, when the voltage of the AC input supply exceed 275 V, the resistance of the Varistor becomes nearly zero and act as a short circuit. Therefore, the over-voltage of input will not compromise rest of the system.

Another protection mechanism is high voltage protection. An Op-Amp as a comparator compares the output voltage with a given value and whenever it reaches the maximum value, it activates an interrupt with the highest priority. In the interrupt, first all PWM modules set to off-level, and then the interrupt flag set to zero for future interrupts (Figure 40).

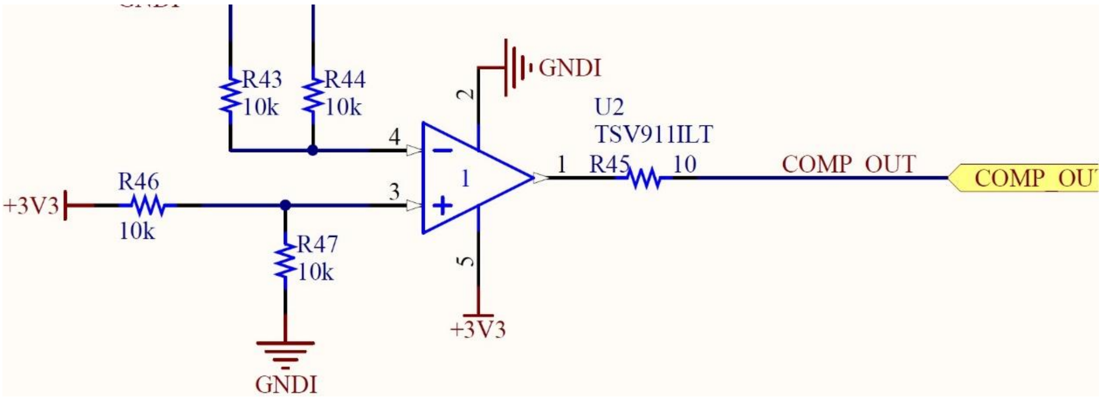

Figure 40. A maximum voltage protection circuit that activates the MCUs interrupt with high priority.

Chapter 4

SIMULATION AND EXPERIMENTAL TESTS

In this chapter an accurate simulation model of the Half-bridge battery charge with its battery-pack load is presented. The process of choosing the right constants for the PI controller is investigated. At the end the simulation and test results are presented.

4.1 Simulation Model

In modeling the battery charger, two factors are considered coherently. First, accuracy of the model and its reliability, and then its simplicity to perform the simulation. Figure 41 and 42 indicate a simulated model for the battery pack and its result.

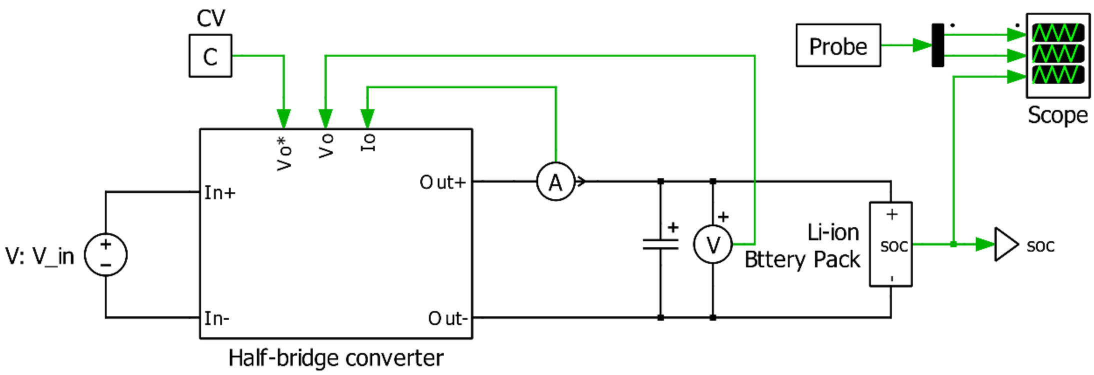

Figure 41. Battery pack and converter model.

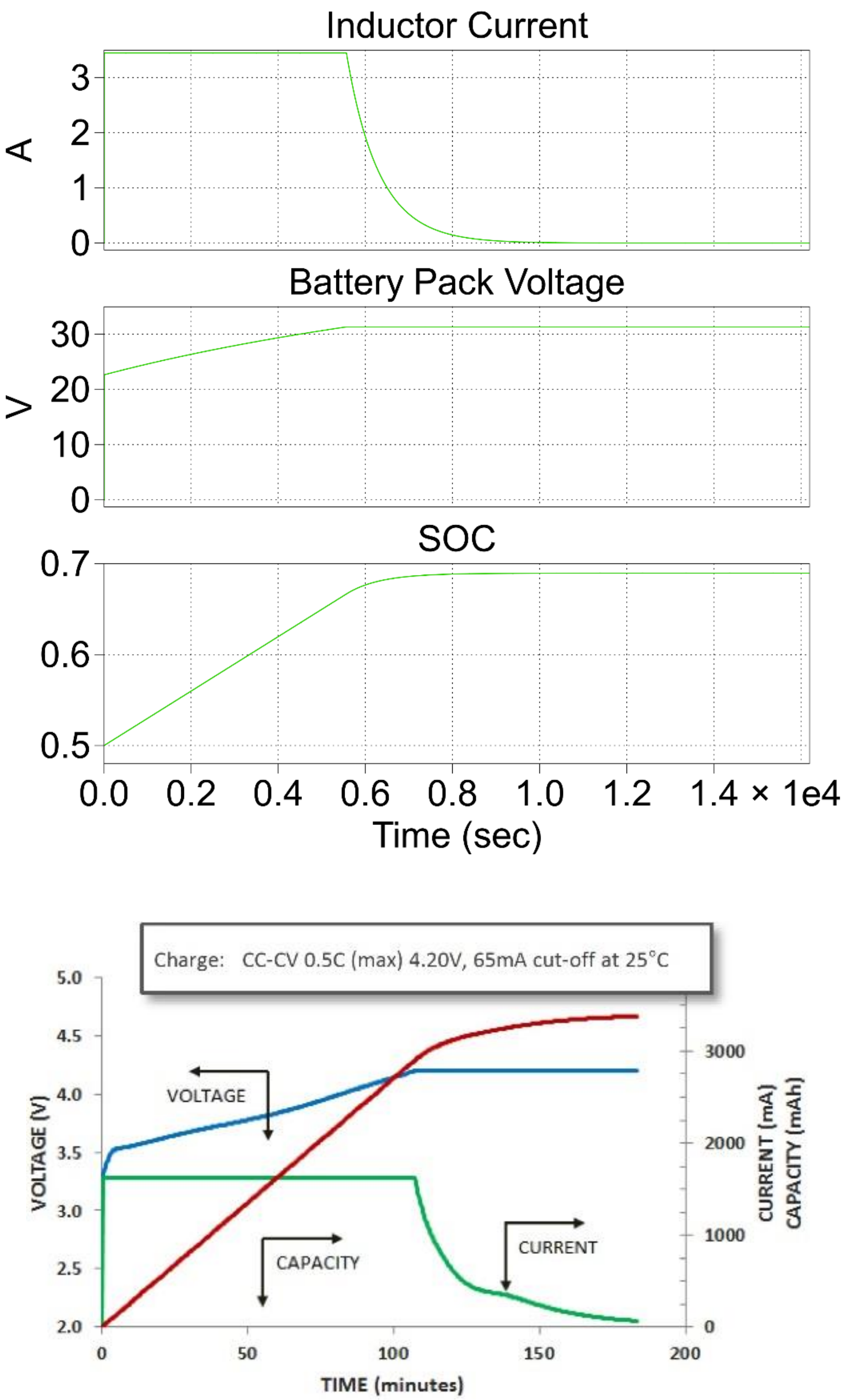

Figure 42. NCR18650B equivalent model charging cycle vs. datasheet of the company.

For the Half-bridge model, two approaches have been investigated. First, the calculated transfer function in chapter 3 is used in MATLAB and the uncompensated and compensated control system have been proposed mathematically. In another method, the simulated model in PLECS is used to obtain the other variable in the converter such as inrush current limiter.

As shown in figure 26, the system suffers from a steady-state error. It means when the time *t* goes to infinity in time domain, the variable *s* goes to zero in s-domain. To calculate the steady-state error, first it is required to obtain the closed-loop system:

$$\textit{Closed-loop} = \frac{220\,s + 4.532\times10^{6}}{s^{2} + 8174\,s + 3.645\times10^{7}} \qquad (36)$$

when $s = 0$, $T_{CL}(0) = 0.124$.

To remove this error, and speed up the transient time, a PI controller is proposed as follow:

$$\mathbf{G(s)} = 15 + 5\times10^{4}/s \qquad (37)$$

According to fig 32, equation 35 and 37, the K_p and K_i become 15 and 3333 respectively.

In most of the time, the one important consideration for digital controller is the sample time of the system. Here in this digital controller, the Microcontroller Unit (MCU) has an Interrupt Service Routine (ISR) that occurs every 20 µS. In each interrupt analogue values of voltage and current are captured by the Analogue to Digital Converter (ADC) inside the MCU. Therefore the signal is not continuous anymore and it is translated to a digital format that machine can understand. Considering the sample rate of 20 μS, the closed-loop transfer function in Z-domain is as follow:

$$H(Z) = \frac{0.03659\, z^3 - 0.02173\, z^2 - 0.03579\, z + 0.02254}{z^3 - 2.759\, z^2 + 2.56\, z - 0.7993} \quad (38)$$

The step response of the closed-loop system and Bode diagram of the open-loop system are shown in figures 43 and 44 respectively.

Figures 43 shows the step response of the closed-loop system after using the controller. It is simulated in MATLAB and EMIs, noises and other disturbance are not considered. For a perfect simulation model, it is recommended to consider a noise and disturbance source.

As it is indicated in figure 43 and 44, the steady state error is completely terminated and the phase margin of the system is about 60 degrees.

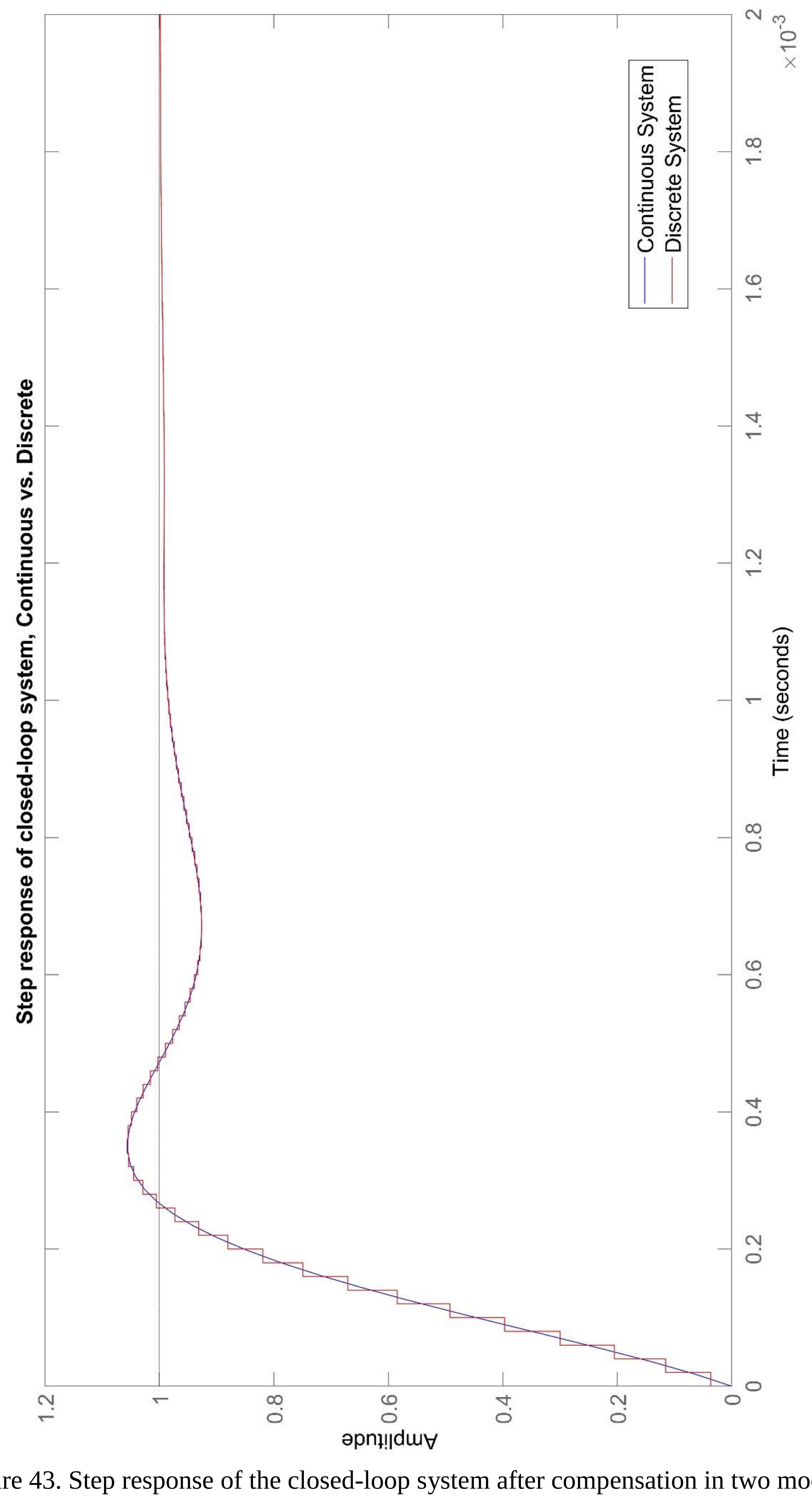

Figure 43. Step response of the closed-loop system after compensation in two mode, continuous and discrete.

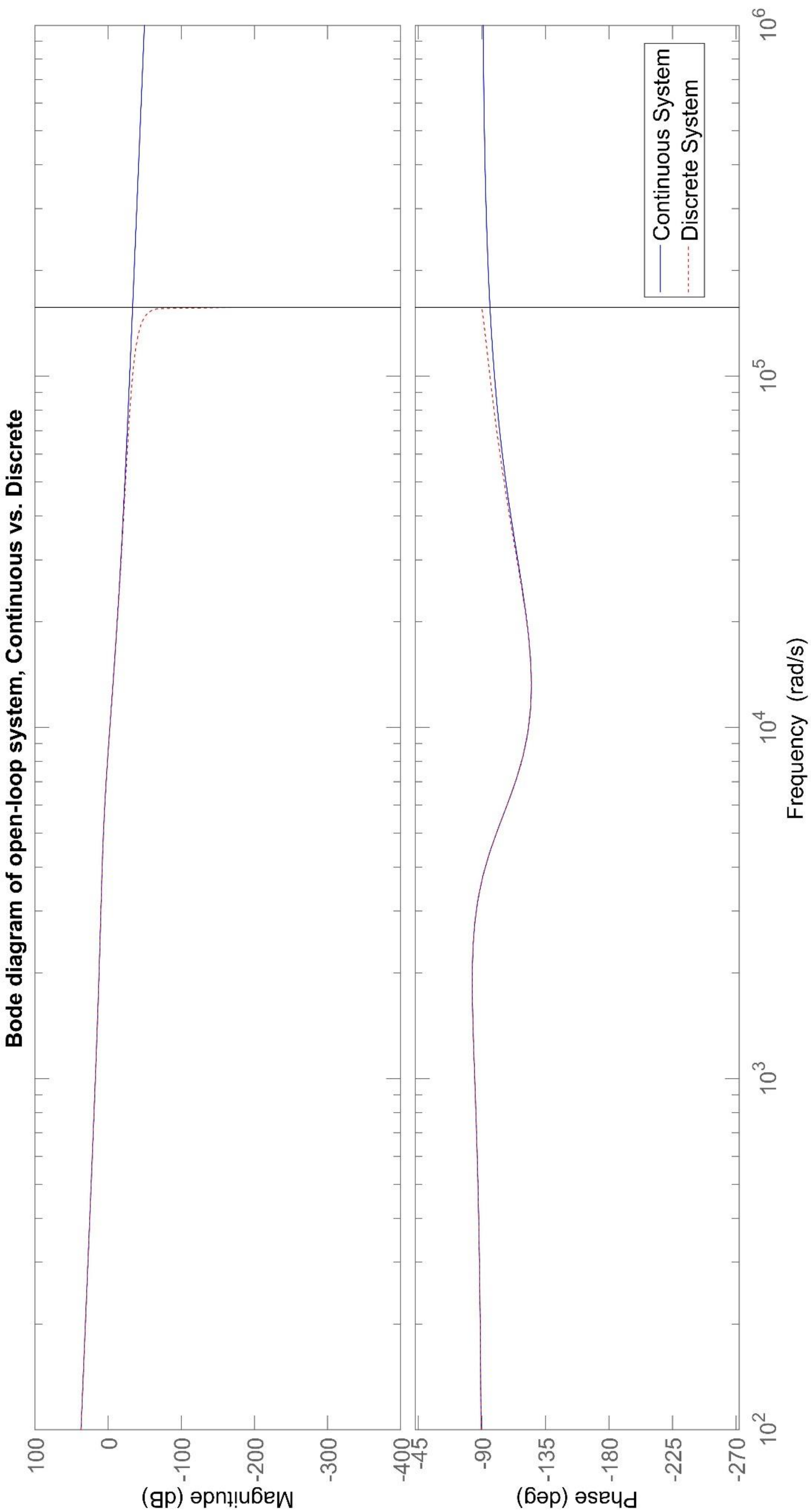

Figure 44. Bode diagram of the open-loop system after compensation in two mode, continuous and discrete.

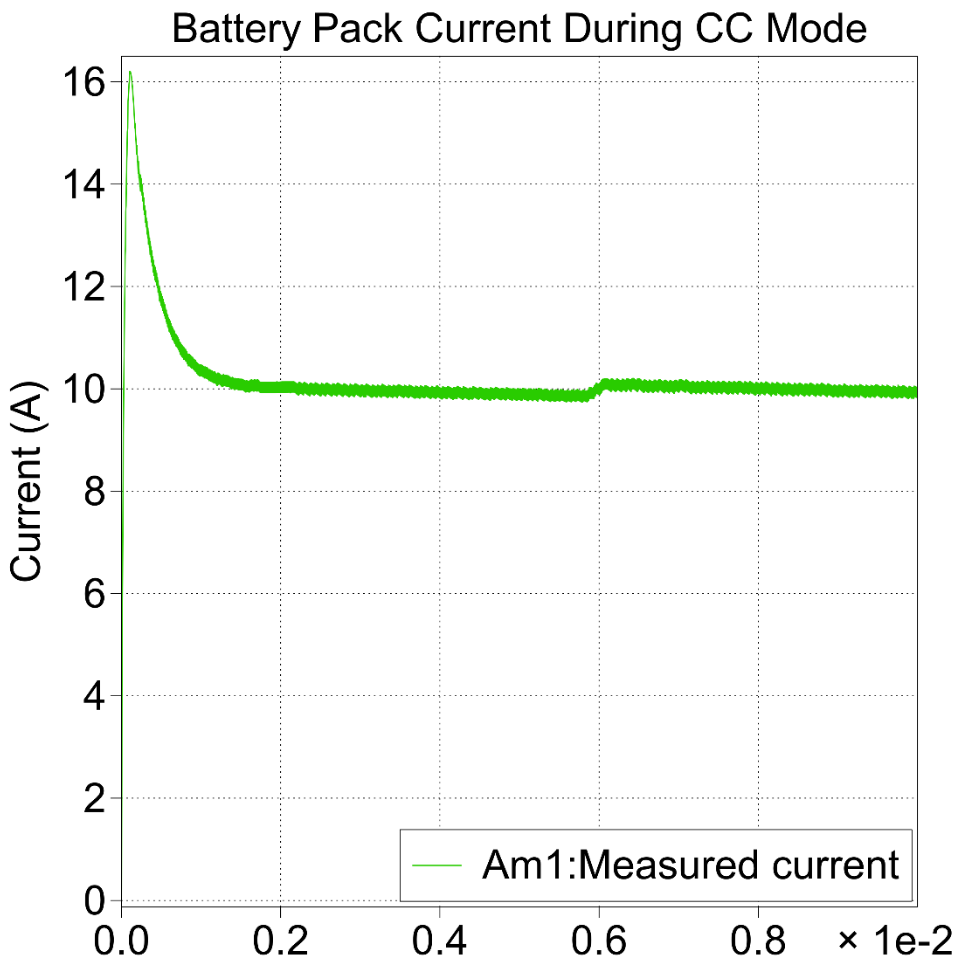

Figure 45. Test result of the system during step from 0 to 10 A during CC mode.

As indicated in figure 45, at start there is an overshoot equal to 60%. However, the rated current of the battery pack is much higher than 16 A and therefore it will not damage the batteries. Furthermore, the steady-state error for 10 A is completely eliminated and system is stable and robust.

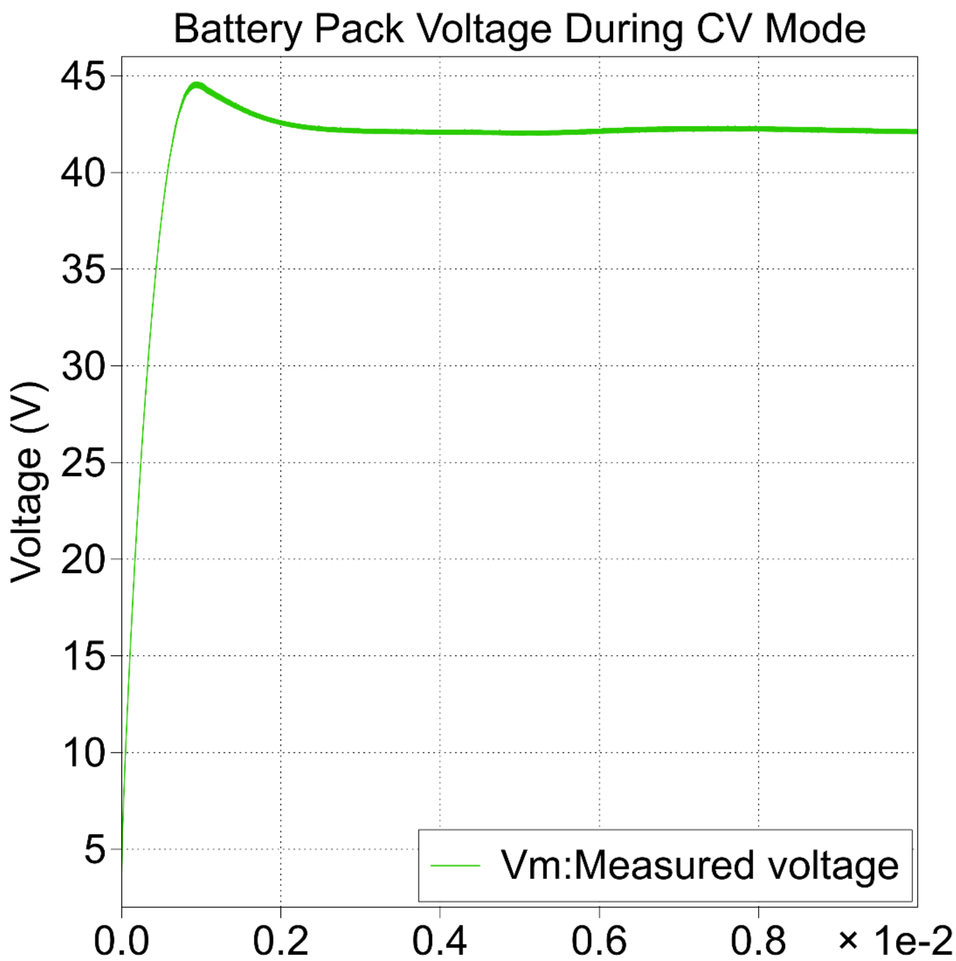

Figure 46. Test result of the system during step from 0 to 42 V during CV mode.

As it is shown in figure 46, at start the system faces an overshoot equal to 4%. Moreover, the steady-state error is almost zero.

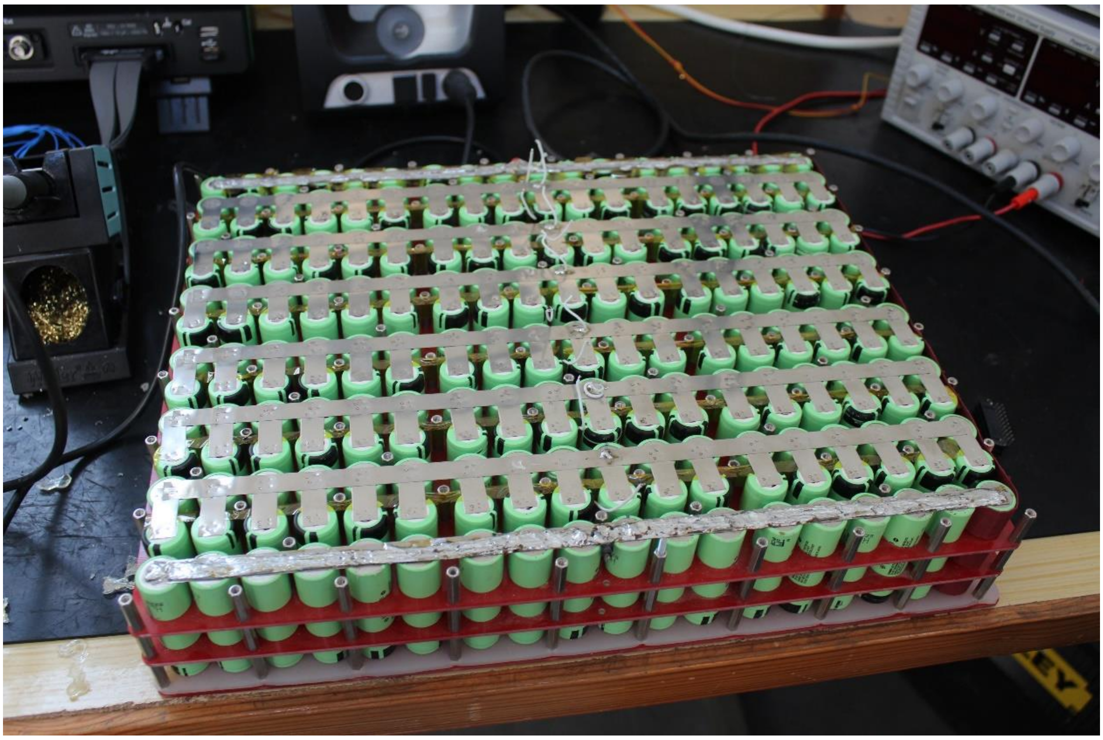

Figure 47. NCR18650B Panasonic batteries that used in the experiments.

In figure 47 an original battery pack that have been used in the experiments is show.

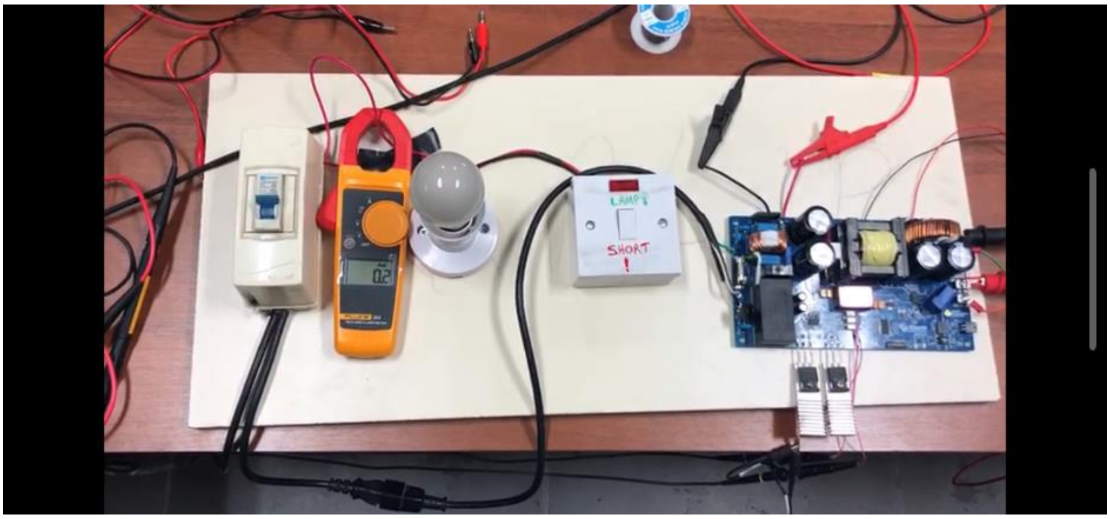

Figure 48. Setup of the experiments.

In the experiment, to illustrate if the short circuit is occurring or not, the circuit in figure 48 is used. In this manner, if there is a short circuit or inrush current at start the lamp turns on and gradually turns off.

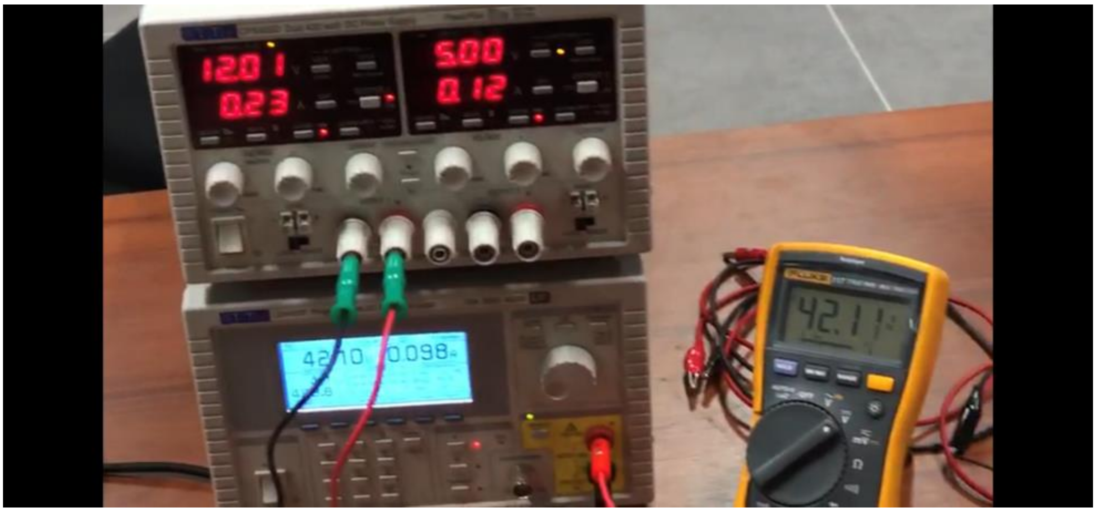

Figure 49. Power supply and digital load.

In figure 49, before testing the battery charger for NCR18650B, a digital load was employed for analysis and troubleshooting. In this figure, the battery charger is working in CV mode at 42 V.

Figure 50. Thermal camera used to monitor the components temperature.

It is essential to monitor the temperature of all components during developing an apparatus. In figure 50, a thermal camera is being used to monitor thermal state of all components, specially, switching components such as Diodes and MOSFETs.

Figure 51. Tektronix oscilloscope to monitor the voltage and current.

To observe and capture all control and power signals during designing and implementing the battery charger, a digital oscilloscope with bandwidth of 200 MHz and sample rate of 1GS/s is used (figure 51). It is necessary to use proper voltage probe and current probe when working with high power system such as medium power converters.

Chapter 5

CONCLUSION

In this study, an already known method for charging Lithium-Ion batteries, the CC-CV scheme is implemented on a prototype Half-bridge DC-DC power converter. During the design and implementing, many constraints had to be considered and managed. Charging a Li-Ion battery requires a proper battery charger with accurate sensing and regulating capability. The difficulties during the designing and implementing the battery charger are addressed. To produce a proper battery charger, protection and monitoring systems are necessary. Without the support of the protection circuits, one small error can easily damage the battery charger or the battery pack permanently.

Different power converter topologies were compared and their advantages and drawbacks were investigated. The best option to charge a battery pack consists of hundred cells of Panasonic NCR16850B (10x in series time 10x in parallel) is the half-bridge DC-DC converter. It is the optimum choice considering the cost of materials, the voltage stress on switching devices, and the power output. Afterwards, a digital controller was assigned to regulated the PWM module for the gate-drive. During the experimentation, a TI C2000 F28027D chip was tested and it showed a fine resistance against EMIs and environmental noises.

According to the simulation and experimental test, during constant voltage regulating, a Half-bridge converter is working properly. However, for keeping the current in a constant level it has some difficulties and need more complex control techniques. One important factor that is required for an advance constant-current technique is reading voltage of the input, although, in this prototype it was not possible to install such a sensor. In conclusion, the PI controller can effectively eliminate the steady-state error and it is sufficient as a compensator, since the gain margin and phase margin of the prototype is in acceptable range.

For future works, one way is to enhance the control method with an adaptive PI controller. The implementation is in such a way that the parameter of PI controller, K_p and K_I, will be updated in each interrupt of microcontroller. The new K_p and K_I will be picked in such a way that the best output will delivered to the load. This option is a powerful control method for loads that vary too much, or in places that the input voltage has a high tolerance. With the best pick of K_p and K_I the transient response can be enhance and the immunity of the system against noise and disturbances will be increased.

Another suggestion for future work is to design and implement a resonant converter as a battery charger. The resonant converter inherently suffer from high ripple current in output, however, with some proper control method and filtering this drawback can be reduced. Another issue with resonant converter is that it is not an excellent power converter for high output power. With some consideration it will be possible to use these very high efficient converters in medium and high power converters. Moreover, a complex control method with a very fast DSP are required for controlling the gate drive of these converters.

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