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A Digital Control System for UPS Systems with Smart Grid Capability

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A Digital Control System for UPS Systems with Smart Grid Capability

by

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A THESIS

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Abstract

Smart grids have recently become the center of attention for modernizing the grid system. In future smart-grids, energy storage systems are one of the key components, which can complement intermittent renewable energy sources and in turn increase reliability and efficiency of the grid system. Modern Uninterruptible Power Supply (UPS) systems can provide storage capacity for future smart grids since they usually include batteries. UPS systems can also provide instant electrical power to sensitive equipment and grid during various events such as brownout, power failures, spikes, voltage surges, EMI/RF noise, and frequency variations.

Future UPS systems require to have much better dynamics in order to deal with transients. The control system of UPS systems mainly determines their dynamical performance and transient response. The existing state-of-the-art UPS control systems are based on linear PI controllers for the most part. Thus, current UPS systems usually show a sluggish transient response and they are not suited for future smart grid applications where instant power is required to maintain the system.

In this thesis, new UPS systems with improved transient response are proposed. The proposed UPS system utilizes a new controller that is able to improve the dynamic performance and allows for various smart grid functionalities. The proposed control system is based on the adaptive control theory, which adaptively changes the controller's parameters based on the UPS operating conditions. Furthermore, the proposed control system isolates the double-frequency ripple from the battery in the normal/charging mode as well as in the backup/discharging mode. Therefore, the new UPS system is well-suited for single-phase systems utilizing lithium-ion battery as storage.

Mathematical analysis, simulation, and experimental results are presented to verify the performance of the proposed control system and demonstrate its superior performance.

Preface

This thesis is an original work by the author. No part of this thesis has been previously published.

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*Dedicated to my mother, **Parivash**, my father, **Jamshid**,
my beloved husband, **Mokhtar***

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List of Symbols, Abbreviations and Nomenclature

<u>Symbol</u>	<u>Definition</u>
ω	Grid frequency (Rad/S)
ϕ	Displacement angle (Rad)
C_{dc}	DC-bus Capacitor (F)
C_f	Active filter Capacitor (F)
C_o	Output filter Capacitor (F)
d	Duty cycle of full-bridge
d_f	Duty cycle of active filter
E_{C_f}	Energy of active filter capacitor (J)
E_r	Energy of DC-bus ripple current (J)
f_{sw}	Switching frequency of converter (Hz)
f_{fsw}	Switching frequency of active filter (Hz)
i_{grid}	Grid current (A)
i_{in}	Secondary current of tap-changer (A)
i_{dc}	DC-bus current (A)
i_{batt}	Battery current (A)

i_f	Active filter current (A)
$i_{f_{pk}}$	Peak current of active filter (A)
$i_{C_{dc}}$	DC-bus capacitor current (A)
I	Amplitude of grid current (A)
L	Input inductor(H)
L_{leak}	Leakage inductor(H)
L_f	Active filter inductor (H)
L_o	Output filter inductor (H)
n	Turn ratio of tap-changer
p_{grid}	Grid power (W)
p_{load}	Load power (W)
p_{in}	Input power of converter (W)
$p_{C_{dc}}$	DC-bus capacitor power (W)
p_{dc}	Average DC power (W)
T_s	Switching period of converter (s)
T_f	Switching period of active filter (s)
v_{grid}	Grid voltage (V)
v_f	Active filter capacitor voltage (V)
v_{batt}	Battery voltage (V)
v_{in}	Secondary voltage of tap-changer (V)
v_{tri}	Triangular voltage (V)
$v_{control}$	Control voltage (V)
v_{AB}	Output voltage of inverter (V)

v_{load}	Load voltage (V)
v_r	Ripple voltage (V)
V	Amplitude of grid voltage (V)
V_{dc}	DC-bus voltage (V)
<u>Abbreviation</u>	<u>Definition</u>
AEO	Annual Energy Outlook
ADC	Analogue to Digital Converter
ANF	Adaptive Notch Filter
$CPUC$	California Public Utility Commission
CH	Charging Mode
DCH	Discharging Mode
EMI	Electromagnetic Interference
EV	Electric Vehicle
ESR	Equivalent Series Resistance
ESS	Energy Storage System
$FPGA$	Field Programmable Gate Arrays
FC	Fuel Cell
GHG	Greenhouse Gas
GW	Gigawatt
HC	Harmonic Compensator
IMP	Internal Model Principle
LPF	Low Pass Filter

<i>LED</i>	Light-Emitting Diodes
<i>MUX</i>	Multiplexer
<i>MOSFET</i>	Metal-Oxide-Semiconductor Field-Effect Transistor
<i>PLL</i>	Phase Lock Loop
<i>PI</i>	Proportional-Integral
<i>PR</i>	Proportional-Resonant
<i>PV</i>	Photovoltaic
<i>PWM</i>	Pulse Width Modulation
<i>PSIM</i>	PowerSim
<i>PE</i>	Persistency of Excitation
<i>RF</i>	Radio Frequency
<i>RL</i>	Relay signal
<i>RIB</i>	Ripple Isolator Block
<i>SOGI</i>	Second Order Generalized Integrators
<i>UPS</i>	Uninterruptible Power Supply
<i>VHDL</i>	VHSIC Hardware Description Language

Chapter 1

Introduction

1.1 Background and Motivation

Smart grids have become a center of attention when considering the modernization of the electrical grid. The implementation of smart grids increases the reliability, robustness, and efficiency of electrical systems [2–4]. Fig.1.1 displays the block diagram of a smart grid. Future smart grids will likely be based on the distributed power generations scheme where renewable energy sources will make up most of the power generation. This will be a significant paradigm shift from the current centralized power generation scheme and presents new requirements and challenges. One of the main challenges to be addressed is the intermittent nature of renewable energy sources.¹

Managing this challenge can be dealt with in two primary ways. One solution is to use backup power generations. Conventional power plants, such as gas turbines, can be overbuilt to ensure excess capacity in times when renewable generation is scarce. Similarly, transmission lines can be expanded to move power from regions of abundance to those in need. This solution, however, will not help to reach the main goal of smart grids, which is to mitigate the Greenhouse (GHG) emissions. Another solution is to use energy storage

¹Wind turbines generate electricity only if wind blows and solar panels generate electricity only if the sun shines. To maintain smart grids reliability, however, generation and load must match on a second-by-second basis.

systems. In particular, energy storage systems have long been viewed as having the potential to be a direct and elegant solution to the problem of intermittency, along with providing valuable ancillary services to the grid [2–7].

Figure 1.1: Block Diagram of a Smart Grid.

Recently, there has been a surge in the policies supporting energy storage technologies. For example, in 2013, the California Public Utility Commission (CPUC) set a mandate for the state’s investor-owned utilities to procure 1,325 MW of energy storage by 2020 under Assembly Bill 2514. In January 2018, New York set a target of 1500 MW of energy storage by 2025. Aside from targets, some states, such as Nevada, allow energy storage to be included in renewable portfolio standards. Moreover, some states have provided financial

incentives for energy storage including grants, support for pilot projects, and tax incentives. In 2018, Maryland began to offer a tax credit of 30% on the installed costs for residential and commercial systems [1,8].

It is expected to have more regions to change their regulations and policies in order to facilitate the development of energy storage systems in the recent future. The next section describes all potential storage applications and reviews different energy storage systems.

1.2 Energy Storage Systems

Energy storage systems offer several benefits to the grid. Storages can be used to smooth out extreme variability of renewable generations, to store excess power generated from renewable resources, and to release it when demand is high. Moreover, storages can mitigate the variability and uncertainty of the entire grid by leveling load, responding to power plant failures, and providing the uninterruptable power supply. Furthermore, it can provide ancillary services such as voltage support, frequency regulation, and other fast-acting services. Therefore, energy storage systems are considered to be one of the fundamental components in the future smart grids, and micro-grids, which substantially increase the reliability and security of grids [1–8].

There are a number of energy storage technologies available which are mainly categorized in mechanical, electrical/magnetic fields and electrochemical storages. Each technology has been developed for a different application according to its strengths and weaknesses. The categorization of energy storage systems is displayed in Fig.1.2. According to this figure, mechanical storages include compressed air energy storage, pumped hydro storage, and flywheels. In the compressed air energy storage, the energy is stored by compressing the air in an underground cavern where the air can later be heated and expanded in a turbine to generate electricity. In the pumped hydro energy storage, the energy is stored by pumping water up to a large-scale reservoir. When extra electricity is needed, the water can be re-

leased through a turbine to generate electricity. Although compressed air and pumped hydro storages constitute the majority of large-scale energy storage systems, their usages are limited to specific geographies. Therefore, they are not viewed as a scalable solution for smart grid applications. In the flywheel energy storage, the energy is stored as kinetic energy by spinning a rotor in a frictionless enclosure. Since flywheels have high power losses, they are only useful for short-term energy storage applications such as power management. In electrical/magnetic field storage, the energy is saved in the electrical field established between the plates of ultra-capacitors. The electrochemical storages are different types of batteries that store the energy as electrochemical reactions which is later released by discharging to electrical energy.

Figure 1.2: Categorization of Energy Storage Systems.

The batteries' industry has been receiving large technological advancements in recent decades. At the same time, by dropping the cost of batteries, new economic opportunities open up for battery energy storages that can provide a wide range of grid services. Furthermore, batteries can provide flexible, efficient and clean energy storage compared to other

energy storages. Therefore, battery energy storage will make up the most storage capacity in the near future.

In the United State, the Annual Energy Outlook (AEO) forecasts the future power capacity of the renewable energy sources and battery energy storages until 2050 [1]. Based on the AEO projections, the wind capacity growth of 50 gigawatts (GW) and large-scale solar photovoltaic capacity growth of nearly 150 GW by 2050. Furthermore, in order to support the renewable energy sources, the capacity of battery energy storage systems will be increased to 40 GW by 2050, as shown in Fig.1.3 [1,9]. In the next subsection, the two most popular battery energy storage systems and their features are reviewed.

Figure 1.3: Wind, Solar, and Battery Storage Capacity Projections (2020–2050) of the United State [1].

1.2.1 Battery Energy Storage System

Two of the most common types of battery storage systems are lead-acid and lithium-ion batteries. Lead acid batteries are one of the oldest forms of the battery storage which their

development started in the 19th century. They are commonly adapted to be used in different applications such as off-grid power systems, Uninterruptible Power Supply (UPS) systems, Electric Vehicles (EV), and etc. Lead acid batteries can provide large storage capacities with relatively low cost. However, their lifetime is short compared to the other battery technologies. Moreover, their power density is lower than other technology types. For these two main reasons, more attention has been made towards other battery systems in the recent decades. Specifically, lithium-ion batteries have become the center of attention.

In the last decade, lithium-ion batteries have become the most popular type of batteries. Large-scale lithium-ion batteries accounted for about 86% of the U.S. installed capacity in 2016 [1]. Lithium-ion batteries can provide higher power density and higher efficiency. Although lithium-ion batteries are relatively expensive, their technologies are continuously developing and their cost is falling progressively. The main benefit of these batteries is that they can be charged and discharged more often compared to the lead-acid batteries without significant deterioration of lifetime and capacity. Therefore, lead-acid batteries are progressively substituted by the lithium-ion batteries in many applications such as the electric vehicles and UPS systems. UPS systems, in particular, are switching from lead-acid batteries to incorporate lithium-ion batteries. The switching trend has significantly grown in the past few years. This thesis focuses on the lithium-ion based UPS systems. The next subsection introduces the UPS systems and their applications.

1.2.2 Uninterruptible Power Supply

UPS is a device that instantaneously provides electricity for the sensitive loads when power outages happen. UPS systems can efficiently integrate batteries into the grid and load through a converter [7, 10–13]. UPS systems operate in two modes: normal mode and backup mode. In the normal mode, the UPS is used as an interface to provide high-quality power for the load by amplifying/attenuating and filtering the line voltage. In the event of power failure, the UPS enters backup mode, the utility grid is disconnected from the load

and the energy stored in batteries is made available to the load by the UPS [14–17].

UPS devices have been used in various applications. Data centers, for example, are using the UPS systems to ensure the continuous provision of electricity. Without the UPS systems, any power outages and fluctuations can result in hardware damage or data loss. The vast growth in data centers and cloud storage systems in the recent years has tremendously increased the demand for the UPS systems [18–22].

UPS systems are also crucial for hospitals, where power fluctuations can be very dangerous for patients. Modern healthcare facilities depend on UPS systems not only to operate these device constantly but also protect vital electronic data. Even short power outages or fluctuations can be detrimental to patients in critical care or who are undergoing surgery. Furthermore, UPS systems will be important to some emerging applications such as future smart cities, smart grids, micro grids, etc. Thus, they are essential for many applications and their usage will likely grow exponentially in the near future [23].

The industry of the UPS systems is moving toward adopting lithium-ion batteries instead of the lead-acid batteries. However, using lithium-ion batteries in the UPS system introduces some challenges. The following section explores the main challenges of the UPS systems in more detail.

1.3 Main Challenges of the UPS Systems

The analysis of existing state-of-the-art configuration and control systems of the UPS system confirms that the UPS systems can provide high reliability and stability standards for the future smart grids if they can offer fast transient performance. The control system is critical to improving the transient performance of the UPS system. Lithium-ion batteries will likely form the battery storage systems for the future UPS systems. Although lithium-ion batteries have high power density, efficiency, and lifetime, they cannot handle low-frequency ripples. Therefore, there is a great need to find a configuration and a control system that can eliminate

low-frequency current ripples on the battery side and provide a fast transient performance for the UPS system, respectively. The main problems with the existing configuration and control systems are mentioned below:

- Bulky DC-bus capacitor.
- High Low-frequency ripple in the battery current.
- High voltage and current stress.
- Sluggish transient response.
- Low stability margin.
- High complexity and low reliability.
- Not robust against frequency variations.

1.4 Thesis Contribution

The followings are the main contributions of this thesis:

- A configuration of the UPS system with an active filter has been introduced for the future smart grids. This configuration is utilized in order to suppress the double-line frequency in the battery side of the UPS system.
- A new digital control system has been proposed for the control system of the UPS system with an active filter. The proposed control system improves the dynamic performance of the UPS systems.
- Stability analysis of the proposed control system has been conducted. The Lyapunov stability theory is provided to prove the stability of the proposed control system.

- The proposed control system has been successfully simulated in the PowerSIM (PSIM) and been implemented experimentally. The prototype of UPS system with an active filter has been developed using PCB design software (Althium Designer) and evaluated in the normal and backup modes of operation. Furthermore, due to verify the superior performance of the proposed control system, both the proposed and the conventional control systems have been investigated through the simulation and experiment.
- The mathematical modeling and design procedure for the components of the UPS system have been derived and explained.
- A Field Programmable Gate Array (FPGA) device and VHSIC Hardware Description Language (VHDL) have been used to implement the digital control system of the proposed control system for the UPS system with an active filter.

1.5 Thesis Outline

The thesis is outlined as follows:

- Chapter 2: This chapter reviews the different configurations of the UPS systems. Furthermore, several methods of mitigating the double-frequency ripple in the single-phase converter are introduced. Finally, the main drawbacks and advantages of each method are studied in detail.
- Chapter 3: In this chapter, the mathematical model of the UPS system with an active filter is derived in both the normal and backup modes. Furthermore, the procedures for designing components of the UPS system are explained in detail.
- Chapter 4: In this chapter, a new control system for the UPS system with an active filter is proposed. Furthermore, the stability of the proposed control system is investigated by the Lyapunov theory. Finally, a comparative analysis between the con-

ventional control system and the proposed control system is analyzed, and then the performance of the proposed control system is evaluated through simulations.

- Chapter 5: In this chapter, the experimental results of the UPS system with an active filter are presented. These results verify the superiority of the proposed control system compares to the conventional ones.
- Chapter 6: This chapter summarizes the thesis chapters along with all of the contributions of the thesis. This chapter is supplemented by recommendations for future work.

Chapter 2

literature Review

The global UPS market has experienced vast growth in recent years due to a tremendous increase in data centers and cloud storage systems. UPS systems are also crucial for hospitals where power fluctuations can be very dangerous for patients. UPS systems will be essential to some emerging applications such as future smart cities and traffic, smart grids, micro-grids (they can provide storage capacity for micro-grids), etc. [10–13]. Thus, they are essential for many applications and their usage will grow exponentially in the near future.

UPS systems can provide instant electrical power to sensitive equipment during various events such as brown-out, power failures, spikes, overvoltages, Electromagnetic Interference/Radio Frequency (EMI/RF) noise, and frequency variations. UPS systems operate in two modes: normal mode and backup mode. In the normal mode, the UPS is used as an interface to provide high-quality voltage for the load by amplifying/attenuating and filtering the grid voltage. In the event of power failure, the utility grid is disconnected from the load and the stored energy in batteries is made available to the load by the UPS (the backup mode) [14–18]. Consequently, the UPS provides protection for sensitive equipment as they prevent them from instant shut-off or being exposed to the distorted grid voltage.

2.1 Classification of UPS Systems

In this section, various UPS configurations are described. The common configurations are: Offline (standby), Line-interactive, and Online [18–22]. In the following subsections, these configurations will be described.

2.1.1 Offline UPS Systems

Fig.2.1 shows the block diagram of an offline UPS system. In offline UPS systems, a static switch is used to switch between the normal mode and backup mode. In the normal mode, the battery is charged through an AC/DC battery charger and the load is directly connected to the grid. Therefore, in the normal mode operation, offline UPS systems have the highest efficiency since no components are used between the load and the grid. In the backup mode, the static switch disconnects the grid from the load and connects the battery to the load through a DC/AC inverter [24]. The main benefits of the offline mode architecture are its simplicity, high efficiency in the normal mode, low cost, and high power density (since it does not use a line-frequency transformer). However, the main drawback of offline UPS systems is that the load is continuously exposed to spikes, transients, and voltage sags and surges present at the utility grid, which can damage sensitive equipment [15, 16].

Figure 2.1: Circuit Diagram of Offline UPS system.

2.1.2 Line-Interactive UPS Systems

Fig.2.2 shows the block diagram of a line-interactive UPS system. Line-interactive UPS systems are the most common configuration used for small businesses, web, data centers, and departmental services. Line-interactive UPSs consist of an autotransformer, a bidirectional AC/DC converter, and batteries. In the normal mode of operation, the static switch connects the utility grid to the load via an auto-transformer [24,25]. The auto-transformer allows for stepping-up or stepping-down of the grid voltage when there are voltage sags or surges in the power line. The bidirectional AC/DC converter is placed between the battery and the load. This converter acts as a battery charger in the normal mode of operation and acts as an inverter in the backup mode (when static switch disconnects the power line from the load). The main difference between the line-interactive UPS and the offline UPS is the auto-transformer. The autotransformer is able to effectively regulate the grid voltage in the normal mode while maintaining the cost low (the cost of a line-frequency auto-transformer is considerably low). However, since a line-frequency transformer takes up huge space, the power density is consequently low for line-interactive UPSs [25].

Figure 2.2: Circuit Diagram of Line-interactive UPS System.

2.1.3 Online UPS Systems

Fig.2.3 shows the block diagram of an online UPS system. Online UPS systems have a very different architecture in the normal mode of operation. In online UPSs, a back-to-back converter is used to supply the load in the normal mode of operation. The battery is connected to the high voltage DC bus through a bidirectional DC/DC converter. The main advantage of using online UPS systems is that the load is always supplied with a very clean and smooth AC voltage independent of the line conditions. The back-to-back converter effectively isolates the adverse impacts of the utility grid from the load. Thus, it can provide high-quality voltage for sensitive equipment regardless of the line quality. In addition, online UPSs have much higher power density compared to line-interactive UPSs due to the elimination of the line-frequency transformer. Although online UPSs can demonstrate very high performance and provide high-quality power for sensitive loads, their efficiency can be low during the normal mode of operation. Online UPSs have more conversion stages and in turn may have more losses in the online mode, which deteriorate their efficiency [18,19]. Also, their cost is higher compared to the other types since the cost of back-to-back converters are more than a line-frequency auto-transformer.

Figure 2.3: Circuit Diagram of Online UPS System.

Due to the high reliability of line-frequency transformers and their high efficiency, most

of the UPS products in the market are based on the line-interactive UPS configuration. In particular, the reliability of power electronic components cannot compete with the reliability of line-frequency transformers. Thus, despite the multiple difficulties caused by the line-frequency transformer (e.g., low power density, packaging issues, etc.), most of the products in the market use line-frequency tap-changers. Table.2.1 demonstrates the detailed comparison between the three UPS configurations.

Table 2.1: Comparison of UPS System Configurations

UPS System topologies			
Attributes	Off-Line	Online	Line-Interactive
Power Application	Low power	High power	Medium/high power
	0-0.5 (kW)	5-5000 (kW)	0.5-5 (kW)
Efficiency	High	Low	High
Isolation of loads from utility	No	Yes	Yes
Power regulating & compensation capabilities	No	Yes	Yes
Cost, size, and weight	Low	High	Medium
Transition performance	4-10 (ms)	very low	1-5 (ms)
Inrush currents possibility	Yes	No	Yes
Inverter always operating	No	Yes	No

2.2 Topology of Single-Phase AC/DC Converter

Single-phase AC/DC converters are widely used in low-power applications such as UPS systems, Photovoltaic (PV) systems, Light-Emitting Diodes (LEDs) drivers, Fuel Cell (FC) power systems, Electric Vehicle (EV), and battery chargers, etc [26, 27]. One of the main difficulties with the single-phase AC/DC converter is the existence of the double-frequency power in the DC-bus. Unfortunately, this inherent double-frequency ripple power results in

undesirable low-frequency ripple on DC-bus voltage/current. Fig.2.4 shows a single-phase AC/DC converter. According to this figure, i_{grid} is the grid current and v_{grid} is the grid voltage of the single-phase AC/DC converter are given by:

Figure 2.4: Circuit Diagram of Single-Phase AC/DC Converter.

$$v_{grid} = V \cos(\omega t) \quad (2.1)$$

$$i_{grid} = I \cos(\omega t + \phi) \quad (2.2)$$

where V and I are the amplitudes of grid voltage and current, respectively and ω is the grid frequency. ϕ is the displacement angle between voltage and current of the grid which is desirable to be zero for unity power factor operation. The instantaneous power of the grid, p_{grid} , is given as follow:

$$p_{grid} = i_{grid}v_{grid} = \frac{1}{2}VI \cos(\phi) + \frac{1}{2}VI \cos(2\omega t + \phi) \quad (2.3)$$

When the phase shift is zero, $\phi = 0$, the grid power can be rewritten as:

$$p_{grid} = i_{grid}v_{grid} = \frac{1}{2}VI + \frac{1}{2}VI \cos(2\omega t) \quad (2.4)$$

The instantaneous grid power consists of the average output power ($\frac{1}{2}VI$) and the ripple power ($\frac{1}{2}VI \cos(2\omega t)$) which oscillates at double-line frequency. This ripple power will appear in the voltage or current of DC-bus. This ripple makes the control system more complicated and has a detrimental impact on the performance and efficiency of the converter. Therefore, this ripple should be suppressed by a decoupling circuit.

In a line-interactive UPS system, there is a significant amount of current ripple drawn from or injected into the battery in both charging and discharging modes of the battery. This current ripple drastically reduces the lifetime and durability of the battery. Lead-acid batteries are commonly used in UPS systems as they can safely handle high amounts of current ripple. Nevertheless, their lifetime is significantly reduced by this ripple. Presently, lead-acid batteries are being replaced by more efficient lithium-ion batteries [28]. LI batteries are very sensitive to low-frequency current ripples and they can only safely handle very small amounts of ripples [28–31]. Apart from disastrous effects on the batteries, the existence of these current ripples may have a deleterious functional impact on the transient performance of the UPS system and cause reduced conversion efficiency [32–35]. Thus, in the future UPS systems, the current ripple should be suppressed in order to protect the batteries and ensure the reliability and performance of the system. In the recent years, multiple studies have attempted to mitigate the double-frequency current ripple on the DC side of single-phase AC/DC converters [27, 36–47]. Their solutions are broadly classified into passive decoupling and active decoupling techniques. In this section, different topologies that have been suggested to mitigate and suppress the double-frequency ripple are explained.

2.2.1 Single-Phase AC/DC Converter with C/LC Filter

The most common method to mitigate the double-frequency ripple current is the passive decoupling method which involves the insertion of energy storage devices/passive components to the DC-bus of single-phase converters [36–38]. In the conventional topology, a bulky electrolytic capacitor was recommended to decrease the low-frequency ripple current and smooth DC-bus voltage. The main issue of this method is that the equivalent series resistance (ESR) of the electrolytic capacitor causes large losses and heats up with larger ripples. This heat leads to reduce power density and shorten the component lifetime. To reduce the amount of the electrolytic capacitor and detrimental impacts of electrolytic capacitor's power losses, the LC filter connected in parallel with the DC capacitor has been suggested in [48,49]. In this technique, a small film capacitor has been adopted instead of the large electrolytic capacitor, which has lower ESR component. The LC filter is tuned to the double-frequency. However, extra passive components which introduce to the system have their power density limitation. Furthermore, although the implementations of these methods are very simple, they cannot completely eliminate the ripple from the battery side. Therefore, they are not suitable to be adopted for the UPS system with lithium-ion batteries.

2.2.2 Two-Stage AC/DC/DC Converter

The main idea of the active decoupling method is to absorb the ripple power by another energy storage component via an extra active switching circuit. In [39–42, 50, 51], an extra power decoupling circuit is proposed, which utilizes a two-stage DC/DC-AC converter along with the existing DC-link electrolytic capacitor. Fig.2.5 shows the topology of the two-stage converter. This topology is constructed two stages: the first stage is a full-bridge AC/DC converter and the second stage is a boost DC/DC converter. Since the main power will be passed through the DC/DC converter, switches of the DC/DC converter should have the same features of the four switches of full-bridge which lead to considerably increase conduction losses and additional cost. Furthermore, this topology still needs a bulky electrolytic

capacitor in order to smooth output voltage and reducing current ripple. Therefore, although the two-stage converter is able to significantly attenuate the low-frequency ripple, it has relatively low efficiency, high complexity, and high costs. Also, this method has a very low transient performance.

Figure 2.5: Circuit Diagram of Two-Stage AC/DC/DC Converter.

2.2.3 Single-Phase AC/DC Converter with an Active Filter

Another active decoupling method is to install an active filter in parallel with the DC-bus and make the ripple power solely supplied by this additional bidirectional DC/DC converter [27, 52–58]. Fig.2.6 shows the topology of the bidirectional converter with an active filter. In this method, the bulky electrolytic capacitor is replaced by a small film capacitor which is only responsible for handling the high-frequency ripples. Although the proposed topology still suffers from having an extra active auxiliary circuit, it can ensure eliminating the double-frequency ripple from the battery side. Therefore, this topology is appropriate to utilize with lithium-ion batteries. Furthermore, the auxiliary DC/DC converter only carries the double-frequency ripple that leads to significantly lower conducted loss compared with the two-stage converter. Due to all these advantages, a single-phase AC/DC converter with active filter has been used for the line-interactive UPS system application. The focus of this thesis is on the control system of the active filter.

Figure 2.6: Circuit Diagram of AC/DC Converter with an Active Filter.

2.3 Control System of a Single-Phase AC/DC Converter

In the line-interactive UPS systems, bidirectional AC/DC converters are utilized for interfacing the battery energy storage to the utility grid. The line-interactive UPS systems operate in two modes of normal and backup modes. In the normal mode, the bidirectional AC/DC converter is used as a rectifier to charge the batteries. In the backup mode, the bidirectional AC/DC converter is operated as an inverter and the batteries provide the power for the load or grid utility. The control of the AC/DC converter is great importance to the integration of the battery energy storage into the grid and load.

The control system of a bidirectional single-phase AC/DC converter usually includes two cascaded control loops. Fig.2.7 shows the control system of an AC/DC converter when it acts as a rectifier. According to this figure, the control system of the converter consists of both an external and an internal current control loop. The external current loop is responsible for regulating the DC current to a reference value and the internal current loop is responsible for ensuring that the input current tracks a sinusoidal reference signal synchronized with the grid voltage.

In the external current control loop, the Proportional-Integral (PI) controller can be

Figure 2.7: Control System of a Single-Phase Rectifier.

utilized to adjust the DC current to the reference value. PI-controllers have high gain at a frequency of zero, therefore, it can accurately track a DC reference. The output of the aforementioned PI-controller is then multiplied by a template of the grid voltage that is produced by a Phase Lock Loop (PLL) block, denoted by v_{grid} in order to create a reference signal for the transformer current.

The inner current control loop is responsible to force the grid current following the sinusoidal reference. However, tracking a sinusoidal reference seems to be challenging because the control loop should have a very high gain at the frequency of the reference signal (i.e., line frequency) [59–61]. In the conventional control system, the PI-controller has widely been used in the bidirectional converters [62–65]. Since the grid frequency is 60 Hz which is relatively low, PI-controller is able to provide a reasonably high gain at the grid frequency as well. Although a PI-controller with high bandwidth can technically be used for this application, its high bandwidth introduces instability in the control system. Furthermore, the high gain of PI-controller causes some phase delay in following the sinusoidal reference current which causes deterioration of the power factor. Therefore, the PI-controller is not the appropriate controller for this application. Different controllers have been presented in the literature to address this issue.

• PR-Controller

Proportional-Resonant (PR) controllers have been proposed in [61,66,67]. PR-controllers are basically bandpass filters that can be tuned to the grid frequency. Therefore, a PR-

controller can provide a very high gain at the grid frequency, leading to nearly perfect tracking of the sinusoidal reference according to the Internal Model Principle (IMP) [68,69]. The PR-controller has widely been used in bidirectional converters to ensure that the grid current precisely follows a sinusoidal reference synchronized with the grid voltage. The transfer function of the PR-controller is defined as:

$$H_{PR} = \frac{s}{s^2 + 2\zeta\omega s + \omega^2} \quad (2.5)$$

where ω is the center frequency of the bandwidth and ζ is the damping ratio. The damping parameter, ζ , determines the width of the bandpass. High damping ratio causes phase transition in the controller. Due to having sufficient gain to nearly perfectly track the sinusoidal signal, the PR-controller with very low damping ratio, $\zeta = 0$, is usually used. The transfer function of the PR-controller by $\zeta = 0$ is defined as:

$$H_{PR} = \frac{s}{s^2 + \omega^2} \quad (2.6)$$

The PR-controller should be designed and tuned at the grid frequency of 60 Hz, which ensures the grid current follow the sinusoidal reference signal. The z-domain transfer function of the PR-controller using the bi-linear transformation can be derived as follow:

$$H_{PR}(z) = \frac{b(1 - z^{-2})}{1 + az^{-1} + z^{-2}} \quad (2.7)$$

$$b = \frac{2T_s}{T_s^2\omega^2 + 4} \quad (2.8)$$

$$a = 2\frac{T_s^2\omega^2 - 4}{T_s^2\omega^2 + 4} \quad (2.9)$$

Where T_s is the sampling period.

• PR-Controller with Harmonic Compensator

The PR-controller performs such that the grid current precisely tracks this sinusoidal wave-

form by providing a high gain at the line-frequency. However, the bandwidth of the PR-controller is limited which leads to appearing the other harmonics in the grid current. These harmonics come from the non-linearity in the system. Therefore, the control system needs harmonic compensator in order to eliminate the harmonic contents of the grid current. In [70], a PR-controller combined with Harmonic Compensators (HC) are proposed to suppress the harmonics in the grid current. The harmonic compensator is basically the PR-controller which its centre frequency is tuned to the respective harmonic frequency (3rd, 5th, 7th, ...). Therefore, the harmonic compensators provide high gains at the harmonic frequencies which leads to rejection of the harmonics. The control system of PR-controller with a harmonic compensator for the bidirectional AC/DC converter is shown in Fig.2.8. The general transfer function of the harmonic compensator is given by:

$$H_{HC} = \sum_{h=2,3,\dots}^n -k \frac{s}{s^2 + (h\omega)^2} \quad (2.10)$$

Figure 2.8: Current Control loop of a AC/DC Converter with a Harmonic Compensator.

• PR-Controller and PI-Controller with Harmonic Compensator

Since the PR-controller has a lower gain in the zero frequency, it has a negligible effect on the DC component of the error signal. DC components can be introduced into the closed-loop control system from various sources, such as sensors. Therefore, the PI-controller is used along with PR-controller and harmonic compensators in order to compensate for any

DC-offset of the error signal. Although the PR-controller along with a PI-controller and the harmonic compensator can technically provide perfectly tracked the sinusoidal reference signal, there are several difficulties with the digital implementation of this control system [71].

Fig.2.9 shows this control system.

Figure 2.9: Current Control loop of AC/DC Converter with PR-controller, PI-Controller and Harmonic Compensator.

• Adaptive PR-Controller

The frequency of the utility grid can vary in the smart grid due to the intermittent nature of renewable energy sources. The regulatory standards for interconnecting renewable energy sources with the utility grid (e.g. IEEE1547) determine the range of frequency variation. The PR-controller is only able to accurately track the sinusoidal reference with the 60Hz frequency because the coefficients of the PR controller are tuned to the fixed value of the line frequency. Therefore, this controller is not robust against the frequency variations. The discrepancy between the tuned frequency and the grid frequency in the PR-controller creates a steady-state error in the tracking of the reference signal. In [71], an adaptive PR-controller has been proposed to address the frequency variation problem. Furthermore, this paper proposes the time-domain controller which is designed based on the dynamics of the system in order to improve the transient response of the AC/DC converter by providing kind of

prediction of the system dynamics. The control system of the adaptive PR-controller along with time-domain controller is shown in Fig.2.10. According to this figure, the coefficients of the PR-controller adaptively are changed based on the error of the grid current from the reference value and the grid frequency calculated by the PLL block. New coefficients of the adaptive PR-controller are calculated based on Update laws which are given by:

Figure 2.10: Current Control loop of AC/DC converter with Adaptive PR.

$$\dot{\hat{a}} = \alpha e_{i_{grid}} \sin(\omega t) \quad (2.11)$$

$$\dot{\hat{b}} = \beta e_{i_{grid}} \sin(\omega t) \quad (2.12)$$

With reference to the z-domain transfer function of the PR-controller and new equations for the coefficients of the adaptive PR-controller, the proposed frequency domain control equations in the discrete domain are given by:

$$u_{i_{grid}}(n) = \lambda(n) - \lambda(n-2) - u_{i_{grid}}(n-1)\hat{a}(n) - u_{i_{grid}}(n-2) \quad (2.13)$$

$$\lambda(n) = \hat{b}(n)e_{i_{grid}}(n) \quad (2.14)$$

$$\hat{a}(n) = a_0 + \hat{\phi}_a(n) \quad (2.15)$$

$$\hat{b}(n) = b_0 + \hat{\phi}_b(n) \quad (2.16)$$

$$\hat{\phi}_a(n) = \alpha e_{i_{grid}}(n) \sin(\omega n T_s) + \hat{\phi}_a(n-1) \quad (2.17)$$

$$\hat{\phi}_b(n) = \beta e_{i_{grid}}(n) \sin(\omega n T_s) + \hat{\phi}_b(n-1) \quad (2.18)$$

Fig.2.11 shows the block diagram of the digital implementation of the adaptive PR-controller. The coefficients of the PR-controller are updated according to the amplitude and the phase of the grid current. Due to variable coefficients, the bandwidth of the adaptive PR-controller is virtually increased to cover the variation of grid frequency in the system and have a high gain for the fundamental component and the harmonics. Therefore, the adaptive PR-controller is able to precisely tracks the sinusoidal reference signal which leads to much better steady-state performance. Furthermore, by virtually increase the bandwidth of the PR-controller, the control system does not require an extra PI-controller and harmonic compensator. Thus, the digital implementation of this control system becomes considerably simple compared with the conventional current controller.

Fig.2.12 shows the control system of a bidirectional single-phase converter when it acts as an inverter. Similar to the control system of the rectifier, it includes two cascaded control loops. The control system consists of an external voltage controller cascaded with an internal current controller. Since the grid voltage is absent, the voltage controller is responsible to regulate the output voltage. The internal current loop compensates for input supply disturbances and the external voltage loop generates the reference for the internal current controller. In this control system, PR-controllers or adaptive PR-controller can be utilized for both voltage and current control loops.

Figure 2.11: Digital Implementation of the Adaptive PR-Controller.

Figure 2.12: Control System of a Single-Phase Inverter.

2.4 Modulation of a Single-Phase AC/DC Converter

The output of PR-controller in the inner current control loop of the single-phase converter will give to the Pulse Width Modulation (PWM) modulation block in order to create the switching pulses for the power semiconductors. According to Fig.2.13, a bidirectional single-phase converter consists of two legs of power semiconductors that the power semiconductors within a leg must not turn on simultaneously to avoid a short circuit across the DC-link. There are various techniques for creating the switching pulses based on the controlling signal which comes from the controller. One of the prominent modulation techniques is the

PWM. To implement PWM technique for a bidirectional single-phase converter, two basic modulation schemes have been presented in the literature, known as bipolar and unipolar modulation [72].

Figure 2.13: Topology of a Single-Phase Converter.

Bipolar Modulation Scheme

Fig.2.14 shows the performance of PWM with bipolar modulation. According to this figure, two complement control signals are required in the control system. The duty cycle is technically a sinusoidal wave which is compared to a triangular waveform. Therefore, this variable duty cycle (the absolute value of a sinusoidal waveform varies over time) contributes to the alternating width of the power semiconductor gate pulses. Two operation states for bipolar modulation are described as follow:

- State 1: S_1 and S_4 are on. S_2 and S_3 are off. (when $v_{control} > v_{tri}$)
- State 2: S_2 and S_3 are on. S_1 and S_4 are off. (when $v_{control} < v_{tri}$)

Fig.2.15 shows the waveforms of the bipolar modulation. In this modulation scheme, the output voltage (v_{AB}) of inverter fluctuates between positive and negative values of the

DC-link voltage $[-V_{dc}, +V_{dc}]$. That is the reason why this PWM modulation technique is called bipolar modulation.

Figure 2.14: Bipolar PWM Control Scheme.

Figure 2.15: PWM with Bipolar Voltage Switching (Single-Phase)

Unipolar Modulation Scheme

Fig.2.16 shows the control scheme of unipolar modulation. According to this figure, the legs of the AC/DC converter in this scheme are controlled separately by two different sinusoidal modulation waves (i.e., $v_{control}$ and $-v_{control}$) compared with a common triangular wave to shape gating signals. These sinusoidal modulation waves have the same magnitude with the 180-degree phase difference. Therefore, the opposite power semiconductors do not switch simultaneously. In particular, there are four operation states for unipolar modulation as follows:

Figure 2.16: Unipolar PWM Control Scheme.

- State 1: S_1 and S_4 are on. S_2 and S_3 are off.
- State 2: S_1 and S_3 are on. S_2 and S_4 are off.
- State 3: S_2 and S_3 are on. S_1 and S_4 are off.
- State 4: S_2 and S_4 are on. S_1 and S_3 are off.

Fig.2.17 shows the performance of PWM with bipolar modulation. According to this figure, the output voltage of the bidirectional AC/DC converter either fluctuates between zero and $+V_{dc}$ or between zero and $-V_{dc}$ for the positive half cycles and the negative half cycles, respectively. Therefore, the two legs of full-bridge are not controlled simultaneously.

Figure 2.17: PWM with Unipolar Voltage Switching (Single-Phase).

Since the output voltage in the unipolar modulation is fluctuated between from $+V_{dc}$ to zero or from zero to $+V_{dc}$ (and also from $-V_{dc}$ to zero or from zero to $-V_{dc}$) has lower switching losses compared with the bipolar modulation. Furthermore, in unipolar modulation, the switching frequency that will see from the output voltage is twice switching frequency of the actual system (the switching frequency in bipolar modulation). Therefore, the low-

frequency distortion will appear in the output of converter with unipolar modulation. As a consequence, the filtering of harmonics in unipolar switching is easier than bipolar switching.

2.5 Summary

In this chapter, different configurations of the UPS system have been reviewed and the advantages and disadvantages of each configuration have been mentioned. Most of the UPS products in the market are based on the line-interactive UPS configuration, because they not only provide highly efficient and reliable power in backup mode, but also provide voltage regulation in the normal mode for the sensitive loads. The topology of the line-interactive UPS system includes the bidirectional single-phase AC/DC converter. The main issue with the single-phase converter is the existence of the double-frequency ripple on the converter's DC side. In line-interactive UPS system, there is a significant amount of current ripple drawn from or injected into the battery in the both charging and discharging modes of the battery. This current ripple drastically reduces the lifetime and durability of the battery. Moreover, it deteriorates the efficiency and transient performance of the UPS system.

In the second section, different methods of mitigation of the double-frequency ripple, such as passive decoupling and active decoupling method (two-stage converter, and active filter) have been introduced. The AC/DC converter with an active filter can completely eliminate the double-frequency ripple from the battery current. Moreover, it has higher efficiency compared with other topologies. Thus, in this thesis, the AC/DC converter with an active filter has been selected for the UPS application. The control system of converter includes two parts: the control system of the single-phase AC/DC converter and control system of the active filter (DC/DC converter). The control of the AC/DC converter plays a crucial role in the integration of the battery energy storage into the utility grid and load, whereas the control of the DC/DC converter is important to mitigate the current ripple.

The third section investigates the various control systems of the AC/DC converter by

providing advantages and disadvantages of each method¹.

In the last section, the bipolar and unipolar modulation schemes which are used to implement the PWM modulation are described.

¹Different control systems of the active filter are reviewed in chapter 4.

Chapter 3

Configuration of UPS System with an Active Filter

The main challenge regarding the single-phase UPS systems is to suppress the double-frequency current ripple from the battery. In particular, this ripple is very problematic for lithium-ion batteries and drastically deteriorates the lifetime of batteries. Using an active filter is an efficient approach to address this issue. This chapter focuses on the UPS system with an active filter and the design of its components.

Fig.3.1 shows the configuration of a line-interactive UPS system with an active filter. According to this figure, the UPS system includes a tap-changer transformer along with its relay circuitry, a bidirectional AC/DC converter, and an active filter. The UPS system operates in two modes: the normal mode and backup mode. In the normal mode, the tap-changer adjusts the output voltage to desirable levels by altering the turns ratio of the transformer. Therefore, the load will have a constant voltage regardless of grid voltage variations. Furthermore, during this mode, the converter acts as a rectifier to charge up the battery. In the backup mode, the load is isolated from the grid and the battery provides power for the load through the DC/AC inverter.

The active filter which is a bidirectional DC/DC converter is used to deal with the double-

frequency ripple present at the battery side. It effectively isolates the double-frequency ripple from the battery [73]. Thus, the battery is being charged and discharged with a nearly DC current (very low amount of ripple). The model of the UPS system is presented in this chapter. Furthermore, procedures for designing the DC-bus capacitor, filter capacitor, and inductor are discussed.

Figure 3.1: Topology of a Line-Interactive UPS System with an Active Filter.

3.1 Normal Mode of UPS System

This section describes the mathematical model of the UPS system with an active filter in the normal mode. In the normal mode, the grid provides power for the load and the battery. The battery will be charged by the grid through the bidirectional AC/DC converter. The bidirectional AC/DC converter operates as a rectifier to convert AC power from the grid to DC power and charge up the battery. Furthermore, the line-interactive UPS incorporates a tap-changer transformer in order to regulate the load voltage by adjusting transformer taps as the grid voltage varies. The tap changer also adjusts the voltage to the level compatible with the battery. This system has the advantage of providing galvanic isolation of the battery from any disturbances generated from the grid. Fig.3.2 depicts the UPS system with an active filter in the normal mode. According to this figure, the leakage inductance of the tap-changer is used as an input filter for the AC/DC converter. By considering bipolar

modulation over a switching period, T_s , and using the KVL the dynamics of the system is given by:

Figure 3.2: Circuit Diagram of Bidirectional AC/DC Converter in Normal Mode.

$$\begin{cases} L_{leak} \frac{di_{in}}{dt} = v_{in} - v_{batt} & 0 < t < dT_s \\ L_{leak} \frac{di_{in}}{dt} = v_{in} + v_{batt} & dT_s < t < T_s \end{cases} \quad (3.1)$$

where L_{leak} is the leakage inductance of the tap-changer transformer, v_{in} is the voltage across the tap changer on the converter side, and v_{batt} is the voltage across the battery. The input voltage and current of the converter can be derived based on the grid voltage and current.

$$v_{in} = nv_{grid} \quad (3.2)$$

where, i_{load} is the current of the load and n is the ratio of the tap-changer transformer. By using the KCL law, the voltage of the DC-bus capacitor is calculated by:

$$\begin{cases} C_{dc} \frac{dv_{batt}}{dt} = i_{in} - i_{dc} & 0 < t < dT_s \\ C_{dc} \frac{dv_{batt}}{dt} = -i_{in} - i_{dc} & dT_s < t < T_s \end{cases} \quad (3.3)$$

where i_{dc} is the current of DC-bus before the active filter. The current of the active filter inductor is derived by:

$$\begin{cases} L_f \frac{di_f}{dt} = v_{batt} - v_f & 0 < t < d_f T_f \\ L_f \frac{di_f}{dt} = v_{batt} & d_f T_f < t < T_f \end{cases} \quad (3.4)$$

where i_f is the current of the active filter and v_f is the voltage across the filter capacitor. d_f and T_f are the duty cycle and switching period of the active filter. The voltage of the active filter capacitor is calculated by:

$$\begin{cases} C_f \frac{dv_f}{dt} = i_f & 0 < t < d_f T_f \\ C_f \frac{dv_f}{dt} = 0 & d_f T_f < t < T_f \end{cases} \quad (3.5)$$

By considering equation.(3.1)-(4.5), the average model of the UPS system with an active filter is given by:

$$\begin{cases} L_{leak} \frac{di_{in}}{dt} = v_{in} + (1 - 2d)v_{batt} \\ C_{dc} \frac{dv_{batt}}{dt} = -i_{dc} + (2d - 1)i_{in} \\ L_f \frac{di_f}{dt} = v_{batt} - d_f v_f \\ C_f \frac{dv_f}{dt} = d_f i_f \end{cases} \quad (3.6)$$

During the normal mode, the battery could be fully charged and does not accept any further power from the grid. In this situation, the rectifier will be turn off and the grid only provides power for the load.

3.2 Backup Mode of UPS System

When the grid is faced with a significant disturbance, the relay circuit disconnects the load from the grid, and the UPS system goes to the backup mode. In the backup mode, the battery provides power for the load for a specific amount of time. Fig.3.3 depicts the UPS system during the backup mode. The AC/DC converter operates as an inverter, and the DC/DC converter is absorbing the ripple power of the DC-bus. Therefore, DC power is converted to AC power to provide sinusoidal voltage and current for the load. The mathematical model

of the UPS system with an active filter during the backup mode is similar to its model in the normal mode. However, the only difference is in the equations of the input voltage and current of converter that can be calculated by:

$$v_{in} = nv_{load} \quad (3.7)$$

$$i_{in} = \frac{1}{n}(-i_{load}) \quad (3.8)$$

Figure 3.3: Circuit Diagram of Bidirectional AC/DC Converter in Backup Mode.

3.3 Component Design of UPS System with an Active Filter

The objectives of the proposed UPS system with an active filter is not only to attenuate the ripple current but also to reduce the amount of the DC-bus capacitor. In order to design the active filter, first, the amount of DC-bus power ripple of the UPS system is derived. Second, the amount of the DC-bus capacitor in the absence of an active filter is calculated. Finally, the procedure for designing the proposed UPS system with an active filter and effect of this

method to reduce the DC-bus capacitor is described in detail. In the normal mode, the grid power is defined by:

$$p_{grid} = p_{load} + p_{in} \quad (3.9)$$

where the p_{load} is the power of the load and p_{in} is the charging power of the battery. The input current after tap-changer transformer, i_{in} , and the input voltage of the bidirectional AC/DC converter, v_{in} , are given by:

$$v_{in} = V \cos(\omega t) \quad (3.10)$$

$$i_{in} = I \cos(\omega t + \phi) \quad (3.11)$$

where V and I are the amplitudes of the input voltage and current, respectively, and ω is the grid frequency. For simplicity, the power factor is considered to be unity, and therefore, the displacement angle between the input voltage and current is zero ($\phi = 0$). The instantaneous input power of the bidirectional converter, p_{in} , is given as follows:

$$p_{in} = \frac{1}{2}VI + \frac{1}{2}VI \cos(2\omega t) = p_{dc} + p_{C_{dc}} \quad (3.12)$$

The instantaneous input power consists of the average DC power ($\frac{1}{2}VI$) and the ripple power ($\frac{1}{2}VI \cos(2\omega t)$) which oscillates at the double-line frequency. In the UPS system without an active filter, this ripple power will appear in the voltage or current of DC-bus.

3.3.1 Design of the DC-Bus Capacitor

In the UPS system without the active filter, the DC-bus capacitor should not only suppress the high switching frequency ripple but also handle the double-frequency power that exists in the DC-bus. Therefore, a bulky electrolytic capacitor is usually used for this application. The DC-bus voltage, v_{batt} , and the current through C_{dc} , i_c , can be derived as:

$$v_{batt} = V_{dc} + v_r \quad (3.13)$$

$$i_c = C_{dc} \frac{dv_{batt}}{dt} = C_{dc} \frac{dv_r}{dt} \quad (3.14)$$

where V_{dc} is the DC value of the output voltage, and v_r is the ripple voltage of the output voltage. Therefore, the power of the capacitor is derived by:

$$p_{C_{dc}} = v_{batt} i_c = (V_{dc} + v_r) C_{dc} \frac{dv_r}{dt} \quad (3.15)$$

Assuming $V_{dc} \gg v_r$, therefore power of capacitor is calculated by:

$$p_{C_{dc}} = V_{dc} C_{dc} \frac{dv_r}{dt} = 0.5VI \cos(2\omega t) \quad (3.16)$$

Therefore, the ripple voltage is:

$$v_r = \frac{0.5VI}{2\omega C_{dc} V_{dc}} \sin(2\omega t) \quad (3.17)$$

If the peak to peak ripple of the voltage is considered as Δv_{dc} , the required DC-bus capacitance for the bidirectional AC/DC converter can be derived as:

$$C_{dc} = \frac{0.5VI}{\omega V_{dc} \Delta v_{dc}} \quad (3.18)$$

The energy which is stored in the DC-bus capacitor over a charging period of the capacitor is called the ripple energy and can be calculated as:

$$E_r = \frac{0.5VI}{\omega} = C_{dc} V_{dc} \Delta v_{dc} \quad (3.19)$$

Usually, the UPS system without the decoupling circuit requires a bulky DC-bus capacitor

to handle the ripple power. Based on the equation.(3.18), the amount of this capacitor is designed with respect to the output power ($0.5VI$), the average DC output voltage (V_{dc}), and the peak to peak ripple voltage (Δv_{dc}). For the UPS system with the power capacity of $650W$, the output DC voltage of $48V$, and the ripple voltage of $7\%V_{dc}$, a capacitor with up to $8mF$ is required. This bulky electrolytic capacitor is necessary to control the DC-bus ripple power, however, it has relatively high power losses and short lifetime.

In this vein, an active filter has been suggested to use in the DC-bus. The active filter can reduce the amount of DC-bus capacitor and eliminate the double-frequency ripple from the current and voltage of the battery. Theoretically, the active filter can be implemented by any type of bidirectional converters such as buck, boost, or buck-boost [74–76]. In this thesis, a boost converter is adapted for the active filter of the UPS system. The next two subsections discuss the design of the boost bidirectional converter which involves the specification of the active filter capacitor and inductor.

3.3.2 Design of the Active Filter Capacitor

The capacitor of the active filter can store the ripple current in the positive cycle and then discharge in the negative cycle [76–78]. Thus, the ripple of DC-bus will be transferred to the active filter capacitor and eliminated from the battery side. By assuming the voltage across the active filter capacitor is v_f and the peak to peak ripple of this voltage is Δv_f , the energy storage in the active filter capacitor can be derived as:

$$E_{C_f} = C_f v_f \Delta v_f \quad (3.20)$$

In the ideal case, all the ripple of DC-bus will be derived into the active filter. Therefore, the energy ripple of DC-bus will be equal to the energy stored in the active filter. By substituting equation.(3.19) into equation.(3.20), the active filter capacitor can be calculated by:

$$C_f \approx \frac{E_{C_f}}{v_f \Delta v_f} = \frac{E_r}{v_f \Delta v_f} \quad (3.21)$$

$$\frac{C_f}{C_{dc}} = \frac{V_{dc} \Delta v_{dc}}{v_f \Delta v_f} \quad (3.22)$$

$$C_f = \frac{0.5VI}{\omega v_f \Delta v_f} \quad (3.23)$$

Based on the equation.(3.23), the amount of the active filter capacitor can be designed with respect to the output power, the average voltage across the filter capacitor v_f , and the peak to peak ripple voltage Δv_f . The amount of the filter capacitance can be reduced by allowing the voltage across the filter capacitor to be higher than the voltage of the DC-bus. For the UPS system with an output power of 650W, the voltage across the active filter capacitor of 65V, and the ripple voltage of 10% V_f , the required active filter capacitor will be up to 3mF. Since all the power ripple is absorbed by the active filter, there is no need to use a large electrolytic capacitor on the DC-bus. Therefore, The DC-bus capacitor is only responsible for switching frequency and hence a small film capacitor (such as 500mF) can be used.

3.3.3 Design of the Active Filter Inductor

The bidirectional DC/DC converter requires the active filter inductor in order to filter out the switching frequency from the current of the active filter. The current of the active filter consists of the double-frequency ripple and the switching component. The mathematical expression of filter ripple current, Δi_f , can be derived by [76–78]:

$$\Delta i_f = \frac{(v_f - v_{batt})v_{batt}}{f_{sw}v_f L_f} \quad (3.24)$$

where f_{sw} is the switching frequency and L_f is the filter inductance. In order to ensure the active filter inductor operates in the critical continuous current mode, the amplitude of Δi_f should satisfy:

$$\Delta i_f \leq 2i_{f_{pk}} \quad (3.25)$$

where $i_{f_{pk}}$ is the peak value of the filter current which is the peak value of the double-frequency current ripple. Therefore, by substituting equation.(3.24) into equation.(3.25), the active filter inductor should satisfy:

$$L_f \geq \frac{(v_f - v_{batt})v_{batt}}{2i_{f_{pk}}f_{sw}v_f} \quad (3.26)$$

Based on the equation.(3.26), the amount of this active filter inductor can be designed according to the voltage across the filter capacitor, the voltage of the battery, switching frequency of the AC/DC converter, and the peak value of the ripple current. For the UPS system with battery voltage of 48V, the voltage across active filter capacitor of 65V, switching frequency of 25KHz, and the peak ripple current of 7.5A, the require active filter inductor will be up to $38\mu H$.

3.4 Line-Interactive UPS System with 1100W and 2000W Power Capacity

UPS systems can be designed for a wide range of power. By increasing the power, the source of the variation and oscillation will be increased in the system. This kind of oscillations appears in the system by increasing ripple of the current and voltage. The current and voltage ripple can have an adverse impact on the longevity of the energy storage components as well as increased stress and power losses in the semiconductor switches. Therefore, it is essential to keep the current and voltage ripple as low as possible. Interleave techniques

are widely used in the energy storage power electronics interfacing to address the concerns, reducing current ripples and simultaneously increasing the power capacity of the converter. Using interleaved technique allows achieving the same current ripple by a smaller inductor in terms of size and weight. The number of legs can be appropriately chosen based on the required minimum current ripples.

Figure 3.4: Topology of a Line-Interactive UPS System with an Active Filter (1100W).

Figure 3.5: The Input Current and the Interleaved Inductors' Current of the Active Filter (1100W UPS System).

The block diagram of the UPS system with 1100W power capacity is shown in Fig.3.4.

A two-phase interleaved bidirectional DC/DC converter is used for the active filter. The two legs of the active filter have the same inductors and switches. In this circuit, two bidirectional DC/DC converters operate with a 180-degree phase-shift in order to reduce the input current ripple. Fig.3.5 shows the input current of the active filter and current of each interleaved inductors. According to this figure, the current ripple of each legs are inverse due to the 180-degree phase-shift. Therefore, the ripple current of input active filter will be reduced significantly.

Figure 3.6: Topology of a UPS System with an Active Filter (2000W).

Fig.3.6 shows the UPS system with 2000W power capacity. In this configuration, three parallel legs are implemented for the AC/DC converter. As the current of AC/DC converter is divided by the three legs, the current stress in each switches are reduced. For the active filter, a three-phase interleaved bidirectional DC/DC converter is used. Each phase/leg of the active filter should have a 120-degree phase difference. According to Fig.3.7, these phase-shifts of interleaved inductors lead to significantly mitigate the current ripple in the input current of the active filter.

Figure 3.7: The Input Current and the Interleaved Inductors' Current of the Active Filter (2000W UPS System).

3.5 Summary

In this chapter, the mathematical model of the UPS system with an active filter is described in the normal mode and the backup mode. In the normal mode, the grid connects to the battery through a tap-changer transformer and a bidirectional AC/DC converter. The bidirectional converter operates as a rectifier to convert the AC power of the grid to DC power due to charge up the battery. The DC/DC converter is absorbing the ripple power of the DC-bus. The tap-changer transformer regulates the load voltage by adjusting transformer taps as the grid voltage varies. In the backup mode, the load is disconnected from the grid by the relay circuit, and the battery provides power for the load. The AC/DC converter operates as an inverter, and it converts the DC power of the battery to the AC power to support the load.

In the next section, the procedure for the design of the active filter describes in detail. Designing of these components requires special considerations; since the transient performance of the UPS system and the amount of ripple reduction are directly associated with the appropriate design of these components. These components design with respect to the amount of power ripple present in the DC-bus.

In the last section, the configuration of the high power UPS systems is explained. In the high power UPS systems, interleaved techniques are widely used for the energy storage components to handle the ripple current and simultaneously increasing the power capacity

of the converter. The two-phase and three-phased interleaved DC/DC converter is used for the active filter of the high power UPS system to reduce the ripple current of the active filter.

Chapter 4

Control System

In the future smart grid, energy storage systems with fast dynamics are required due to provide efficient power management and offer high reliability for all utility grids. The control system of the UPS plays a crucial role in the integration of the UPS system into the smart grid and load. Furthermore, the control system of the active filter is significant in eliminating the ripple on the battery side and providing high transient performance. In order to properly implement the control system of the active filter, the double-frequency ripple of the DC-bus current must be calculated with high precision as it is used to generate the reference signal for the current controller. In this thesis, a new control system is introduced for estimation of the double-frequency ripple. The proposed control system is able to improve the dynamic performance of the UPS systems, facilitating their integration into smart grids. In this chapter, the proposed control system is described in detail.

4.1 Proposed Control System for the UPS System with an Active Filter

In this section, the proposed control system of the UPS system with an active filter is described in detail. Fig.4.1 shows the block diagram of the proposed control system. This

block diagram illustrates the control loops for the main bridge and the active filter. According to this figure, multiple control loops are utilized to regulate the battery current in the normal mode and the output voltage in the backup mode. In the normal mode, the control system consists of both an external and an internal current control loop. The external current loop is responsible for regulating the battery current to a DC reference value. Since the reference is DC, a PI controller is suitable. The output of the PI controller is multiplied by a template of the grid voltage to generate the reference signal for the grid current. Power factor correction is performed by adding a phase shift to the grid voltage template. A PR is used in the internal current loop to ensure that the transformer current precisely tracks the sinusoidal reference signal. In the backup mode, the control system includes an external voltage controller and an internal current controller. Since there is no grid voltage in the backup mode, the control system is wholly responsible for creating the sinusoidal template for the reference voltage. The external voltage loop generates an appropriate reference signal for the internal current loop to regulate the load voltage. The control system uses PR controllers for both voltage and current controllers. The PR control is able to eliminate the steady-state error because it can introduce a very high gain at the line frequency (i.e., $60Hz$). A multiplexer (MUX) block is used to switch the control system between the normal mode and the backup mode.

Fig.4.1 also shows the control system of the active filter. The active filter is used to suppress the double-frequency ripple presents on the battery side ensuring that only DC current is flowing through the battery. The proposed control system for the active filter includes a Ripple Isolator block and a current controller. The Ripple Isolator block extracts the ripple from the DC-bus current and produces an appropriate reference signal for the current control loop of the active filter. Extracting the double-frequency ripple on the DC-bus current without compromising the dynamic response is very challenging. The main contribution of this thesis is the development of an adaptive observer which can calculate the ripple by observing the DC value of the DC-bus current. When compared with other methods, the observer excels in its transient performance. The proposed adaptive observer is

Figure 4.1: Block Diagram of the Proposed Control System for the UPS System with an Active Filter.

implemented in the Ripple Isolator block to generate an appropriate reference signal without compromising dynamics of the UPS system. According to Fig.4.1, the Ripple Isolator block estimates the double-frequency ripple based on the DC-bus current. The current controller uses a PR controller to regulate the active filter current. Typically, the DC-bus current has a DC component and an AC component at double-line frequency. Therefore, the DC-bus current is represented by:

$$i_{dc} = I_{dc} + I_r \cos(2\omega t) \quad (4.1)$$

The Ripple Isolator block is designed to accurately estimate the double-frequency components, $I_r \cos(2\omega t)$. The system dynamics are derived according to:

$$\Sigma_{i_{dc}} : \begin{cases} \dot{x}_1 = 2\omega x_2 \\ \dot{x}_2 = -2\omega(x_1 - I_{dc}) \end{cases} \quad (4.2)$$

where $x_1 = i_{dc}$, $x_2 = \frac{\dot{x}_1}{2\omega}$ are the state variables of the system. To make the system observable, the following change of variables is applied: $z_1 = x_1$, $z_2 = x_2 - x_1 - I_{dc}$. The system dynamics after the exchange of variables is given by:

$$\Sigma_{i_{dc}} : \begin{cases} \dot{z}_1 = 2\omega(z_2 + z_1 + I_{dc}) \\ \dot{z}_2 = -4\omega z_1 - 2\omega z_2 \end{cases} \quad (4.3)$$

The new variables make the system dynamics observable and permit the estimation of the DC component of DC-bus current. It is possible to calculate the double-frequency ripple by subtracting the DC component from the DC-bus current. Therefore, the adaptive observer can be designed based on the equation.(4.3). The observer for the proposed Ripple Isolator block is given by:

$$\Sigma_{\hat{i}_{dc}} : \begin{cases} \dot{\hat{z}}_1 = 2\omega(\hat{z}_2 + z_1 + \hat{I}_{dc}) + \mu_1 \tilde{z}_1 \\ \dot{\hat{z}}_2 = -4\omega z_1 - 2\omega \hat{z}_2 + \mu_2 \tilde{z}_1 \\ \dot{\hat{I}}_{dc} = 2\mu_3 \omega \tilde{z}_1 \\ i_f^* = z_1 - \hat{I}_{dc} \end{cases} \quad (4.4)$$

where, $\mu_i \in \mathbb{R}^+$, $\tilde{z}_1 = z_1 - \hat{z}_1$, $\tilde{z}_2 = z_2 - \hat{z}_2$, and $\tilde{I}_{dc} = I_{dc} - \hat{I}_{dc}$.

According to the equation.(4.4), the error dynamics of the adaptive observer is given by:

$$\Sigma_{\tilde{i}_{dc}} : \begin{cases} \dot{\tilde{z}}_1 = 2\omega(\tilde{z}_2 + \tilde{I}_{dc}) - \mu_1 \tilde{z}_1 \\ \dot{\tilde{z}}_2 = -2\omega \tilde{z}_2 + \mu_2 \tilde{z}_1 \\ \dot{\tilde{I}}_{dc} = -2\mu_3 \omega \tilde{z}_1 \end{cases} \quad (4.5)$$

The block diagram of the proposed Ripple Isolator block is shown in Fig.4.2. According to this figure, i_{dc} is passed through the low-pass filter to isolate its high-frequency components from the control system. Then, the reference current of the active filter is calculated accord-

Figure 4.2: The Proposed Ripple Isolator Block.

ing to equation.(4.4). Due to the adaptive nature of the Ripple Isolator block, the parameters of control system functions are modified according to variations in the grid frequency.

4.2 Stability Analysis

In this section, the stability of the Ripple Isolator block is investigated. The Lyapunov stability theory is adapted to prove the stability of the proposed method. The Lyapunov

function is defined based on the system error dynamics as shown in:

$$V = \frac{1}{2}\tilde{z}_1^2 + \frac{1}{2}\tilde{z}_2^2 + \frac{1}{2\mu_3}\tilde{I}_{dc}^2 \quad (4.6)$$

The derivative of the Lyapunov function is calculated:

$$\dot{V} = \tilde{z}_1\dot{\tilde{z}}_1 + \tilde{z}_2\dot{\tilde{z}}_2 + \frac{1}{\mu_3}\tilde{I}_{dc}\dot{\tilde{I}}_{dc} \quad (4.7)$$

By substituting the error dynamics of the Ripple Isolator block the equation.(4.4) into the equation.(4.7), the Lyapunov function becomes:

$$\dot{V} = -\mu_1\tilde{z}_1^2 - 2\omega\tilde{z}_2^2 + (2\omega - \mu_2)\tilde{z}_1\tilde{z}_2 + 2\omega\tilde{z}_1\tilde{I}_{dc} + \frac{1}{\mu_3}\tilde{I}_{dc}\dot{\tilde{I}}_{dc} \quad (4.8)$$

According to the equation.(4.8), the derivative of the Lyapunov function has a quadratic structure. Therefore, by properly choosing the coefficients the derivative can be rendered negative. Specifically, the derivative can be rendered negative semi-definite ($\dot{V} \leq 0$). Negative semi-definiteness indicates that the Lyapunov derivative will always be either zero or negative and guarantees the local stability of the error dynamics. However, asymptotic stability is not guaranteed. In non-autonomous systems, Barbalat's Lemma can be used to prove the asymptotic stability of a negative semi-definite system [79,80]. Barbalat's Lemma states that if the Lyapunov function of a non-autonomous system satisfies three conditions, then the error dynamics of the system are asymptotically stable. The three conditions are listed below:

1. V is bounded below,
2. $\dot{V}$ is negative semi-definite, and
3. $\dot{V}$ is uniformly continuous in time (if $\ddot{V}$ is finite)

The first two conditions are met based on the equations.(4.6) and (4.8), respectively. In

order to prove that $\dot{V}$ is uniformly continuous, $\ddot{V}$ must be calculated.

$$\ddot{V} = -2\mu_1\ddot{z}_1\dot{z}_1 - 4\omega\ddot{z}_2\dot{z}_2 = 4\omega(\mu_2 - \mu_1)\dot{z}_1\dot{z}_2 + 2\mu_2^2\dot{z}_1^2 + 8\omega^2\dot{z}_2^2 - 4\mu_1\omega\dot{z}_1\dot{I}_{dc} \quad (4.9)$$

Since all terms of $\ddot{V}$ are bounded, $\dot{V}$ is uniformly continuous. Therefore, $(\dot{z}_1, \dot{z}_2, \dot{I}_{dc}) = (0, 0, 0)$ is the asymptotic stable equilibrium point for the error dynamics.

While Barbalat's Lemma proves the asymptotic stability of the error signals at the equilibrium point, it does not ensure the asymptotic convergence of $\tilde{i}_{dc}$. To prove the asymptotic convergence of $\tilde{i}_{dc}$ the Persistency of Excitation (PE) theorem is employed. The PE theorem states that the estimation error system is globally asymptotically convergent if $\hat{i}_{dc}$ satisfies the following condition for the two positive real values of k and T [81–83]:

$$\int_t^{t+T} \hat{I}_{dc}^2 d\tau \geq k. \quad (4.10)$$

The updated law (i.e., $\dot{\hat{I}}_{dc} = 2\omega\mu_3\tilde{z}_1$) is continually being excited because the double-frequency ripple is inherently present at the DC-bus current. Therefore, the condition for the PE theorem is satisfied, and the asymptotic convergence of $\hat{I}_{dc}$ is guaranteed.

4.3 Comparative Analysis

In order to estimate the sinusoidal current and voltage, different methods have been suggested in the literature. Bandpass filters have conventionally been used to extract the double-frequency ripple present at the DC-bus. The most common bandpass filters for this application are Second Order Generalized Integrators (SOGIs) and Active Notch Filters (ANFs) [84–87]. In this section, the proposed Ripple Isolator block is compared to the SOGI and ANF methods.

The general block diagram of the SOGI is depicted in Fig.4.3. According to this figure, the SOGI filter is basically a bandpass filter with a center frequency tuned to twice the line

frequency, $\omega = 2\omega_{line}$ [84, 85]. This enables the extraction of the double-frequency ripple from the DC-bus current by the SOGI filter. The dynamics of the SOGI filter is given by:

$$\ddot{x} + 2\zeta\omega\dot{x} + \omega^2x = \omega^2i_{bus} \quad (4.11)$$

Figure 4.3: Block Diagram of Second Order Generalized Integrators (SOGIs).

where ω is the center frequency and ζ is the damping ratio.

According to equation.(4.11), the SOGI filter operates based on the center frequency and the damping ratio. Fig.4.4 shows the Bode plots of the SOGI transfer function for the four different damping ratios. According to this figure, a smaller damping ratio narrows the bandwidth and leads to better filtering performance. However, if there is a slight deviation in the center frequency, the filter cannot provide satisfactory performance. Thus, it is necessary to find a reasonable compromise between the quality factor and the bandwidth. The SOGI filter may not result in a sufficiently accurate estimation of the double-frequency ripple because it contains a fixed resonant frequency. Furthermore, the SOGI is susceptible to the harmonics contained in the DC-bus waveform. To ensure that the control system is robust against the harmonics, multiple SOGI filters with different resonant frequencies should be used. Therefore, in order to eliminate each harmonic, a specific SOGI filter with individual parameters should be designed. This method will drastically increase the complexity of the

system.

Figure 4.4: Bode Plots of the SOGI Transfer Functions for Different Values of ζ .

Another method to estimate the double-frequency ripple is the ANF [86, 87]. The block diagram of an ANF is shown in Fig.4.5. The structure of the ANF is very similar to the SOGI filters. However, the ANF uses an additional adaptive law to estimate the frequency in real-time [88]. The dynamics of the ANF is given by:

$$\ddot{x} + 2\zeta\hat{\omega}\dot{x} + \hat{\omega}^2x = 2\zeta\hat{\omega}^2i_{dc}$$

$$\dot{\hat{\omega}} = \gamma x(\hat{\omega}\dot{x} - \hat{\omega}^2i_{dc}) \quad (4.12)$$

where ζ and γ are the ANF gain values. These parameters determine the speed of

convergence as well as the estimation accuracy for $\hat{\omega}$.

Figure 4.5: Block Diagram of Adaptive Notch Filter (ANF).

Alternatively, another form of the ANF exists, which based on the modified version of Regalia's ANF in the continuous form [89]. This modified version is given by:

$$\ddot{x} + 2\zeta\hat{\omega}\dot{x} + \hat{\omega}^2x = i_{dc}$$

$$\dot{\hat{\omega}} = \gamma x(2\zeta\dot{x} - i_{dc}) \quad (4.13)$$

The Regalia's ANF dynamics provide a faster convergence time at higher frequencies and have better stability of x at low frequencies.

The ANF is robust against frequency variations because of an adaptive center frequency. However, the frequency estimation introduces more complexity into the control system which becomes a nuisance during digital implementation. Therefore, this method cannot typically offer fast dynamics for the UPS application.

Unlike the ANF and SOGI methods, the estimate of the double-frequency ripple with the

proposed Ripple Isolator block is able to provide fast and accurate performance. The Ripple Isolator block is based on the system dynamics and has an adaptive structure that tracks any changes in the DC-bus current. The methods mentioned above have different levels of complexity in terms of digital implementation.

Table 4.1: Simulation Parameters

Symbol	Parameter	Value
p_{load}	Output Power	650W
v_{grid}	Grid Voltage	120V(AC)
i_{grid}	Grid Current	5.4A(AC)
V_{batt}	Battery Voltage	48V(DC)
f_{sw}	Switching Frequency of Converter	25kHz
f_{fsw}	Switching Frequency of Active Filter	80kHz
C_{dc}	DC-Bus Capacitor	500 μ F
C_f	Active Filter Capacitor	3mF
L_f	Active Filter Inductor	40 μ H
L_{leak}	Leakage Inductor	140 μ H

4.4 Simulation Results

In this section, the simulation results of the proposed control system for the UPS with the active filter are presented. PowerSim V11.0.3 (PSIM) software is used to obtain the simulation results. The goal of the simulation is to verify the performance of the proposed control system and compare it with conventional methods. Parameters of the simulation are presented in Table 4.1.

Fig.4.6 (a) and (b) depict the performance of the UPS system without the active filter in the normal and the backup modes, respectively. These figures depict that the battery current in both modes contains a double-frequency ripple component and a DC component. This ripple is not appropriate for lithium-ion based UPS systems. By connecting an active filter in parallel with the battery, the double-frequency ripple can be eliminated from the

Figure 4.6: Performance of the UPS System without an Active Filter in a) Charging Mode b) Discharging Mode.

battery side, as shown in Fig.4.7. Therefore, the battery current in both normal and backup modes will be left with a very low ripple. The amount of the ripple current is less than 5%.

Apart from analyzing the effects of adopting an active filter in the UPS system, the performance of the proposed control system is investigated through the simulation. Performance of the proposed Ripple Isolator block is depicted in Fig.4.8. This block precisely extracts the double-frequency ripple from the DC-bus current and sends it to the active filter control system as the reference signal with a 180phase-shift. Therefore, the active filter current has the

Figure 4.7: Performance of the UPS System with the Proposed Control System a),c)in Charging Mode b),d) in Discharging Mode.

same amplitude as the double-frequency ripple of the DC-bus current. The double-frequency ripple is derived from the battery, and the smooth DC current is conducted to the battery.

Fig. 4.9 shows the performance of the proposed control system under non-linear load. In particular, in Fig. 4.9, 2% of the third harmonic, 2% of the fifth harmonic and 1% of the seventh harmonic, have been applied to the load at $t=0.06s$. According to this figure, after the $t=0.06s$ the harmonics are appeared in the load current. Fig. 4.9 (c) demonstrates the capability of the proposed control system in precisely tracking various harmonics/disturbances.

Figure 4.8: Performance of the Ripple Isolator Block in a) Charging Mode b) Discharging Mode.

Therefore, the proposed control system is able to extract the double-frequency ripple from the polluted DC-bus current. Therefore, the proposed control system is able to create the precise reference current for active filter according to the new conditions of the system. In other words, the existence of the harmonics in the DC-bus current has not deteriorated the performance of the active filter.

Figure 4.9: Performance of the UPS system with the proposed control system against load harmonics (2% of the third harmonic, 2% of the fifth harmonic and 1% of the seventh harmonic at $t=0.06$ s) a) transformer current and voltage b) load current c) current of battery, DC-bus and active filter.

Figure 4.10: Performance of the UPS System for Switching from the Normal Mode to the Backup Mode with a) Conventional Control System (SOGI) b) Proposed Control System (RIB).

Figure 4.11: Transient Performance (from the Normal Mode to the Backup Mode) of the Proposed Controller Versus the Conventional Controller (SOGI).

In order to compare the performance of the proposed Ripple Isolator block with the conventional filters, a simulation was carried out using the SOGI-based control system. The performance of the SOGI-based and the ANF-based filters are very similar. However, the ANF-based controller is robust against frequency variations. Fig.4.10 (a) demonstrates the transient performance of the UPS system when switching from the normal mode to the

Figure 4.12: Comparison of the Transient Performance of the UPS System to a Step Change in the Battery Reference Current (5 A(DC) to 15 A(DC)) (Charging Mode).

backup mode. Since the SOGI controller has a low bandwidth, the current of the battery shows very high overshoot and undershoot during the transient. Consequently, this system has a low stability margin. In Fig.4.10 (b), the performance of the proposed control system when subject to the same conditions is exhibited. According to this figure, the proposed control system has a very smooth transient without any overshoot or undershoot because the Ripple Isolator block can quickly respond to any changes in the system.

Figure 4.13: Comparison of the Transient Performance of the UPS System in the Backup Mode to a Step Change in the Load (650W to 325W) (Discharging Mode).

Fig.4.11 shows the transient response of the proposed controller and the conventional controller switching from the normal mode to the backup mode. According to this figure, the SOGI-based controller needs more than two line-cycles to reach the reference DC value, while the proposed control system shows a high-speed transient performance, converging in less than one line cycle. Therefore, the proposed control system can provide a high-speed and smooth transient performance for the UPS system, leading to the reliable integration of the UPS system into smart grids.

Figure 4.14: Performance of the UPS system when the line frequency changes from 60 (Hz) to 61 (Hz) a) input voltage and current of converter b) ANF control system.

Fig.4.12 illustrates the transient performance of the UPS system with both the SOGI-based controller and the proposed controller. The test is completed in the normal mode and a step change is applied to the battery reference current. During the step change, the DC battery current reference increases from 5A to 15A. Same as the previous result, the SOGI-based controller shows very sluggish response during the transient.

Fig.4.13 displays performance of the UPS system with the SOGI-based controller and the proposed controller in the backup mode under a step change in the load. In this test, the load is decreased from 650W to 325W. This figure verifies that the proposed control system is robust and provides a fast transient performance under the load variation.

Figure 4.15: Performance of the UPS system when the line frequency changes from 60 (Hz) to 61 (Hz) a) SOGI control system b) reference current of the active filter for the both SOGI and ANF controllers.

Figs. 4.14 and 4.15 show the performance of the UPS system with the conventional control systems (SOGI and ANF) and the proposed control system when it is subject to frequency variation. According to these figures, the frequency changes from the nominal value of 60 Hz to the 61 Hz occurs in 0.12 second. Fig. 4.14 (b) shows the performance of the ANF control system and the proposed control system. In both methods, the frequency is estimated by the PLL and is given to the control systems. Therefore, both of them are robust against frequency variation. However, the RIB is able to recover the estimated value very quickly which results in fast transient response compared to the ANF control system. Fig.

Figure 4.16: Performance of the UPS system when line frequency changes from 60 (Hz) to 59 (Hz) a) input voltage and current of converter b) ANF control system.

4.15 (a) depicts the performance of the SOGI control system versus the proposed control system. Since the frequency of the SOGI control system is constant, the control system cannot track the frequency variation, when the line frequency changes to 61 Hz. Therefore, the SOGI-based controller is not able to create the accurate reference current for the active filter which in turn leads to presence of more ripple in the battery current. The reference currents of active filter that are created by the SOGI and ANF control system are shown in Fig. 4.15 (b). When the line frequency is 60 Hz, the reference currents of both SOGI and ANF control system are mostly the same. However, when the line frequency changes to 61 Hz, there is a slight phase-shift between their reference currents (the phase-shift is

approximately equal to 3.5°).

Figure 4.17: Performance of the UPS system when line frequency changes from 60 (Hz) to 59 (Hz) a) SOGI control system b) reference current of the active filter for the both SOGI and ANF controllers.

Figs. 4.16 and 4.17 show the same comparison when the line frequency changes from 60 Hz to 59 Hz. Same as before, the ANF and the proposed control systems are able to track the frequency variation. Therefore, the battery current becomes smooth DC after the transient time. However, since the SOGI control system cannot follow the change in the line frequency, the ripple of the battery current is considerable.

4.5 Summary

In this chapter, a new control system is proposed for the UPS system with an active filter. The proposed control system includes a Ripple Isolator block which is able to precisely extract the double frequency ripple component from the DC-bus and isolate it from the battery. The stability analysis of the proposed control system is investigated by the Lyapunov stability theory in this chapter. Furthermore, due to verify the superiority of the operation of the proposed control system, the simulations of both the proposed and the conventional control systems are implemented. The simulation results confirm that the proposed control system provides a prompt transient performance in comparison with the conventional methods (SOGI). Therefore, the proposed method would be extremely appropriate for future smart grids, where fast dynamics is critical to provide high-reliability.

Chapter 5

Experimental Results

In this Chapter, experimental results and design considerations of the proposed control system are presented. To verify the feasibility of the proposed control system and analyze its performance, a 650W experimental prototype has been implemented. Fig.5.1 shows the experimental prototype which includes an AC/DC bidirectional converter, an active filter, and a controller. The AC/DC bidirectional converter is a full-bridge converter created using two half-bridge cards. The active filter uses a single half-bridge card. The control system utilizes an FPGA for computation, all necessary FPGA circuitry and peripherals are included on the FPGA control card. Specifications for the experimental UPS system appear in Table. 5.1.

Table 5.1: Experimental Parameters

Symbol	Parameter	Value
p_{load}	Output Power	650W
V_{grid}	Grid Voltage(AC)	120V
f_{sw}	Switching Frequency of Converter	25kHz
f_{fsw}	Switching Frequency of Active Filter	80kHz
C_{dc}	DC-Bus Capacitor	500 μ F
C_f	Active Filter Capacitor	3mF
L_f	Active Filter Inductor	50 μ H
L_{leak}	Leakage Inductor	200 μ H

Figure 5.1: Experimental Set-up of the Proposed UPS System with an Active Filter.

The implemented control system uses an FPGA. FPGAs can provide a fast and reliable solution to implement the proposed control system digitally. Specifically, Cyclone IV *EP4CE22F17C6N* FPGA from Altera is the model used to implement the digital control system. VHDL is used to program the control system on the FPGA. The control loops in the VHDL code are based on the IEEE “fixed-point” library, which is supported by VHDL-2008 compilers.

FPGAs have become very popular for implementing complex control systems due to provide a high speed and reliability performance. To implement the analog control system digitally, as required by the FPGA, the system dynamics should be converted from the time-domain to the z-domain. The bilinear transform (also known as Tustin’s transform) is used to approximate the analog transfer function to a digital representation. Although the bilinear transform is more complicated compared to the backward Euler and the forward Euler, it provides a more accurate approximation [90–92]. By applying the bilinear transform approximation in the equation.(4.4), the discrete format of the Ripple Isolator block dynamics can be presented according to:

Figure 5.2: Digital Implementation of the Ripple Isolator Block (RIB).

$$\hat{z}_1[n] = \hat{z}_1[n-1] + T_s \omega (\hat{z}_2[n] + \hat{z}_2[n-1] + z_1[n] + z_1[n-1] + \hat{I}_{dc}[n] + \hat{I}_{dc}[n-1]) + \frac{T_s \mu_1}{2} (\tilde{z}_1[n] + \tilde{z}_1[n-1])$$

$$\hat{z}_2[n] = \hat{z}_2[n-1] + \frac{T_s}{2} ((-4\omega(z_1[n] + z_1[n-1]) - 2\omega(\hat{z}_2[n] + \hat{z}_2[n-1]) + \mu_2(\tilde{z}_1[n] + \tilde{z}_1[n-1]))$$

$$\hat{I}_{dc}[n] = \hat{I}_{dc}[n-1] + T_s \omega \mu_3 (\tilde{z}_1[n] + \tilde{z}_1[n-1])$$

$$i_f^*[n] = z_1[n] - \hat{I}_{dc}[n] \quad (5.1)$$

The digital implementation of the proposed Ripple Isolator block is demonstrated in Fig.5.2. According to this figure, the reference signal for the proposed active filter controller is generated by the grid frequency and the DC-bus current. To estimate the grid frequency, an ANF filter based on equation (4.13) is used. Thus, the Ripple Isolator block is robust against the frequency variations because the ANF uses an additional adaptive law to estimate the frequency in the real-time.

(a)

(b)

Figure 5.3: Experimental Results of the UPS System for 50% of the Load a) without an Active Filter b) with an Active Filter.

5.1 UPS System with an Active Filter

Fig. 5.3 (a) depicts the performance of the UPS system without using an active filter in the back up mode. This figure shows that the battery current has a significant amount of the double-frequency ripple. The current of the battery oscillates between zero to 22 A. There-

Figure 5.4: Experimental Results of the UPS System for the Full-load a) without an Active Filter b) with an Active Filter.

fore, the UPS system output would not be appropriate for adapting lithium-ion batteries. Furthermore, this figure shows that the current and voltage of load have 180hase shift during the back up mode. Fig. 5.3 (b) depicts the experimental results when the active filter is connected to DC side of the UPS system. This figure demonstrates that the active filter can

effectively absorb the double-frequency ripple of DC-bus current. Therefore, the smooth DC current will be drawn from battery in backup mode. The ripple of the battery in the UPS system with active filter is less than 5% which is acceptable for Lithium-Ion batteries. These tests are completed at half-load.

(a)

(b)

Figure 5.5: Experimental Results of the UPS System in Charging Mode (50% Load) a) without an Active Filter b) with an Active Filter.

Figure 5.6: Experimental Results of the UPS System with an Active Filter in Charging Mode (Full-Load).

In the digital control system, all measured currents and voltages are conditioned and then converted from analog to digital. Therefore, conditioning circuits, which provide desired gains and offsets have been implemented before applying the signals to ADCs. Thus, different notations show the measured signals at different points. For instance, in Fig. 5.4, i_{batt} represents the actual current of the battery and $i_{batt(ADC)}$ depicts the conditioned signal, which is applied to the ADC. Accordingly, i_{bus} and i_{filter} show the actual value of current in the DC bus and the active filter and $i_{bus(ADC)}$ and $i_{filter(ADC)}$ represent the conditioned signals.

Figs. 5.5 (a) show the performance of the UPS system without an active filter in normal mode. According to this figure, the current of battery has a DC value and the double frequency ripple. This figure also shows that the current and the voltage of the grid have the same phase during the normal mode. When an active filter is connected to DC-bus, the double-frequency ripple will absorb by the active filter. Therefore, the smooth DC current will be injected to the battery. The capability of the active filter to remove the double-

frequency ripple from the battery side during normal mode for half-load and full-load are presented, in Figs. 5.5 and 5.6, respectively. According to the Fig. 5.6, the current of the active filter, $i_{filter(ADC)}$, has a 180hase shift compared to the DC-bus current, $i_{filter(ADC)}$, which results in eliminating the double frequency ripple from the battery current.

(a)

(a)

Figure 5.7: Transient response of the UPS system to a step change in the load (from half-load to full-load) a) with the conventional control system (SOGI) b) with the proposed control system (RIB).

(b)

(b)

Figure 5.8: Transient response of the UPS system to a step change in the load (from full-load to half-load) a) with the conventional control system (SOGI) b) with the proposed control system (RIB).

5.2 Transient Performance of the UPS System

Fig. 5.7 shows the transient performance of the UPS system in the backup mode when its load changes from half-load to full-load. In Fig. 5.7 (a) the UPS system has the SOGI con-

trol system. The SOGI control system is based on a bandpass filter with limited bandwidth. Therefore, it cannot provide a fast transient response. This figure also demonstrates that the battery current requires five line-cycles to become stable in the new value. Five line cycles are too slow of a response for the future smart-grid transient performance requirements. Furthermore, due to the sluggish transient, the battery current faces undershoot and overshoot which is unacceptable for lithium-ion batteries. In contrast, the superior capability of the proposed control system is shown in Figs. 5.7 (b). Since the proposed control system is based on the non-linear observer, it can respond to any change in the system quickly. According to this figure, the proposed control system can estimate the new DC value of the DC-bus current in less than one-line cycle resulting in fast transient response. Since the proposed control promptly responds to any changes to the system, the battery current ripple is limited. Thus, the UPS system with the proposed controller can provide high reliability and security for future smart-grids.

Fig. 5.8 depicts the performance of the UPS system in the backup mode when its load changes from full-load to half-load. Same as previous experimental results, the SOGI control system has sluggish transient with a high amount of undershoot and overshoot in the battery current (transient time is 75ms). However, the proposed control system provides smooth and fast transient performance (transient time is 18ms).

5.3 Summary

In this Chapter, the proposed control system for the UPS system with an active filter is implemented on the experimental prototype. First, the performance of the UPS system with and without an active filter are analysed. The experimental results confirm that by adopting an active filter, the double-frequency ripple can be eliminated from the battery side. Therefore, the battery would be protected from the deteriorated impacts of the low-frequency ripple. Apart from eliminating the double-frequency ripple, the transient performance of

the UPS system is very crucial for the smart grids application. Thus, the experimental tests are implemented with both the conventional and the proposed control system. In this thesis, a new adaptive observer is proposed for the estimation of the double-frequency ripple, which significantly accelerate the transient performance of the UPS system. The experimental results also verify the superior performance of this control system compares to the conventional ones. Furthermore, the digital implementation and design consideration of the proposed control system is explained in this chapter.

Chapter 6

Conclusion

6.1 Summary of Contributions

This thesis has presented the design, development, and analysis of a new control system and configuration for the single-phase line-interactive UPS system. The main challenges of the contemporary UPS system have been identified and addressed through the proposed control system and the configuration presented in this thesis. The main conclusions and contributions of this thesis are summarized as follows:

- In order to suppress the double-frequency ripple on the battery side of the single-phase UPS system, an active filter has been proposed. This configuration employs a DC/DC converter as an active filter on the battery side to absorb the double-frequency during the normal and backup modes. The double-frequency ripple has problematic effects on the batteries and drastically deteriorates the lifetime of batteries. Particularly, in the last two decades, lead-acid batteries have been superseded by lithium-ion batteries due to high efficiency and high-power density. However, lithium-ion batteries cannot handle a high amount of low frequency. Therefore, eliminating the double-frequency ripple on the battery side is essential for the future lithium-ion based UPS systems. In the proposed configuration, the lithium-ion batteries are being charged and discharged

with a nearly DC current (very low amount of ripple).

- A new digital control system based on adaptive control theory has been proposed in order to improve the transient response of the UPS system. In future smart grids, energy storage systems with fast dynamics will be required due to provide efficient power management and offer high reliability for all utility grids. The proposed control system of the active filter is significant in providing high transient performance and eliminating the ripple on the battery side. In order to properly implement the control system of the active filter, the double-frequency ripple of the DC-bus current must be calculated with high precision as it is used to generate the reference signal for the current controller. The proposed control system includes a Ripple Isolator block, which accurately estimates the double-frequency ripple of the DC-bus current. Furthermore, this Ripple isolator block is an adaptive observer, which changes the controller's parameters based on the operating conditions of the UPS system. Therefore, this system is robust against any variations in the system. The proposed control system improves the dynamic performance of the UPS systems, facilitating their integration into smart grids. The stability of the proposed control system has been proven by using Lyapunov theory.
- For high power application of the UPS system, an interleaved technique has been proposed for the active filter's inductors. By raising the power, the source of the variation and oscillation will increase in the system. These oscillations appears in the system by amplifying ripple in currents and voltages of the system. This ripple can have an adverse impact on the longevity of the energy storage components as well as increased stress and power losses in the semiconductor switches. Therefore, it is essential to keep the current and voltage ripple as low as possible. Interleaved inductors offer high-frequency ripple attenuation. Furthermore, using interleaved technique provide the same current ripple by a smaller inductor in terms of size and weight. The number

of interleaved inductors can be appropriately chosen based on the required minimum current ripples.

- The proposed control system has been successfully simulated in the PowerSIM and been implemented experimentally. The prototype of the UPS system with an active filter has been developed using PCB design software (Altium Designer) and evaluated in the normal and backup modes. Furthermore, the proposed and the conventional control systems are investigated through the simulation and experiment due to verify the superior performance of the proposed control system. The results confirm that the proposed control system provides a prompt transient performance in comparison with the conventional methods (SOGI). Therefore, the proposed method is appropriate for future smart grids, where fast dynamics is critical to high-reliability standards.

6.2 Suggested Future Works

A continuation of this research can be conducted in the following areas:

- The current line-interactive UPS systems use relays to change taps between the secondary windings of the transformer. Since relays are electromechanical components, they have an adverse impact on the lifetime of UPS products. They also have a very sluggish response. For future work, a study should be conducted to investigate the impact of replacing relays with MOSFETs, in order to increase the lifetime and reliability of UPS products and improve their speed.
- The power circuits of many current UPS products are based on a line frequency tap-changer transformer, which creates many challenges for operation (a tap-changer is a transformer with multiple taps, which provide variable gains for the transformer). In particular, the line frequency tap-changer has substantial detrimental impacts on the power density, dynamic response, and efficiency of UPS products. In the future, a

new solid-state tap-changer could be designed and developed in order to address the challenges imposed by the line frequency tap-changer.

- In high power application of the UPS system, three current sensors are required to control currents of the active filter inductors. However, extra current sensors not only exceed cost but also introduce noise into the control system. Designing the sensorless techniques to estimate the inductors current should be performed in future works.
- In future work, the optimal magnetic design of the UPS systems could be performed. In order to design the magnetics, specifications such as flux density, air gap, magnetizing, and leakage inductance will be calculated and optimized. Then, the magnetic design will be verified through the MagCoupler Module in PowerSim Software.

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