Integrated Voltage Current Converter and Current Source Inverter Drive System for Three Phase AC Machines

by
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Project Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in the
School of Engineering Science
Faculty of Applied Sciences

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SIMON FRASER UNIVERSITY
Spring 2019

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## Approval

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Abstract

This project is focused on developing a current source inverter (CSI) motor drive system that can be used for a variety of electrical vehicle applications. Voltage source inverters (VSIs) were the primary option for most inverter applications. Generally, VSIs have a number of issues such as larger inverter dimensions, shorter lifetime, and higher cost. A VSI requires a large and costly DC bus capacitor, which also contributes to inverter reliability issues. CSIs are the possible solutions to eliminate the aforementioned problems as they do not need a large DC bus capacitor. Instead, they utilize three small AC filter capacitors and one energy storage component (inductor). In addition to the reduced cost and size, CSIs have several other significant advantages compared to VSIs, including increased reliability and dependability, higher and more stable power suitable for changes in the AC motor speed, and greater motor efficiency and lifespan. This report discusses two of the main components in developing a state-of-the-art CSI drive system. First, the design of the voltage-current (V-I) converter or the controlled current source is presented. Second, the development of a three-phase DC/AC CSI inverter is explained. The V-I converter and the CSI were developed separately, they were integrated and tested for motor or generator operations. Both components of the inverter system are designed and developed using the Matlab/Simulink environment. The system includes a motor or generator load, a three-phase inverter incorporating the space-vector Pulse Width Modulation algorithm. All simulation results are analyzed based on the three phase output voltage and current waveforms.

Keywords: converter; inverter; induction motor; motor drive
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### List of Acronyms

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<th>Description</th>
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<tbody>
<tr>
<td>CSI</td>
<td>Current Source Inverter</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>SVM</td>
<td>Space Vector Modulation</td>
</tr>
<tr>
<td>TPWM</td>
<td>Trapezoidal Modulation</td>
</tr>
<tr>
<td>VI</td>
<td>Voltage Current</td>
</tr>
<tr>
<td>VSI</td>
<td>Voltage Source Inverter</td>
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Chapter 1.

Introduction

A power inverter is a power electronic device that converts direct current (DC) to alternating current (AC). While the applied voltage is fixed, the load voltage can change according to the load nature. An inverter system can be single-phase or three-phase, depending on the application. One of the popular applications is Uninterruptible Power Supply (UPS) system, the inverter converts the DC energy stored in the battery to AC energy for various loads such as computer networks or data servers. Single-phase inverters can be used to provide power for all home appliances and three-phase inverter drive systems for three-phase electrical machine applications.

1.1. Goals and Objectives

The main goal of this project is to establish a current source inverter (CSI)-based motor drive system that can handle the issues that occurred in the earlier version of the CSI systems summarized in [1] and that will be a better alternative than the commonly used voltage source inverter (VSI) systems.

Conventional CSIs did not have ability to recharge the batteries because of the irreversible dc choke current. They were not able to control the supply current and the speed of the connected motor load in the low speed zones. They needed additional diodes to block the voltages forward and reverse direction as required. The development of the semiconductor Insulated gate-bipolar-transistor (IGBT) with reverse-blocking capability (RBIGBT) eliminated the diodes [1] and the design topology will be discussed with the details in the next chapters provided ability to do bidirectional work during motor or generator operations.
A three-phase inverter can be used to adjust the speed of an AC induction machine by adjusting the current of the supplied power. Typical three-phase inverters have six switching semiconductor devices for converting the fixed DC supply voltage to three-phase AC voltage. A simplified block diagram of a CSI-based motor drive system is shown in Figure 1.1. A voltage current (V-I) converter provides two modes of operation and has a bidirectional power flow functionality. The discharge mode is the process of removing energy from the battery bank and using it to supply power to the CSI.

The topology of the drive system includes a rechargeable battery that generates the input voltage ($V_b$). The rest of the circuit is composed of a voltage-to-current source (V-I) converter, a CSI bridge (CSIB) using RBIGBTs, and an electric motor/generator (M/G) that can operate as either a motor or a generator. Figure 1.2 shows details of the drive system. The V-I converter is comprised of two switches ($S_a$ and $S_b$), two diodes ($D_a$ and $D_b$), and a DC choke, $L_{dc}$. The V-I converter transforms the voltage source of the battery into a current source for the inverter block and can control the DC bus current ($I_{dc}$) at a desired value. The V-I converter also allows the inverter to charge the battery without the need for reversing the direction of the DC bus current. The inverter (CSIB) includes six switches ($S_1$-$S_6$) together with three AC capacitors ($C_a$, $C_b$, $C_c$) [1].
1.2. Literature Review

Since the main elements of the CSI system are the V-I converter and CSI circuits, previous studies that dealt with related systems, subsystems, or control techniques pertinent to VI converter, CSI, or VSI are analyzed and summarized in this subsection.

1.2.1. Pulse Width Modulation Techniques

The pulse width modulation (PWM) technique is a well-known technique used in DC/AC inverters. While the input had DC voltage and current, the output of the inverter is a variable voltage in order to provide power for variable speed electrical motor applications. Depending on the application and the complexity of the PWM algorithms, advanced digital systems and microcontrollers can be used to make the PWM algorithms faster and more precise [3]. In this project, the three-phase space vector PWM will be used. When PWM is used with VSIs for variable-speed electric motor applications, high voltage slopes can occur in the stator windings [4]. This can create tension on the insulation and result in bearing problems. To prevent this, PWM can be used with CSIs to obtain a sinusoidal voltage and current waveforms in the stator [4]. The CSI Space Vector Modulation (SVM) will control the current in both transient and steady-state cases. The system also controls the stator flux, torque, and motor starting in-rush currents. By controlling the DC input currents, switching loss of the CSI system will be reduced and short circuit currents will be prevented [5]. The Space Vector PWM
(SVPWM) method is the most popular method among all PWM methods which provides more control flexibility and better dynamic performance [2, 6].

1.2.2. Voltage Current Converters (DC Voltage / Current Converters)

V-I converter implementation includes two modes of operation. The battery discharge mode is when the current is fed to the electrical machines through the CSI, while the battery charging mode is when the current leaving the electrical machine recharges the battery. If the system is in the motoring mode, the battery is discharging. In contrast, if the system is in decelerating or generator mode the battery will be charged. The charge mode of operation uses the electrical machine to recharge the battery bank through the CSI. This is accomplished by rectifying the AC voltage and regulating the amount of current flowing into the batteries.

![Diagram](Figure 1.3: VI converter system as a buck/boost (DC/DC) converter.)

Figure 1.3 shows a bidirectional VI as a DC-DC converter capable of interfacing a battery bank with the CSI. Without changing of hardware, the VI converter can provide bidirectional current flow from battery bank to the CSI or from the CSI to the battery bank. During discharge of the battery bank, the bidirectional buck/boost converter is used to increase the battery voltage to a level higher than the output of the CSI so that current can flow from the battery to the electrical machines. The buck/boost DC/DC bidirectional converter is controlled using a proportional-integral (PI) control strategy [5, 3]. During the charge mode, the DC/DC VI converter regulates the current flow into the rechargeable battery bank.
The following section will briefly explain about the inverters and their applications. DC electrical power to AC electrical power converters are known as inverters. Based on the type of power supply and the design topology, they can be classified into two main groups, known as voltage source inverters (VSIs) and current source inverters (CSIs) [8,9,10].

### 1.2.3. Voltage Source Inverter

The three-phase DC/AC VSIs are used widely in motor drive systems and various PWM strategies to generate a controllable frequency and variable AC voltage. As the output voltage does not depend on the load, the magnitude of the input voltage can be kept constant. The load current varies based on the nature of the load [2].

The simplest three-phase VSI (Figure 1.4) has six switches and the switching patterns can be designed depending on the modulation scheme. The input DC voltage can be obtained from various power sources such as battery banks, photovoltaics, or three-phase utility power supplies through a diode-bridge rectifier and LC or C filters. PWM-controlled voltage waveforms have higher harmonics which are detrimental to the performance of the load, therefore; those harmonics should be reduced to minimum via certain modulation methods [7].

![Typical three-phase voltage source inverter circuit](image)

**Figure 1.4:** Typical three-phase voltage source inverter circuit
VSI requires a costly and bulky high-performance DC bus capacitor to eliminate the ripple currents. Capacitors occupy a large area in the inverter and can arise reliability concerns. Furthermore, the rapid changes of the voltage can cause damage to the insulation in the motor components [1, 9].

1.2.4. Current Source Inverter (CSI)

CSIs are mainly used for three-phase motor applications such as induction motors, synchronous motors (SM), and brushless permanent magnet synchronous motors (PMSM) [1, 5]. Since the electrical components are current sensitive and torque is directly proportional to the current, using a CSI is more beneficial than using a VSI. Several switching methods can be used with the CSI such as, PWM switching, six-step operations (which has harmonic problems), carrier-based PWM switching, and SVM switching [2]. In PWM switching, during one period, each switch turns on and off thousands of times so it reduces the harmonics. SVM switching is the most advanced switching technique. Since it is a computation-intensive method, it will increase control capability of CSI by implementing it in microprocessors or digital systems [11, 12].

The simplest three-phase CSI (Figure 1.5) has six switches where the switching patterns are designed according to the modulation scheme. Input current is adjustable while the amplitude of the output current is independent of the load. The output voltage can fluctuate according to the load type. No feedback diodes are needed in CSI circuits whereas these diodes are required in VSI circuits [2].
1.2.5. Comparison of Voltage and Current Source Inverters

Voltage and current source inverters were compared in [10] with respect to their topologies, semiconductor switching device, manufacturer and model. While IGBT displayed a better performance to use in CSI compared to the other switching devices such as SCR, GTO, and SGCT, it did not indicate any significant increase in the efficiency or reliability to use in VSI compared to other semiconductor device.

There are also functional differences between CSI and VSI. Since they have different filtering components, CSIs maintain a constant output current while VSIs provides a constant output voltage. Whereas CSIs require a large inductance series to their output, VSIs require capacitors to be in parallel to their output. CSIs also require accurate current sensors and a high frequency PWM circuit in their control system to reduce the ripple in the currents. In contrast, frequency is fixed VSIs. While VSIs have a constant DC input voltage, CSIs can have variable DC voltage input. VSIs also have faster responses to the system dynamics compared to CSI due to the usage of an inductor ($L_{dc}$) [5].
Table 1.1 Comparison of VSI and CSI [1-12]

<table>
<thead>
<tr>
<th>VSI</th>
<th>CSI</th>
</tr>
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<tbody>
<tr>
<td>VSI is fed by constant or variable current but the applied voltage is constant [8]</td>
<td>CSI is fed by constant current [3, 8]</td>
</tr>
<tr>
<td>Gating signals should be adjusted to prevent short circuit [12]</td>
<td>Gating signals will not cause short circuit [12]</td>
</tr>
<tr>
<td>The switching devices should handle the maximum current [10]</td>
<td>Since the current is fixed, that problem is solved [10]</td>
</tr>
<tr>
<td>The commutation circuit is complicated [2]</td>
<td>The commutation circuit is simple [2]</td>
</tr>
<tr>
<td>VSI requires freewheeling diodes [12]</td>
<td>CSI does not require freewheeling diodes [12]</td>
</tr>
<tr>
<td>Various semiconductors can be used in the VSI gating circuits [9, 10]</td>
<td>Limited number of semiconductor circuits can be used in CSI gating circuits [9, 10]</td>
</tr>
<tr>
<td>A voltage-controlled converter is required [8]</td>
<td>A current controlled converter is required [8]</td>
</tr>
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1.3. Outline of Project

This work has the goal of developing a V-I and CSI system to control AC loads.

Chapter 1 provides overall information about the project and the inverter systems and explains why the inverter systems need further technological improvements. The chapter also has a literature review of V-I and CSI systems and describes the importance of PWM techniques.

Chapter 2 provides a technical review of the V-I converter, and information about V-I working principles. Design and development of VI converter is described with regards to the expected motoring and generator operations. Simulation results are included for motoring, decelerating, and generator operations.

Chapter 3 introduces the suggested space vector pwm techniques. Detailed mathematical modeling of the technique is presented with the advantages explained. Design and development steps are shown for the SVM-C SI system.

Chapter 4 describes the SVM-C SI system developed in Matlab-Simulink environment and provides simulation results for three-phase voltage, and current waveforms. The design and evaluation of the controller system are discussed in detail. To reduce or eliminate the harmonics, control strategies are implemented and presented.
Chapter 5 deals with the integration of V-I and CSI systems that were developed in Chapter 2 and Chapter 4. After the successful simulation of the individual V-I and CSI components, the two systems are combined and the simulation results for the combined system is also provided. Chapter 5 also presents the results of the motoring load and induction motor simulation.

Chapter 6 develops and simulates the SVM-CSI for the regenerative loads or generator operations. In this chapter, the system performance is measured and simulations are based on generator work operations.

Chapter 7 concludes the thesis and summarizes the objectives to design a 3-phase VI-CSI drive system and to make it available for variety of applications such as 3phase AC motors, hybrid or electric vehicles. Each objective is reviewed with respect to the work completed in the project and is supported by simulation results. Finally, potential future works are proposed.
Chapter 2.

Design and Simulation of Voltage Current (V-I) Converter

Voltage Current V-I converters provide bi-directional DC-DC current flow in either direction based on motoring or generator states. The converter is used as a battery charger/discharger [1]. The DC-DC converter acts as a buck (step-down) converter when the output voltage is less than the input voltage, while acting as a boost (step-up) converter when the output voltage is greater than the input voltage.

Depending on the state of the switches in the V-I converter, four different operating modes are possible for the system, as explained in the following [1]:

1. **Mode I**: Switches $S_a$ and $S_b$ are both ON. In this condition, the battery voltage ($V_b$) is applied to the inverter through the inductor ($L_{dc}$). The output voltage of the V-I converter ($V_s$) will then be equivalent to the battery voltage ($V_s = V_b$) (Figure. 2.1).

![Figure 2.1: V-I converter operation in Mode I](image-url)
2. **Mode II**: $S_b$ is ON while $S_a$ is OFF which disconnects the battery from the inverter so that $V_S = 0$ (Figure. 2.2).

![Figure 2.2: V-I converter operation in Mode II](image)

3. **Mode III**: $S_a$ is ON while $S_b$ is OFF. Thus, the battery will be disconnected from the inverter (CSIB), i.e., $V_S = 0$ (Figure. 2.3).

![Figure 2.3: V-I converter operation in Mode III](image)
4. **Mode IV**: Both $Sa$ and $Sb$ switches are OFF. Thus, the DC choke current ($I_{dc}$) flows through the diodes ($D_a$ and $D_b$) to charge the battery which results in $V_S = -V_B$ (Figure 2.4).

![Diagram of V-I Converter Operation in Mode IV](image)

**Figure 2.4**: V-I converter operation in Mode IV

Figures 2.5 and 2.6 summarize operating modes of the V-I converter. The M/G unit in the motoring mode provides torque boost to the engine, while in the regenerative braking mode, it ensures an adequate level of state of charge in the battery. To maintain a desired level of DC choke current, the V-I converter is active in Mode I and in either of Mode II or III for the motoring mode (Figure 2.5). Similarly, for the regenerative braking mode, the V-I converter is active in Mode IV and in either of Mode II or III (Figure 2.6).

During M/G regenerative operations, the input voltage ($V_{in}$) of the inverter changes its polarity and the controller causes the V-I converter to switch to Mode IV to charge the battery.

![Diagram of V-I Converter Operation Waveforms in the Motoring Mode](image)

**Figure 2.5**: V-I converter operation waveforms in the motoring mode [1]
During any of its operating modes, the V-I converter always receives a DC voltage ($V_{in}$) and delivers a sinusoidal modulated pulse sequence in each phase of its output current, namely, $i_a$, $i_b$, and $i_c$. The current pulse sequence is produced by changing the ON-OFF states of the switches $S_1$ to $S_6$, according to the chosen PWM strategy known as space vector modulation (SVM). This strategy is implemented in the controller block of the CSIB unit. The pulsed phase currents ($i_a$, $i_b$, $i_c$) are then filtered by a simple network of three capacitors, namely, $C_a$, $C_b$, and $C_c$, which results in production of near sinusoidal currents ($i_{am}$, $i_{bm}$, $i_{cm}$) and sinusoidal voltages ($V_{a0}$, $V_{b0}$, $V_{c0}$) to drive the M/G unit [1].

The rechargeable battery is the only power source for the voltage current V-I converter. The working principle for this type of V-I DC-DC converter, described by above operation modes, is based on properly controlling the switching position. This retains the output current at the desired level. The output current of the V-I converter can be adjusted with the PWM generator at a desired level by comparing the reference current with the load current and controlling the switching sequence via gate signals. For the V-I converter to work in the motoring or generator state, the following switching configuration is required (Table 2.1). Zeros indicate the off states and ones indicate on states switches.

<table>
<thead>
<tr>
<th>Modes</th>
<th>Diode 1</th>
<th>Switch 1</th>
<th>Diode 2</th>
<th>Switch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Mode II</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Mode III</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Mode IV</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

In the following sections, the design, simulation and operation of the (V-I) converter are discussed in detail.
2.1. V-I Converter Design for Motoring Operation

The following circuit design has been developed in the Simulink environment based on the aforementioned principles in the beginning of the chapter. The V-I converter includes a rechargeable battery, a parallel capacitor, two diodes, two ideal switches, an output inductance, and a DC voltage source that represents the current source inverter unit. The gate signal generator (Figure. 2.8) is a subsystem that contains the controller. This unit produces the PWM gate signal to switch 1, so that the output current tracks the reference current (which is set to 10A in the simulation). Table 2.2 summarizes the model parameters used in Figure 2.7.

Figure 2.7: V-I converter’s Simulink model in the motoring state

To operate in the motoring state, Mode I and either of Mode II or III are active. The approach is to apply constant value of 1 (ON) to switch 2 while switch 1 is receiving its gate signal input from the controller. Figure 2.7 illustrates the Simulink implementation of the V-I converter model in the motoring state.

Table 2.2: V-I Converter component parameters

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<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Nominal Voltage</td>
<td>150 Volt</td>
</tr>
<tr>
<td>Capacitance</td>
<td>1e-6 F</td>
</tr>
<tr>
<td>Inductance</td>
<td>50e-3 H</td>
</tr>
<tr>
<td>DC Voltage Source</td>
<td>100 Volt</td>
</tr>
</tbody>
</table>
The gate signal generator unit shown in Figure 2.8, is where the load current is compared to the reference current to form the error signal. The reference current is selected as 10 Ampere constant current and the load current feedback is from the output of the inductance L. This error is then fed as an input to the PID controller. Table 2.3 shows the parameters of the PID controller.

\[
PID(s) = P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}}
\]  

(2.1)

\[
PI(s) = \frac{s + 20}{s}
\]  

(2.2)

Figure 2.8: Simulink model of the gate signal generator circuit in the motoring state

<table>
<thead>
<tr>
<th>PID Controller Setup</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional (P)</td>
<td>1</td>
</tr>
<tr>
<td>Integral (I)</td>
<td>20</td>
</tr>
<tr>
<td>Derivative (D)</td>
<td>0</td>
</tr>
<tr>
<td>Filter Coefficient (N)</td>
<td>100</td>
</tr>
</tbody>
</table>

The repeating sequence frequency is chosen at 10 KHz.
2.2. V-I Converter Motoring Operation Simulation Results

In this section, simulation results for the motoring state are provided. Figure 2.9 depicts the overall tracking performance of the controller as well as the voltage $V_s$, which is the voltage before the output inductance ($L_{dc}$). Due to the inductance $L$, the load current starts from zero and linearly increases until 10A. After the load current reaches the 10A, the gate signal generator (via using the appropriate gating signals) starts controlling the changes in the load current and keeps it constant at a desired level.

![V-I converter simulation results in the motoring state](image-url)
Figure 2.10 shows a sample taken from Figure 2.9 to better illustrate the system performance. As shown in this figure, when the load current increases from 10A to 10.1A, $V_s$ is equal to 175 volts, and when the current linearly decreases from 10.1A to 10A, $V_s$ becomes zero. During linear increment of the load current, the Voltage ($V_s$) is constant while throughout the linear decrement of the current, $V_s$ is zero.

### 2.3. V-I Converter Design for Generator Operation

Since the V-I converter system is a bidirectional system, as summarized in Section 2.2, during the motoring mode, the rechargeable battery provides the required power for the load. When the load does not need electrical power or it returns power back to the rechargeable battery, the system works in the generator stage. Here, the approach is to apply a constant value of 0 to switch 2 while switch 1 is receiving its input from the gate signal generator. The V-I converter includes all components as in the motoring state, however, the load acts as a power source and produces the current to charge the rechargeable battery. As before, the gate signal generator unit provides the PWM gate signal to switch 1. Figure 2.11 shows the Simulink model in the generator state with the model parameters are shown in Table 2.4.
Figure 2.11: V-I converter’s Simulink model in the generator state

Table 2.4: V-I converter circuit parameters

<table>
<thead>
<tr>
<th>V-I Converter Circuit</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Nominal Voltage</td>
<td>150 Volt</td>
</tr>
<tr>
<td>Capacitance</td>
<td>1e-6 F</td>
</tr>
<tr>
<td>Inductance</td>
<td>50e-3 H</td>
</tr>
<tr>
<td>DC Voltage Source</td>
<td>-100 Volt</td>
</tr>
</tbody>
</table>

The gate signal generator (PWM) circuit (Fig. 2.12) produces the gate signal based on the difference between the load current and the reference current known as the error. The error is then fed as an input to the PID controller. The reference current is set to 10A for the simulation. In Table 2.5, the PID controller parameters are provided.

\[
PID(s) = \frac{5s + 25}{s} \quad (2.3)
\]
Table 2.5: PID controller setup values.

<table>
<thead>
<tr>
<th>PID Controller Setup</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional (P)</td>
<td>5</td>
</tr>
<tr>
<td>Integral (I)</td>
<td>25</td>
</tr>
<tr>
<td>Derivative (D)</td>
<td>0</td>
</tr>
<tr>
<td>Filter Coefficient (N)</td>
<td>100</td>
</tr>
</tbody>
</table>

The repeating sequence frequency \( f \) is set at 10 KHz.

2.4. V-I Converter Generator Operation Simulation Results

Figure 2.13 illustrates the overall performance of the V-I converter in the generator state by showing both the tracking performance and the voltage \( V_s \) measured prior to the output inductance \( L_{dc} \). Figure 2.14 shows a sample captured from Figure 2.13 to provide a better view of the system performance in the generator state. As shown, when the load current linearly increases from 9.95A to 10.05A, \( V_s \) is at zero volts and when it linearly decreases from 10.05A to 9.95A, \( V_s \) is equal to -175 volts.
Figure 2.13: V-I converter simulation results in the generator state

Figure 2.14: V-I converter operation in the generator state
Chapter 3.

**Space Vector Modulation Techniques for Current Source Inverters**

The following modulation techniques can be used to control current source inverters, such as:

- Trapezoidal Modulation (TPWM) [2]
- Selective Harmonic Elimination (SHE) [2]
- Space Vector Modulation (SVM) [2]

Each of these techniques have certain advantages and disadvantages [2, 6]. In this project, the applied modulation technique is space vector pulse width modulation (SVPWM) in order to obtain improved waveform quality and high dynamic performance through low switching losses, and to eliminate the unwanted harmonics [2].

### 3.1. PWM Current Source Inverters

As already mentioned, Inverters can be categorized into two general groups, known as voltage source inverters (VSIs) and current source inverters (CSIs). VSIs produce three-phase PWM voltage waveforms and CSIs produce three-phase PWM current waveforms at the output of the inverter circuits. PWM modulation techniques are developed for high-power inverters and PWM current source inverters use various modulation techniques, such as the SVM technique described in this project [2, 12].
A CSI (Fig. 3.1) is comprised of six switching devices. The inverter produces a sinusoidal PWM output current $i_w$ ($i_{WA}$, $i_{WB}$, $i_{WC}$). The input side of the inverter is an ideal DC current source $I_{dc}$. This current source is used during the design stage of the current source inverter to avoid any complications that will be created by the V-I converter. The three parallel capacitors, one for each phase, $C_f$, are added at the output of the inverter circuit to assist commutation between switching devices and to reduce harmonic distortion. These capacitors prevent possible damages to the switching devices and act as a harmonic filter to produce smooth current and voltage waveforms. The capacitor value can be correlated with the switching frequency [5].

Table 3.1: Parameters of the current source inverter for Simulink simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_d$ (ideal current source)</td>
<td>10A</td>
</tr>
<tr>
<td>$S_1, S_2, S_3, S_4, S_5,$</td>
<td>Ideal switches (IGBT)</td>
</tr>
<tr>
<td>$S_6$</td>
<td>0.3 mF</td>
</tr>
<tr>
<td>$C_f$, capacitors (Farad)</td>
<td>100</td>
</tr>
<tr>
<td>Resistance (Ohms)</td>
<td>100</td>
</tr>
<tr>
<td>Inductance (H)</td>
<td>5e-3</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>1e-05</td>
</tr>
</tbody>
</table>

The DC current source ($I_d$) can be formed by the PWM voltage current converter with a DC current feedback control (see Chapter 2). To adjust the DC current ($I_d$) at a desired level and quality, inductance $L_d$ should be added between the VI converter and the CSI. The magnitude of $I_d$ is controlled by feedback from the VI output and the $I_d^*$ reference.
The PWM CSI has the following characteristics:

- The gating devices used in the inverter are of the symmetrical type, so they do not require antiparallel freewheeling diodes [12]
- The current source inverter produces a three-phase PWM current [12]
- The load current and voltage waveforms are sinusoidal due to the capacitors installed at the inverter output [2]
- The high dv/dt problem associated with VSI does not exist in CSI [5]
- In case of a short circuit at the inverter output terminals, the rate of rise of the DC current is limited by the DC choke, which allows enough time for the circuit to be protected [2]
- The DC current cannot be changed instantaneously during transients, which reduces the system dynamic performance [12]

3.2. Switching States of the Current Source Inverter

PWM switching for CSI allows only two switches in the inverter pass the current at any time instant. First switch is located in the top half of the CSI bridge and the other is in the bottom half. The three-phase inverter has a total of nine switching states including, 3 zero-states and 6 active switching states (see Tables 3.2 and 3.3). In zero-switching states, S₁ and S₄ in inverter phase Leg A, S₃ and S₆ in inverter phase Leg B, S₅ and S₂ in inverter phase Leg C conduct current simultaneously while the other four switches are off. The controlled DC current source is off so \( I_{wA}=I_{wB}=I_{wC}=0 \). In active switching states, S₁ in Leg A and S₂ in Leg C are ON and the DC current \( I_d \) flows through S1-load-S2, and ends up at the DC source so \( I_{wA}=I_d \) and \( I_{wC}=-I_d \). Similarly, all of the active states are summarized in Tables 3.2 and 3.4.
Table 3.2: Zero switching and active switching states [2]

<table>
<thead>
<tr>
<th>Type</th>
<th>Switching State</th>
<th>On-State Switch</th>
<th>Inverter PWM Current</th>
<th>Space Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero States</td>
<td>[14]</td>
<td>S₁, S₄</td>
<td>0 0 0</td>
<td>I₀</td>
</tr>
<tr>
<td></td>
<td>[36]</td>
<td>S₃, S₆</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[52]</td>
<td>S₅, S₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active States</td>
<td>[61]</td>
<td>S₆, S₁</td>
<td>Iᵣ  -Iᵣ  0</td>
<td>I₁</td>
</tr>
<tr>
<td></td>
<td>[12]</td>
<td>S₁, S₂</td>
<td>Iᵣ  0  -Iᵣ</td>
<td>I₂</td>
</tr>
<tr>
<td></td>
<td>[23]</td>
<td>S₂, S₃</td>
<td>0  Iᵣ  -Iᵣ</td>
<td>I₃</td>
</tr>
<tr>
<td></td>
<td>[34]</td>
<td>S₃, S₄</td>
<td>-Iᵣ  Iᵣ  0</td>
<td>I₄</td>
</tr>
<tr>
<td></td>
<td>[45]</td>
<td>S₄, S₅</td>
<td>-Iᵣ  0  Iᵣ</td>
<td>I₅</td>
</tr>
<tr>
<td></td>
<td>[56]</td>
<td>S₅, S₆</td>
<td>0  -Iᵣ  Iᵣ</td>
<td>I₆</td>
</tr>
</tbody>
</table>

Table 3.3: Switching state for the inverter legs

<table>
<thead>
<tr>
<th>Leg</th>
<th>Top</th>
<th>Bottom</th>
<th>State</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>S₁</td>
<td>S₄</td>
<td>On</td>
<td>Iᵣ</td>
</tr>
<tr>
<td>B</td>
<td>S₃</td>
<td>S₆</td>
<td>Off</td>
<td>-Iᵣ</td>
</tr>
<tr>
<td>C</td>
<td>S₅</td>
<td>S₂</td>
<td>Off</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On</td>
<td>0</td>
</tr>
</tbody>
</table>

[1] – Upper switch on
[1] – Lower switch on
[0] – None of the switches in a leg turned on
[2] – Both switches in a leg turned on
Table 3.4: Switching states and space vectors current equations

<table>
<thead>
<tr>
<th>Space Vector</th>
<th>Switching State</th>
<th>On-State Switch</th>
<th>Vector Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_0$</td>
<td>[2 0 0]</td>
<td>$S_1, S_4$</td>
<td>$I_0 = 0$</td>
</tr>
<tr>
<td></td>
<td>[0 2 0]</td>
<td>$S_3, S_6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0 0 2]</td>
<td>$S_5, S_2$</td>
<td></td>
</tr>
<tr>
<td>Active Vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_1$</td>
<td>[1 -1 0]</td>
<td>$S_6, S_1$</td>
<td>$I_1 = \frac{2}{\sqrt{3}} I_d e^{-i\pi/6}$</td>
</tr>
<tr>
<td>$I_2$</td>
<td>[1 0 -1]</td>
<td>$S_1, S_2$</td>
<td>$I_2 = \frac{2}{\sqrt{3}} I_d e^{i\pi/6}$</td>
</tr>
<tr>
<td>$I_3$</td>
<td>[0 1 -1]</td>
<td>$S_2, S_3$</td>
<td>$I_3 = \frac{2}{\sqrt{3}} I_d e^{i3\pi/6}$</td>
</tr>
<tr>
<td>$I_4$</td>
<td>[-1 1 0]</td>
<td>$S_3, S_4$</td>
<td>$I_4 = \frac{2}{\sqrt{3}} I_d e^{i5\pi/6}$</td>
</tr>
<tr>
<td>$I_5$</td>
<td>[-1 0 1]</td>
<td>$S_4, S_5$</td>
<td>$I_5 = \frac{2}{\sqrt{3}} I_d e^{i7\pi/6}$</td>
</tr>
<tr>
<td>$I_6$</td>
<td>[0 -1 1]</td>
<td>$S_5, S_6$</td>
<td>$I_6 = \frac{2}{\sqrt{3}} I_d e^{i9\pi/6}$</td>
</tr>
</tbody>
</table>

3.3. Space Vectors of the Current Source Inverter

Six active and one zero switching states are represented by the active and zero space vectors. The space vector diagram for the CSI is shown in Figure 3.2. The active vectors $I_1, I_2, I_3, I_4, I_5, I_6$ form a hexagon with six equal sectors while the zero vector $I_0$ is at the center of the hexagon. For the three-phase balanced system, we have the following equation:

$$i_{WA}(t) + i_{WB}(t) + i_{WC}(t) = 0$$  \hspace{1cm} (3.1)

The phase currents $i_{WA}$ – Phase A, $i_{WB}$ – Phase B, and $i_{WC}$ – Phase C, are PWM output currents.
Three-phase currents are transformed to the two-phase currents in the α-β plane using the following matrix:

\[
\begin{bmatrix}
i_{\alpha}(t) \\
i_{\beta}(t)
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -\frac{1}{2} \\
\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
i_{WA}(t) \\
i_{WB}(t) \\
i_{WC}(t)
\end{bmatrix}
\]

(3.2)

Figure 3.2: Space vector diagram for the current source inverter [2]
Current as a space vector can be defined as follows:

\[ I(t) = I_A(t) + jI_B(t) \]  

(3.3)

Which in terms of \(I_{WA}, I_{WB}, I_{WC}\) is represented using the blow equation:

\[
\bar{I}(t) = \frac{2}{3} \left[ i_{WA}(t)e^{j0} + i_{WB}(t)e^{j2\pi/3} + i_{WC}(t)e^{j4\pi/3} \right]
\]  

(3.4)

Table 3.5: Mapping the switching states

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Theta</th>
<th>Top Switches</th>
<th>Bottom Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S1</td>
<td>S3</td>
</tr>
<tr>
<td>(I_0)</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(I_1)</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(I_2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(I_3)</td>
<td>I</td>
<td>-30</td>
<td>1</td>
</tr>
<tr>
<td>(I_4)</td>
<td>II</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>(I_5)</td>
<td>III</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>(I_6)</td>
<td>IV</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>-150</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>VI</td>
<td>-90</td>
<td>0</td>
</tr>
</tbody>
</table>

For the active states, the switches are turned on and the inverter PWM currents are as listed in Table 3.5. By using the above equations, we can derive \(I_1, I_2, I_3, I_4, I_5\) and \(I_6\) vectors for the vector definition column in Table 3.4.

\[
\bar{I}_1 = \frac{2}{\sqrt{3}} I_d e^{j(-\pi/6)}
\]  

(3.5)

Based on the active vectors, the general formula is developed as follows:

\[
\bar{I}_k = \frac{2}{\sqrt{3}} I_d e^{j((k-1)\pi/3 - \pi/6)}
\]  

(3.6)

For \(k = 1, 2, 3\ldots, 6\)
The current reference vector $I_{\text{ref}}$ rotates in space at a velocity:

$$\omega = 2\pi f_1 \quad (3.7)$$

$f_1$ is the fundamental frequency of the inverter output current $I_w$. The displacement between $I_{\text{ref}}$ and the $\alpha$-axis of the $\alpha$-$\beta$ plane can be obtained by a $\theta(t)$ function.

### 3.4. Dwell-Time Calculation for the Sectors

The reference current $I_{\text{ref}}$ can be characterized by three vectors, namely, $I_1$, $I_2$, $I_0$, the dwell time; and the duty-cycle time (ON-state or OFF-state time) of the chosen switches during a sampling period $T_s$. The ampere-second balancing equations are as follows:

$$\tilde{I}_{\text{ref}} T_s = \tilde{I}_1 T_1 + \tilde{I}_2 T_2 + \tilde{I}_0 T_0 \quad (3.8)$$

$$T_s = T_1 + T_2 + T_0 \quad (3.9)$$

Where $T_1$, $T_2$, and $T_0$ are the dwell times for the vectors $I_1$, $I_2$, and $I_0$, respectively.

$$\tilde{I}_{\text{ref}} = I_{\text{ref}} e^{j\theta} \quad (3.10)$$

$$\tilde{I}_1 = \frac{2}{\sqrt{3}} I_d e^{-j\frac{\pi}{6}} \quad (3.11)$$

$$\tilde{I}_2 = \frac{2}{\sqrt{3}} I_d e^{j\frac{\pi}{6}} \quad (3.12)$$

$$\tilde{I}_0 = 0 \quad (3.13)$$
Figure 3.3 shows the reference current and its components. Using this, the real ($\alpha$-axis) and imaginary ($\beta$-axis) components of $I_{\text{ref}}$ can be derived as below:

Real Part:

$$I_{\text{ref}}(\cos \theta) T_s = I_d(T_1 + T_2) \tag{3.14}$$

Imaginary Part:

$$I_{\text{ref}}(\sin \theta) T_s = \frac{1}{\sqrt{3}} I_d(-T_1 + T_2) \tag{3.15}$$

$$T_s = T_1 + T_2 + T_0$$

Solving the above equations results in calculation of Dwell-times as follows:

For $-\pi/6 \leq \theta \leq \pi/6$

$$T_1 = m_a \sin \left( \frac{\pi}{6} - \theta \right) T_s \tag{3.16}$$
\[ T_2 = m_a \sin \left( \frac{\pi}{6} + \theta \right) T_s \] \hspace{1cm} (3.17)

\[ T_0 = T_s - T_1 - T_2 \] \hspace{1cm} (3.18)

where \( m_a \) is the modulation index.

\[ m_a = \frac{I_{ref}}{I_d} = \frac{I_{w1}}{I_d} \] \hspace{1cm} (3.19)

The above calculations can be applied to all other sectors. The modulation index range is: \( 0 < m_a < 1 \).

### 3.5. The Switching Sequence for Rotating Sectors

CSI switching sequences should satisfy the following requirements:

a) Transition from one switching state to the next involves only two switches

b) At any time, only two switches are ON

Figures 3.4 and 3.5 show details of the switching sequence and the gate signal arrangements over a fundamental-frequency cycle. Two samples occur per cycle with two samples in each sector.
The reference current vector in sector I, $I_{\text{ref}}$, is synthesized by $I_1$, $I_2$, $I_0$. The sampling period $T_s$ has three members including $T_1$, $T_2$, $T_0$ and their corresponding vectors, $I_1$, $I_2$, $I_0$, respectively. Switching states for the vectors are S6-S1 for $I_1$, S1-S2 for $I_2$, and S1-S4 for the zero-state $I_0$.

Figure 3.4: Switching sequence for $I_{\text{ref}}$ in sector I [2]

Figure 3.5: SVM switching sequence over a fundamental-frequency cycle [2]
Table 3.6: Six-segment switching sequence based on space vector rotation

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Top</th>
<th>Bottom</th>
<th>Top</th>
<th>Bottom</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>switches</td>
<td>S1 S3 S5</td>
<td>S4 S6 S2</td>
<td>S1 S3 S5</td>
<td>S4 S6 S2</td>
<td>S1 S3 S5</td>
<td>S4 S6 S2</td>
</tr>
<tr>
<td>1 (θ = -30°)</td>
<td>1 0 0</td>
<td>0 1 0</td>
<td>1 0 0</td>
<td>0 0 1</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>2 (θ = 30°)</td>
<td>1 0 0</td>
<td>0 0 1</td>
<td>0 1 0</td>
<td>0 0 1</td>
<td>0 0 1</td>
<td>0 0 1</td>
</tr>
<tr>
<td>3 (θ = 90°)</td>
<td>0 1 0</td>
<td>0 0 1</td>
<td>0 1 0</td>
<td>1 0 0</td>
<td>0 1 0</td>
<td>0 1 0</td>
</tr>
<tr>
<td>4 (θ = 150°)</td>
<td>0 1 0</td>
<td>1 0 0</td>
<td>0 0 1</td>
<td>1 0 0</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>5 (θ = -150°)</td>
<td>0 0 1</td>
<td>1 0 0</td>
<td>0 0 1</td>
<td>0 1 0</td>
<td>0 0 1</td>
<td>0 0 1</td>
</tr>
<tr>
<td>6 (θ = -90°)</td>
<td>0 0 1</td>
<td>0 1 0</td>
<td>1 0 0</td>
<td>0 1 0</td>
<td>0 1 0</td>
<td>0 1 0</td>
</tr>
</tbody>
</table>

The inverter PWM current ($I_w$) changes by one cycle when the reference current vector ($I_{ref}$) passes through all the six sectors. The device switching frequency can be obtained as follows:

$$f_{sw} = f_1 \times N_p$$  \hspace{1cm} (3.20)

Also, the sampling frequency is defined as below:

$$f_{sp} = 1/T_s$$  \hspace{1cm} (3.21)

From the above equations, the following can be obtained:

$$f_{sw} = f_{sp} / 2$$  \hspace{1cm} (3.22)

Table 3.7: Six-segment switching sequence with space vectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>I₁</th>
<th>I₂</th>
<th>I₀</th>
<th>I₁</th>
<th>I₂</th>
<th>I₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector I</td>
<td>S6 S1</td>
<td>S1 S2</td>
<td>S1 S4</td>
<td>S6 S1</td>
<td>S1 S2</td>
<td>S1 S4</td>
</tr>
<tr>
<td>Sector II</td>
<td>S1 S2</td>
<td>S2 S3</td>
<td>S2 S5</td>
<td>S1 S2</td>
<td>S2 S3</td>
<td>S2 S5</td>
</tr>
<tr>
<td>Sector III</td>
<td>S2 S3</td>
<td>S3 S4</td>
<td>S3 S6</td>
<td>S2 S3</td>
<td>S3 S4</td>
<td>S3 S6</td>
</tr>
<tr>
<td>Sector IV</td>
<td>S3 S4</td>
<td>S4 S5</td>
<td>S4 S1</td>
<td>S3 S4</td>
<td>S4 S5</td>
<td>S4 S1</td>
</tr>
<tr>
<td>Sector V</td>
<td>S4 S5</td>
<td>S5 S6</td>
<td>S5 S2</td>
<td>S4 S5</td>
<td>S5 S6</td>
<td>S5 S2</td>
</tr>
<tr>
<td>Sector VI</td>
<td>S5 S6</td>
<td>S6 S1</td>
<td>S6 S3</td>
<td>S5 S6</td>
<td>S6 S1</td>
<td>S6 S3</td>
</tr>
</tbody>
</table>
Table 3.6 is prepared based on the counterclockwise rotation of the space vector diagram for the current source inverter. Theta starts from $-30^0$ with the $60^0$ interval and completes the $360^0$ rotation at $-30^0$. Table 3.7 indicates the active switches during one period of the time shown in figure 3.5.
Chapter 4.

Design and Simulation of Current Source Inverter using Space Vector Modulation

SVPWM technique and its background theory were summarized in Chapter 3. In this chapter, that theory is used in the CSI design.

4.1. Design of the SVM Switching Circuit in the Current Source Inverter

The three-phase CSI model (Figure. 4.1) corresponds to the space vector pulse width modulation (SVPWM) switching circuit shown in Figure 4.2. These models are developed using the Simulink environment in MATLAB. In this section, the design procedure for the SVPWM switching circuit in the CSI (Figure. 4.2) is explained. The controlled current source in Figure 4.1 provides a constant input current to the CSI. Three equal 0.3 µF AC capacitors, one for each phase, are used to filter currents and voltages. The RL load in each phase includes a 100Ω resistor and a 5mH inductance.

First, the three-phase sinusoidal reference signal is defined as follows:

\[ I(t) = I_m \cdot \sin(w \cdot t + \theta) = I_m \cdot \sin(2 \cdot \pi \cdot f \cdot t + \theta) \quad (4.1) \]

\[ I_{a\_ref} = 1 \cdot \sin(2 \cdot \pi \cdot 50 \cdot t + \pi/2) \quad (4.2) \]

\[ I_{b\_ref} = 1 \cdot \sin(2 \cdot \pi \cdot 50 \cdot t - 2\pi/3 + \pi/2) \quad (4.3) \]

\[ I_{c\_ref} = 1 \cdot \sin(2 \cdot \pi \cdot 50 \cdot t + 2\pi/3 + \pi/2) \quad (4.4) \]

where \( f = 50 \text{ Hz} \).

Using the techniques explained in Chapter 3, the three-phase reference currents \( (I_a, I_b, I_c) \) are transformed into two-phase currents as provided in the following equations:

\[ i_a(t) = \frac{2}{3} \cdot \left[ i_{WA}(t) - \frac{1}{2} \cdot i_{WB}(t) - \frac{1}{2} \cdot i_{WC}(t) \right] \quad (4.5) \]
\[ i_p(t) = \frac{2}{3} \left[ \frac{\sqrt{3}}{2} * i_{WB}(t) + \frac{\sqrt{3}}{2} * i_{WC}(t) \right] \]  

(4.6)

Extracting the real and imaginary parts, the following equations can be derived where \( I_q \) is the real part and \( I_d \) is the imaginary part of the reference signal.

\[ i_q(t) = \frac{2}{3} * I_{a,ref}(t) - \frac{1}{3} * I_{b,ref}(t) - \frac{1}{3} * I_{c,ref}(t) \]  

(4.7)

\[ i_d(t) = \frac{1}{\sqrt{3}} * I_{b,ref}(t) - \frac{1}{\sqrt{3}} * I_{c,ref}(t) \]  

(4.8)

From equations 4.7 and 4.8, the magnitude and phase of the reference current can be obtained.
Figure 4.1: Simulink model of the SVPWM-controlled current source inverter
Figure 4.2: Simulink model of the SVPWM switching circuit
The phase is then passed to the SVPWM sector calculator module shown in Figure 4.3. Within the sector calculator block, the input theta is compared to the theta values from the space vector diagram (Figure 3.2). The output local theta is used to determine the dwell-time, while the output sector is used as the second input to the signal mapping circuit module (Figure 4.5).

Figure 4.3: Details of SVPWM sector calculator module used in the CSI
To calculate dwell-times $T_1$ and $T_2$, the sampling frequency ($T_s$) is set to 3kHz ($3.33 \times 10^{-4}$ seconds) while $I_{dc}$ is chosen at 10 A.

$$T_1 = \frac{I_{ref}(t)}{10} \sin \left( \frac{\pi}{6} - \theta \right) \cdot T_s$$  \hspace{1cm} (4.9)

$$T_2 = \frac{I_{ref}(t)}{10} \sin \left( \frac{\pi}{6} + \theta \right) \cdot T_s$$  \hspace{1cm} (4.10)

$$T_0 = T_s - T_1 - T_2$$  \hspace{1cm} (4.11)

After determining the dwell-times, they are fed to the vector selector block shown in Figure. 4.4. In the vector selector circuit logic, depending on the dwell-times, following cases are possible:

$$\begin{align*}
0 < t < T_1 & \quad I = I_1 \\
T_1 < t < T_1 + T_2 & \quad I = I_2 \\
T_1 + T_2 < t & \quad I = I_0
\end{align*}$$  \hspace{1cm} (4.12)

Figure 4.5 shows details of the signal mapping module of Figure 4.2. This unit provides gating signals for the top switches $S_1$, $S_3$, and $S_5$ as well as the bottom switches $S_4$, $S_6$, and $S_2$. The first input to the signal mapping module comes from the vector selector block ($I_1$, $I_2$, or $I_0$) while the second input is provided by the sector calculator module.
Figure 4.4: PWM vector selector circuit block
Figure 4.5: SVPWM signal mapping circuit module
4.2. Simulation Results for the Current Source Inverter

The output voltage waveforms of the CSI (Figure 4.1) are shown in Figure 4.6 and the output current waveforms are shown in Figure 4.7. The parameters used for this simulation are summarized in Table 4.1. As shown in figures below, both voltage and current outputs reach the steady-state condition after a short transient.

![Figure 4.6: Three-phase load voltage waveforms for the SVPWM current source inverter](image)

Figure 4.6: Three-phase load voltage waveforms for the SVPWM current source inverter
Figure 4.7: Three-phase output current waveforms for the SVPWM current source inverter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled current source</td>
<td>10 (A)</td>
</tr>
<tr>
<td>Capacitors</td>
<td>0.3 (mF)</td>
</tr>
<tr>
<td>Load resistance</td>
<td>100 (Ω)</td>
</tr>
<tr>
<td>Load inductance</td>
<td>5 (mH)</td>
</tr>
</tbody>
</table>

The desired three-phase currents at the output of the CSI can be represented by an equivalent vector (I) rotating in a counter-clockwise direction (as described in Chapter 3). The magnitude of the vector is related to the magnitude of the output current and the time it takes for the vector to complete one revolution, which is the same as the fundamental time period of the output current. Switching patterns are chosen such that the desired output current waveforms are obtained. At certain intervals, two switches are ON, one upper switch and one lower switch for the active vectors. At the zero-vector mode, both switches in a leg turn on.
Figure 4.8: Three-phase load voltage output waveforms for one period phase A, B, and C.

The CSI acts as a constant three phase AC current source to the motor. The constant AC currents are passed to the phases sequentially, as shown in Figure 4.9. Each phase conducts current for 120° out of each half-cycle. Since two switches are ON at a time, current enters one phase and return through another. The switching sequence is shown in Figure 4.10. During the first interval, switches 1 and 6 are closed so the current flows into phase A and return from phase B, as shown.
Figure 4.9: Three-phase current output waveforms for one period phase A, B, and C

Figure 4.10: Three-phase gating signals for one period
Chapter 5.

Simulation of the Integrated Voltage-Current and Current Source Inverter Drive System for a 3-Phase AC Motor

V-I converters and CSI systems were explained in previous chapters in detail. In this chapter both units are integrated as shown in Figure 5.1 to simulate the entire drive system for the operation of AC motors.

5.1. Integration of V-I and CSI Drive System for a 3-Phase AC Motor

The design of the V-I converter was presented in Chapter 2 and the design of the CSI was provided in Chapter 4. In the integrated V-I and CSI system, the V-I converter acts as a controlled current source. CSI inverts the controlled DC current into 3-phase AC currents, which have a 120-degree phase difference between them.

The V-I converter unit is a DC/DC converter with input from a rechargeable battery. The output of the converter is passed to the CSI unit. The CSI unit includes a 3-phase bridge inverter. These types of inverters are widely used for AC motor drives and general-purpose AC supplies from the stored battery power or solar systems. [10] When the load is operating as an AC motor, the CSI unit receives a DC voltage at its input and delivers an AC voltage to the load. Therefore, it depletes the battery. When the load is operating in a generator mode, the CSI unit receives an AC voltage from the load at its output and delivers a DC voltage at its input to the V-I unit. As a result, the battery is recharged.

Simulations of the CSI with motor load condition are provided in this chapter. similar to previous chapters, the simulations are prepared using the Matlab/Simulink environment.
5.2. Integration of the V-I and CSI Drive System for a 3-Phase AC Motor

The following changes have been made to make the integrated system work smoothly. Since the system is in motoring work, the gating signal for switch #2 at the V-I circuit is provided with a constant signal. The gate signal generator provides PWM pulses only for switch #1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage (V)</td>
<td>15</td>
</tr>
<tr>
<td>Rated Capacity (Ah)</td>
<td>400</td>
</tr>
<tr>
<td>Initial state-of-charge (%)</td>
<td>100</td>
</tr>
<tr>
<td>Battery response time (s)</td>
<td>30</td>
</tr>
</tbody>
</table>

For the V-I converter, C=1µF and L=5mH and the gate signal generator has two inputs. A reference current input is constant at 20A and the load current is the feedback provided from the output of the V-I circuit. Switch #1 controls the current to provide constant current for the CSI.

5.3. Simulation Results for the Integrated System

Figure 5.1 shows the integrated circuit encompassing both V-I and CSI blocks. The switching circuit that produces the gating signals for the CSI is under the SVM system block which was described with the details at chapter 4.
Figure 5.1: Integrated drive system including V-I and CSI units with a motor load
As we can see from Figure 5.2, the 3-phase voltage outputs of the motor load have balanced 3-phase sinusoidal waveforms with reduced harmonics. Similarly, Figure 5.3 shows the 3-phase current waveforms $\text{I}_a$, $\text{I}_b$, and $\text{I}_c$. The currents are square waves, alternative current waveforms between -20A and 20A.

Figure 5.2: VI-CSI integrated system 3-phase load voltage wave forms

Figure 5.3: VI-CSI integrated system motor load current wave forms
The above Figures 5.4 and 5.5 shows 3 phase the balanced voltage and current waveforms, respectively.
5.4. Simulink Model for Integrated VI-CSI Circuit with Induction Motor

In this section, the 3-phase R-L circuit (resembling the motor drive) is replaced by the standard induction machine module from Simulink library. Figure 5.6 shows the integrated VI-CSI system with the standard induction motor. The rest of the circuit components are unchanged.
Figure 5.6: VI-CSI integrated system with 3-phase induction motor load
Table 5.2 Induction machine parameters for Simulink simulation

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Parameters</th>
<th>Advanced</th>
<th>Load Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power, voltage (line-line), and frequency [ $P_n(VA), V_n(Vrms), f_n(Hz)$ ]:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[2238, 220, 50]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stator resistance and inductance [ $R_s(ohm)$, $L_s(H)$ ]:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10, 5e-3]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor resistance and inductance [ $R_r'(ohm)$, $L_r'(H)$ ]:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10, 5e-3]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mutual inductance $L_m(H)$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>69.31e-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertia, friction factor, pole pairs [ $J(kg.m^2)$, $F(N.m.s)$, $p()$ ]:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[0.089, 0.005, 2]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[1, 0, 0, 0, 0, 0, 0]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.5. Simulation Results for the Integrated System with Induction Motor Load

System parameters of the proposed VI-CSI with the induction motor drive are provided in Table 5.2. The CSI as well as the VI Converter are controlled via a rigorous space vector PWM schemes. Figure 5.7 shows the induction motor 3 phase voltage waveforms. Figure 5.8 displays the sinusoidal current waveforms on each phase separately. Figure 5.9 shows the stator current waveforms which are free from the harmonics since the stator provides a perfect filter for the harmonics. Due to the VI converter and inductor, CSI has a firm DC current at its power input and is able to provide a constant torque to the load without affecting the output current waveforms. Therefore, it is beneficial to use the VI-CSI system in the motor control applications which requires to control the torque.
Figure 5.7: VI-CSI integrated system induction motor load 3-phase voltage wave forms

Figure 5.8: VI-CSI integrated system induction motor load 3-phase current wave forms
Figure 5.9: VI-CSI integrated system induction motor stator 3-phase currents wave forms

Figure 5.6 and 5.9 show that CSI can control the motor directly because the inputs of the current fed Induction Motor are stator currents. CSI is very important in the induction motor applications due to several reasons. For instance, electrical components are current sensitive, where in CSI the torque is directly related to the current rather than the voltage. Control of current by VI-CSI confirms the direct and precise control of electromagnetic torque and drive dynamics.
Chapter 6.

Simulation of Integrated Voltage Current V-I and Current Source Inverter CSI Drive System for 3 Phase AC Generator

6.1. Integration of V-I and CSI Drive System for 3 Phase AC Generator

The purpose of this section is to reorganize the circuit for the regenerative breaking or generator mode. One of the main advantages of the CSI drive system is to transfer the current bidirectional way. During the motor work the current flows from the battery banks to the VI converter (DC/DC) and then CSI inverts the DC current to 3-phase AC current to supply the load. During generator or regenerative works, the current flows in the reverse direction, i.e., the stored energy flows from the load to the CSI-VI and then to the rechargeable battery bank.

The Figure 6.1a and b illustrates the generator arrangement of the VI-CSI system. At the VI section, while switch 3 is triggered by gate signal generator, switch 4 is getting a constant zero signal. The 3-phase AC load acts as a 3-phase AC power source and the stored energy flow to the battery bank. This procedure helps for energy saving and efficiency. Energy is consumed by the load whenever and as much as it is needed. By the help of bidirectional work of the system, the amount of unused energy is returned to the source in order to save energy. The related parameters used for the simulation of generator work are listed in the Table 6.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak amplitude (V)</td>
<td>50</td>
</tr>
<tr>
<td>Phase (deg)</td>
<td>120</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>50</td>
</tr>
<tr>
<td>Sample Time</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 6.1a: VI voltage current, CSI current source inverter SVM control block
Figure 6.1b: VI voltage current, CSI current source inverter integrated system generator.
6.2. Simulation Results for the Integrated System

Figure 6.2 illustrates the 3-phase AC voltages at the output of the VI-CSI integrated system. At this point the nominal battery voltage is lower than the VI-CSI fed DC voltage. Since measurements between (0 - 0.1 seconds) are taken from the ideal AC source, there is no initial conditions as well as no harmonics between (0-0.01 seconds). There is 120° phase difference between Phases A, B and C. While Phase A is zero, Phase B 120° and Phase C is -120° in order to create a 3-phase balanced system. 3-Phase voltages vary between (-60 to +60 Volts).

Figure 6.2: Three phase AC voltages provided by AC voltage source which represents 3 phase AC generator
Figure 6.3 illustrates the 3-phase AC/DC currents flowing from output of the VI-CSI integrated system to the battery bank. The initial conditions between (0-0.025 seconds) are due to the inductive nature of the 3phase loads. Unlike to the 3-phase sinusoidal voltage waveforms, the three phase current waveforms are square-wave because of the PWM control of the current waves. Three phase AC currents varies between -20 and +20 Volts.

Figure 6.4: Integrated generator system 3-phase load voltage wave forms. during one period
Figures 6.4 and 6.5 illustrate 3 phase balanced voltage and current waveforms. The motor or generator work does not affect the quality of the waveforms so the energy circulates through the system. The harmonics are not significant, they can be reduced further by fine adjustment of the circuit.

Figure 6.6: CSI provides the current for the battery bank
Figure 6.6 illustrates the tracking performance of the regenerative current. Due to the $L_{dc}$ inductance, current starts from zero and rises linearly to the 20A value. Following that, the PWM gate signal generator circuit keeps the current at 20A constant value.

![Graph showing voltage, current, and SOC over time](image)

**Figure 6.7:** Battery Current, Voltage and State of Charge SOC at motor operations

Figure 6.7 illustrates the 100% charged Lead-Acid battery with the 30 seconds response time voltage, current and SOC changes during induction motor operations. The current increases from 0 to 20A and after that PWM control starts to limit the current further increase. During that time voltage rapidly decrease but after that the decrease of the voltage slows down. The same behavior can be observed from the SOC characteristics.
Figures 6.8 illustrates the 50% charged Lead-Acid battery with the 30 seconds response time, voltage, current and SOC changes during the induction generator operations. The current flow starts at 0.024 seconds at 20A level and the PWM control starts to limit any changes in the current level to keep it constant. After that time the voltage starts to increase slowly, similar to the SOC linear and slow increase. It will follow the charging time duration of the lead acid batteries.

Both, Figures 6.7 and 6.8, show successful performance of the system in motor and generator operations. In the motor operation battery power is consumed while in the generator operation battery is charged.

With the help of the V-I converter, the CSI based induction machine drive is an emerging alternative for EV/HEV applications compared to the current VSI drives. Using CSI Drives will help to reduce the inverter cost and volume, increase the reliability of the inverter and motor, and extend the maximum torque speed range and field-weakening region for constant-power operations.
Chapter 7.

Conclusion

The developed 3-phase VI-CSI drive system can serve in a variety of areas from hybrid or fully electric vehicle applications to renewable energy production facilities such as wind or solar, induction motor related applications and more. In the introduction of this report, VSI and CSI topologies are compared in order to justify development of the VI-CSI based drive system. Although VSI drive systems are very popular for most applications, due to the problems mentioned in this report, CSI drive systems are becoming a better alternative by the help of the improvement in the semiconductor technology, reliability and energy efficiency.

The theoretical components of the project developed based on the collected information from [2]. The most challenging part of this project was to develop the PWM control circuits for VI and SVPWM control circuit for the CSI. The gating signals modules for the CSI system are highly complex and heavily computational but that helps to develop accurate triggering patterns.

Bi-directional DC-DC VI converter system, detailed in chapter 2, was the constant DC current provider part for the motoring or regenerative works. In order to achieve that, the load current feedback information was provided for the gating signal producer circuit. The constant reference current provides the flexibility to change the supply current in a wide range area. The reasons for the selection of the SVPWM technique between the other available techniques were explained in chapter 3 where the theory and the preparation for the design were also summarized. Space vector diagram for the CSI was further developed and six segment switching maps were created accordingly.

The design and simulation of the SVM-CSI system was discussed in chapter 4 with the details. Although SVPWM-controlled CSI was a conventional circuit with six switching gates, ideal switches, ideal current source and the load, the most sophisticated and challenging part was to develop the Simulink model of the SVPWM module for switching signals. The SVPWM switching system made by several sub components such as sector calculator module, vector selector circuit block and signal mapping circuit module.
Although each of those modules have their own complexities, the developed modules were integrated successfully and obtained the expected switching patterns.

The simulation results show the success of the SVPWM-controlled CSI. After the explained developments of the VI converter and SVPWM-CSI inverter circuits, both of those two circuits were integrated in chapter 5 and the circuits were synchronized to make them to work smoothly for the simulated motor load and standard induction motor from Simulink library.

The simulation results indicated that the harmonic free 3-phase stator currents which emphasized the success of the integrated system during the induction motor load operations. This also provided further information about the integrated system which can be used for speed and torque control of the Induction motors. Finally, in chapter 6, VI-CSI system set up for generator work was explained. Both motor and generator working conditions were explained based on the operations of the rechargeable battery voltage, current and SOC. All those parameters confirmed that the system can handle four-quadrant working conditions and provides the energy efficiency and usage optimization.
Future Work

This project is open for improvements. Since output voltage and current waveforms of the CSI are very sensitive to the change in the parameters, the control circuits of V-I converter CSI can be developed further to handle different scenarios of various load conditions. This can be done by using a microcontroller but it will increase the complexity and the cost. The system can be further developed to minimize the energy loss, and to increase the reliability and robustness.
References


