Control of Three Level Boost Converter for Application in EV charging station

A

Thesis

Submitted in partial fulfillment of the requirements for the

Degree of

MASTER OF TECHNOLOGY

by

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M.Tech in Power Engineering

Under the guidance of

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June, 2024

DECLARATION

I hereby declare that the work which is being presented in the thesis entitled, Control of Three Level Boost Converter for Application in EV charging station in partial fulfillment of the requirements for the award of the degree of Master of Technology in power engineering at the Indian Institute of Technology, Guwahati is an authentic record of my work carried out under the supervision of Dr. Ravindranath Adda, and refers to other researchers' work which is duly listed in the reference section. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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CERTIFICATE

This is to certify that the work contained in the thesis entitled, Control of Three Level Boost Converter for Application in EV charging station is a bonafide work of Banoth Vishnuvardhan (Roll No. 224102106), which has been carried out in the Department of Electronics and Electrical Engineering, Indian Institute of Technology, Guwahati under my supervision and this work has not been submitted elsewhere for a degree or diploma.

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ACKNOWLEDGEMENTS

I want to take this opportunity to acknowledge everyone who has assisted me in this enthusiastic and great knowledge-gaining period of my master's program. Firstly I would like to acknowledge my project supervisor Dr. Ravindranath Adda for all his support and guidance throughout this project journey. I am very grateful to him for giving me the opportunity for doing this wonderful project. His hardworking behaviour will be always trademark for me. I would like to thank the Indian Institute of Technology, Guwahati for all the financial, academic and technical support. I want to thank the Department of Electronics and Electrical Engineering for all the support during this project journey. I am very grateful to Vaishnavvignesh Gomathisankaran Iyer for his assistance. Further, I want to extend my sincere thank to Pramit Nandi, Satish Chandra for their support throughout the project.

ABSTRACT

Globally by addressing the climatic changes and pollution all over countries and communities are shifting towards renewable energy sources for meeting demands of electrical energy, in which solar PV technology is one of them to a sought-after option. It is a two stage energy delivering technology in which 1st stage is DC-DC converter and 2nd stage is DC-AC converter. Consider the voltage available at solar panels is low then it is suppose to employ a DC-DC converters to boost the available level to required application level. Conventional converters such as boost, buck-boost, flyback and cuk converters could not boost the voltage upto 2 to 4 times practically but TLBC could boost up the voltage to 2 to 4 times practically too due to more number of components included in the circuit, so TLBC could be prioritized option over all available converters. TLBC is operated with inner current control and outer voltage control loops. This circuit offers less ripple voltage, current and voltage stresses on components which increases the longevity and efficiency of the converter.

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Chapter 1

Introduction

There is a saying by the prominent scientist Einstein "Energy can never be created nor destroyed but can be transformed from one form to another form" based on this statement, in this thesis the concern is about utilization of electrical energy from the solar panels through Three Level Boost Converter (TLBC). This energy is being transformed from the available light energy into the electrical energy with the help of power electronic devices. In fact transformation could be from any kind of energy such as heat, wind, chemical, mechanical into electrical energy. Electrical energy is utilised by the people globally therefore this energy is superior over all kinds of other energies and its interconvertability as well as transportation is easy, it can transmitted to longer distances despite generating stations are located in remote areas. It is most economical and cheapest energy since it is extracted and transformed from the sources that are available in the nature.

The electrical energy utilised by consumers will be in the form of AC, grid delivers power to the load which is received from the traditional energy sources in addition to that solar panels also supports power to the grid. Therefore globally there is shift towards this PV technology by addressing vulnerable climatic changes which is due to green house gas emissions by the conventional energy sources such as thermal, nuclear and gas are the major causes [?] for pollution. So all the countries are prioritizing the growth of PV technology as an alternate option by reducing dependence on fossil fuel sources.

In some applications such as installing solar panels on the rooftops of our houses in unused places and utilising electricity from it could lower the electricity bill. Using solar power to charge electric cars at charging stations and while driving around can help in reduce of pollution and lower temperatures. In some areas PV technology are well known to farmers and they are using it in the agricultural fields, as well as speed of the DC motors are also controlled and used in some other stand alone applications purposes.

BLOCK DIAGRAM.pdf

Figure 1.1: Block diagram of whole system connected to grid

Consider PV panels are injecting AC power into the grid or feeding stand alone AC loads, the power generated by the PV panels are DC in nature after panels DC-DC converters are employed to boost the low available voltage levels at the panels output, voltage boosting will be done as per the load requirement. TLBC is used for boosting up the voltage, after this converter inverters are employed for changing the nature of power which is suitable for the loads further LC filters are designed to smoothen the waveforms available at the output of the inverter. Furthermore these smooth sinusoidal waveform are injected into the grid or fed to the loads directly. This is the brief idea of injecting transformed powers into the grid or feeding to the loads. Block diagram of above discussion is depicted in terms of Fig.1.1.

1.1 Literature Survey

Boosting voltage is necessary in certain situations, like when there is need of high voltage for power transmission or to charge electric vehicles. However, this can put a lot of stress on the switches in the voltage converter, which might cause them to fail. Using high-power switches to handle this stress can be expensive and increase overall costs [?], which isn't ideal. There are different types of converters [?] used for boosting voltage. One common type is the boost converter [?], which can increase voltage but puts a lot of stress on the switches. Another type is the cuk converter, which also faces similar issues with switch stress. To tackle these problems, an advanced converter called the Three-Level Boost Converter (TLBC) has been explored. This converter helps reduce stress on the switches and has less ripple current compared to the boost, cuk and other traditional converters.

TLBC works well for various applications in solar power systems, such as charging batteries, connecting to grid inverters, or standalone inverters. It's efficient and can handle continuous power supply, making it suitable for solar energy setups.

Let us consider only DC-DC converter, in this circuit input voltage is boosted to required voltage levels as per the load requirements. For boosting the available input voltage conventional converters [?] are existing but it is prioritized an advanced boost converter called "Three Level Boost Converter" over conventional. It is so due to certain issues they have high ripple voltage and currents, high switch stress [?] which reduces the life span of the switch and the diodes employed in the circuit. In this TLBC circuit conventional comvertrs.pdf

Figure 1.2: Equivalent circuit of (a) boost converter (b) flyback converter (c) cuk converter (d) buck-boost converter for d ≥ 0.5

TLBC AND BLOCK.pdf

Figure 1.3: (a) Block representation and (b) Three level boost converter circuit.

all the above issues gets mitigated by the factor 2 further which increases the life span of devices further electromagnetic disturbance also decreases. Following are the conventional converters used and these converters are inferior when compared to advanced TLBC converter, which gives us some advantages conventional circuits.

When compared to conventional converters TLBC has finer voltage control and high output voltage quality so this is preferable. Due to parametricity of capacitor unequal voltage voltage charging takes place to balance that balancing techniques are used.

1.2 Motivation and problem formulation:

Compared to a regular boost converter, a three-level boost converter has some advantages. It can control output voltage ripple better because it has an extra voltage level. This means it can filter the output voltage more precisely, reducing ripple and making the output voltage better quality. Also, when compared to boost, cuk and other converters, the three-level boost converter puts less stress on its switches and diodes. It achieves this by spreading the voltage across switches and diodes more evenly. This makes the converter last longer and makes it more reliable.

Additionally, the three-level boost converter can help with electromagnetic interference (EMI) issues, which are disruptions caused near by other electrical devices. Because it has an extra voltage level, it can control the current better, resulting in fewer disruptions and less EMI. This is especially important in situations where meeting EMI standards is crucial. By reducing stress on its components, the three-level boost converter also makes those components last longer and work better. It disperses voltage and current across different levels, leading to fewer losses and higher efficiency for the whole system. Another advantage is that the converter can use smart control methods to make solar power systems more effective. It can adjust to different weather conditions and get the most power from solar panels using techniques like maximum power point tracking (MPPT) and adaptive modulation. This improves the system's performance and makes solar power more efficient overall.

The goal of this project is to design a three-level boost converter for a standalone inverter. This involves simulating the converter with solar panels and MPPT tracking, balancing capacitor voltages, and implementing a single-phase inverter. After simulation, the hardware will be designed, including reducing the size of the inductor. Finally, the system will be operated using a Digital Signal Processor (DSP) for closed-loop control.

1.3 Organisation of thesis:

1.3.1 Chapter-1

This chapter introduces the concept of utilizing solar energy and emphasizes the importance of efficient power conversion. Three-Level Boost Converter (TLBC) are presented as a superior solution for solar power systems due to their ability to reduce switch stress, ripple current compared to traditional converters and deliver high-quality output voltage with finer control. Additionally, it also improves system efficiency by minimizing losses. Facilitate the implementation of Maximum Power Point Tracking (MPPT) for optimal solar panel performance. The chapter motivates the design of a TLBC for a standalone inverter system. The project plan involves TLBC simulation with solar panels and MPPT control and capacitor voltage balancing techniques. Single-phase inverter implementation and hardware design with size optimization. Closed-loop control using a Digital Signal Processor (DSP).

1.3.2 Chapter-2

This chapter introduces a TLBC specifically designed for standalone solar panel systems. A key advantage of the TLBC is its ability to reduce stress on both the switches and filter inductors compared to traditional boost converters. This is achieved by distributing the voltage stress across two capacitors connected in parallel. This chapter delves into the operation of the TLBC for various duty ratio scenarios, including both values greater than and less than 50%. It also provides equations for calculating essential parameters like output voltage, ripple voltage, and ripple current.

To verify the design's effectiveness, simulations were conducted using PSCAD software. The results confirm that the converter successfully boosts the input voltage from 100V to 250V, with some expected ripple present. The capacitors act as a primary filter for these ripples, and additional filtering stages can be implemented at the output for further refinement.

1.3.3 Chapter-3

This chapter focuses on designing a controller for a TLBC employed in a solar panel system. The controller utilizes cascaded PI controllers to meticulously maintain the desired output voltage and inductor current. The document further validates the effectiveness of this controller design by presenting both simulation and hardware results. In this chapter all the circuit analysis of inverter is done and alternating waveforms have been produced at required frequency and magnitude.

1.3.4 Chapter-4

This chapter describes the design of a system that converts DC power to AC power. The system consists of two parts: a TLBC and a full-bridge inverter. The TLBC increases the voltage from a DC source. The inverter then converts the increased DC voltage to AC voltage. Also the design of controllers for both the TLBC and the inverter. The controllers use pulse-width modulation (PWM) to control the output voltage and current of the system. Also presents the results of simulations and hardware tests of the system. The results show that the system can successfully convert DC power to AC power with a sinusoidal output voltage.

1.3.5 Chapter-5

This report successfully designed and tested a three-level boost converter (TLBC) with improved efficiency over conventional designs. Simulations and hardware tests confirmed the TLBC's ability to regulate voltage and current, and its successful operation when cascaded with an inverter. Future work will focus on real-world testing with various loads and power levels, exploring different inverter topologies, and potential integration with a photovoltaic system.

Chapter 2

Open Loop Three-Level Boost Converter

2.1 Introduction:

Three Level Boost Converter aims to reduce stress on switches and make filter inductors smaller. This thesis focuses on designing a converter for a stand-alone solar panel system. The other conventional converter[?] helps transferring more solar energy to power appliances, but it can strain switches, potentially damaging them but TLBC is used to ease this strain by reducing the size of the filter inductor and distributing voltage stress across two capacitors connected in parallel. This circuit comprises an inductor in series to the DC power source, two switches,two diodes, two capacitors across the load, each getting half the output voltage, are connected across both switches to share the voltage and decrease their size.

TLBC.pdf

Figure 2.1: Three level boost converter

Due to the less ripple in current and voltages it leads to reduce the size and cost of the filter components in the circuit which is benefit in compact and economical wise.

2.2 TLBC Working and Operation:

It can be operated in two ways, 1st case is in which output voltage is more than the twice the input available voltage this is possible when the duty ratio is more than 50%, 2nd case in which output voltage is less than the twice the input available voltage this is possible when the duty ratio is less than 50%. These distinct classifications comes into the picture based on the width of the pulse provided to the IGBTs (S_1 and S_2).

2.2.1 When the converter duty ratio is more than 50%:

Fig. 2.2 shows the gate pulses that are given to the IGBTs when the duty ratio is more than 50% where as its resultant output would be more than twice the input voltage. Carrier signal is triangular and constant signal is reference i.e, duty ratio.

d greater 0.5.pdf

Figure 2.2: Gate pulses for S_1 and S_2 when duty ratio is more than 50%

In this case circuit gets operated in four modes, consider Fig. 2.2

- 1st mode - from t_1 to t_2, S_1 & S_2 are ON and D_1 & D_2 are OFF.
- 2nd mode - from t_0 to t_1, S_1 & D_2 are ON and S_2 & D_1 are OFF.
- 3rd mode - from t_1 to t_2, S_1 & S_2 are ON and D_1 & D_2 are OFF(repeated).
- 4th mode - from t_2 to t_3, S_2 & D_1 are ON and S_1 & D_2 are OFF.

During time t_o to t_1 both switches are on and both diodes D_1 and D_2 are in off and the voltage across diode D_1 and D_2 are V_{c1} and V_{c2} and capacitor voltage V_{c1} and V_{c2} is half of output voltage $V_o/2$, equivalent circuit diagram of TLBC for this mode-1 is shown in Fig. 2.3. So the voltage across the inductor is equal to supply voltage V_{in} and capacitor current is equal to the load current I_o. This mode is call as operating mode 1.

bothon.pdf

Figure 2.3: TLBC equivalent circuit when both the switches are on

$$V_L = V_{in}, \quad I_L = I_{in} \tag{2.1}$$

$$V_{C1} = V_{C2} = V_O/2, \quad I_{C1} = I_{C2} = I_o \tag{2.2}$$

Eq.2.7 and 2.8 are inductor and both the capacitor voltages equations. During time t_1 to t_2 switch S_1 is only on and S_2 is off and diode D_1 is off and D_2 is on, equivalent circuit diagram of TLBC for this mode-2 is shown in Fig. 2.9. The voltage across the S_2 is V_{c2} which is half of output voltage, and current i_{c_1} is I_o this mode is called as operating mode 2.

$$V_L = V_{in} - V_o/2 - V_o, \quad I_L = I_{C1} = I_O \tag{2.3}$$

$$V_{C1} = V_{C1} = V_O/2 \tag{2.4}$$

Q1on.pdf

Figure 2.4: TLBC equivalent circuit when S_1 is on and S_2 is off

Eq.2.11 and 2.12 are inductor and both the capacitor voltages equations. During time t_2 to t_3 mode, mode-1 gets repeated and this mode is called as mode-3. During time t_3 to t_4 switches S_1 is off and S_2 is on and diodes D_1 is on and D_2 off, equivalent circuit diagram of TLBC for this time period is shown in Fig. 2.8. The voltage across the S_1 is V_{c1} and voltage across the diode D_2 is V_{c2}. So the voltage across the inductor is equal to supply voltage $V_{in} - V_o/2$. This mode is called as operating mode-4. In all the 2.3, 2.9, 2.8 equivalent circuits the red color path are shown for open circuit and black color path are shown for close circuit.

Q2on.pdf

Figure 2.5: TLBC equivalent circuit when S_1 is off and S_2 is on

$$V_L = V_{in} - V_o/2, \quad I_L = I_{C1} \tag{2.5}$$

$$V_{C1} = V_{C1} = V_O/2 \tag{2.6}$$

Eq.2.9 and 2.10 are inductor and both the capacitor voltages equations.

2.2.2 When the converter duty ratio is less than 50%:

Fig. 2.2 shows the gate pulses that are given to the IGBTs when the duty ratio is less than 50% where as its resultant output would be less than twice the input voltage. Carrier signal is triangular and constant signal is reference i.e, duty ratio.

d less 0.5.pdf

Figure 2.6: Gate pulses for S_1 and S_2 when duty ratio is less than 50%.

In this case circuit gets operate in four modes, consider Fig. 2.6

- 1st mode - from t_1 to t_2, S_1 & S_2 are OFF and D_1 & D_2 are ON.
- 2nd mode - from t_0 to t_1, S_1 & D_2 are OFF and S_2 & D_1 are ON.
- 3rd mode - from t_1 to t_2, S_1 & S_2 are OFF and D_1 & D_2 are ON(repeated).

- 4th mode - from t_2 to t_3, S_2 & D_1 are OFF and S_1 & D_2 are ON.

During time t_o to t_1 both switches are off and both diodes D_1 and D_2 are in on and the voltage across diode D_1 and D_2 are V_{C1} and V_{C2} and capacitor voltage V_{C1} and V_{C2} is half of output voltage $V_o/2$, equivalent circuit diagram of TLBC for this mode-1 is shown in Fig. 2.7. So the voltage across the inductor is equal to supply voltage V_{in} and capacitor current is equal to the load current I_o. This mode is call as operating mode 1.

both off.pdf

Figure 2.7: TLBC equivalent circuit when both the switches are off

$$V_L = V_{in} - V_o, \quad I_L = I_{in} \tag{2.7}$$

$$V_{C1} = V_{C2} = V_o/2 \tag{2.8}$$

Eq.2.7 and 2.8 are inductor and both the capacitor voltages equations. During time t_3 to t_4 switches S_1 is off and S_2 is on and diodes D_1 is on and D_2 off, equivalent circuit diagram of TLBC for this time period is shown in Fig. 2.8. The voltage across the S_1 is V_{c1} and voltage across the diode D_2 is V_{c2}. So the voltage across the inductor is equal to supply voltage $V_{in} - V_o/2$. This mode is called as operating mode-4. In all the 2.3, 2.9, 2.8 equivalent circuits the red color path are shown for open circuit and black color path are shown for close circuit.

Q2on.pdf

Figure 2.8: TLBC equivalent circuit when S_1 is off and S_2 is on

$$V_L = V_{in} - V_o/2, \quad I_L = I_{C1} \tag{2.9}$$

$$V_{C1} = V_{C1} = V_O/2 \tag{2.10}$$

Eq.2.9 and 2.10 are inductor and both the capacitor voltages equations.

During time t_1 to t_2 switch S_1 is only on and S_2 is off and diode D_1 is off and D_2 is on, equivalent circuit diagram of TLBC for this mode-2 is shown in Fig. 2.9. The voltage across the S_2 is V_{c2} which is half of output voltage, and current i_{c_1} is I_o this mode is called as operating mode 2.

$$V_L = V_{in} - V_o/2 - V_o, \quad I_L = I_{C1} = I_O \tag{2.11}$$

$$V_{C1} = V_{C1} = V_O/2 \tag{2.12}$$

Q1on.pdf

Figure 2.9: TLBC equivalent circuit when S_1 is on and S_2 is off

Eq.2.11 and 2.12 are inductor and both the capacitor voltages equations.

Following are the expressions for the output voltage V_o, ripple voltage $\triangle V_c$, and ripple current $\triangle i_L$:

$$V_o = \frac{V_{in}}{(1-D)} \tag{2.13}$$

$$\Delta i_L = \frac{V_{\text{in}}(2D-1)T_s}{2L} \tag{2.14}$$

$$\Delta v_{C_1} = \frac{I_o D_1}{C_1 f_s} \tag{2.15}$$

$$\Delta v_{C_2} = \frac{I_o D_1}{C_1 f_s} \tag{2.16}$$

Circuit has been designed for the power rating of $1500W$, parameters considered [**?**]are input voltage, V_{in} = 100V , output voltage, V_o = 250V , switching frequency, f_s = 10 kHz, ripple in inductor current is 8%, ripple in capacitor voltage is 4%, R=41.67Ω , L = 0.83 mH, C = 72 μ F

Here are the remaining parameters of the circuit listed in the table 2.1.

Table 2.1: Circuit parameters

Parameters	Formula	Values
Output voltage (V_o)	$\frac{V_{in}}{1-D}$	250V
Ripple current in Inductor (Δi_L)	$\frac{V_{in}(2D-1)}{2Lf_s}$	1.2A(8% of I_L)
Ripple voltage in capacitor (Δv_C)	$\frac{I_o D}{f_s C}$	5V(4% of V_C)
Voltage across each capacitors V_{C1} and V_{C2}	$\frac{V_o}{2}$	125V
Voltage across each diodes V_{D1} and V_{D2}	$\frac{V_o}{2}$	125V
Voltage across each switches V_{S1} and V_{S2}	$\frac{V_o}{2}$	125V

2.3 Simulated waveforms for openloop of TLBC

According to the desired output power, a converter is succesfully designed and performs its simulation open loop operation on PSCAD software. Input source voltage is 100V , output voltage is 250V and waveforms are shown in the Fig. 2.10. Input voltage is constant and output voltage has ripple in it as shown in 2.10(b), these ripples are filtered by using filters at the output which makes output further smoother. Similarly input

source and output voltage.pdf

Figure 2.10: (a)input source voltage(b)output load voltage

inductor or source current and output current are shown in the Fig.2.11, peak to peak inductor current has the value 1.2A which is 8% of source current 15A when refers to output current its ripple depends upon the voltage ripple.

inductor and output current.pdf

Figure 2.11: (a)input inductor current(b)output load current

Capacitance voltages of 125V each which is half of output voltage since values of both capacitances are same and they are balanced. Peak to peak voltage for each capacitor is 5V which has ripple of 4% of $V_c = 125$V as per Fig. 2.12. These capacitors itself are acting as filters in this circuit at the same time we can connect a load across individual capacitors.

both cap voltages.pdf

Figure 2.12: both the output capacitor voltages

2.4 Conclusion:

The chapter describes a three-level boost converter (TLBC) designed for a standalone solar panel system. TLBC reduces stress on switches and filter inductors compared to conventional boost converters. It achieves this by distributing voltage stress across two capacitors connected in parallel.

The document explores the TLBC operation for duty ratios greater than and less than 50%. It also presents equations for calculating the output voltage, ripple voltage, and ripple current.

Simulations were conducted using PSCAD software to verify the TLBC design. The results show that the converter successfully boosts the input voltage from 100V to 250V with some ripple. Capacitors help to filter these ripples, and additional filters can be added at the output for further smoothing.

Chapter 3

Closed loop Three Level Boost Converter

3.1 Introduction

Open loop TLBC operates and delivers power for any value of load connected to it irrespective of limit which is undesirable since the components are designed for its rated values i.e, in its linear operating region specifically at knee point after linearity all the components become nonlinear as power ratings exceeds the rated limit so its necessary to design the controllers for inductors and capacitors to maintain operation in the desired region. By addressing this issue controllers could be introduced for controlling inductor current and capacitor voltages. In the Fig.3.5 both voltage and current controllers are showned.

`voltage and current loops in cascade.pdf`

Figure 3.1: voltage and current controller loops in cascade

In the system PI controller is used, K_p and K_i associated with controller decides the response rise time and steady state error hence they are tuned as per requirement. Controller ensures whether the circuit is operated at rated values are appearing or not, so one can say circuit will always operate at fixed reference value.

3.2 Simulated closed loop waveforms of TLBC

3.2.1 Inner current control loop:

This loop is designed to put the inductor current at fixed value. Difference between reference current and actual current is given to the PI controller and that is tuned proper with the values such as K_p= 0.01 and $K_i = 10$ they are designed and decided based on hit and trial method, the output of controller i.e, modulation signal is given to comparator. With this inductor current would be maintained at reference value(rated value).

current controller.pdf

Figure 3.2: Current controller

inductor current with controller.pdf

Figure 3.3: (a) Inductor current with out controller (b) Inductor current with controller

3.2.2 Reference step change of a current controller:

In this closed loop current controlled case waveforms are simulated and showned in the Fig. 3.4, reference value is changed from 15A to 25A it is changed at a instant of 0.5 sec of simulation running time. Now the intent is to check reliability of current controller when the inductor current is supposed to change its value instantly and to check the controller whether it is working properly or not. Whenever the current changes there is a change in output voltage also since the inductor current has been changed. K_p and K_i values of controller remains unaltered only change is that step reference of an inductor current. With this one can conclude the reliability of the current controller.

`step change for current controller.pdf`

Figure 3.4: Inductor current with reference step change

When reference current value changes power flow in the circuit also changes .After step change rating of the circuit is changes from 1500W to 2500W based on reference current value.

3.2.3 Outer voltage control loop:

In this case circuit controller has been designed, then it is being simulated and its output waveforms are showned in the Fig. 3.6, Difference between reference current and actual current [?] is given to the PI controller and that is tuned proper with the values such as K_p= 0.01 and K_i = 10 they are designed and decided based on hit and trial method, the output of controller i.e, modulation signal is given to inner current loop controller, voltage controller modulation signal is acting as reference signal to the current loop. With this output voltage would be maintained at reference value(rated value), considering inductor is maintained at 15A in the inner current control loop

`voltage and current loops in cascade.pdf`

Figure 3.5: voltage and current controller loops in cascade

output voltages with and without control.pdf

Figure 3.6: (a) output voltage with controller (b) output voltage with out controller (c) unbalanced capacitor voltages

voltage step change.pd.pdf

Figure 3.7: Voltage Reference step change response waveform

3.2.4 Reference step change of a voltage controller:

In this closed loop voltage controlled case waveforms are simulated and showned in the Fig. 3.7, reference value is changed from 250V to 280V it is changed at a instant of 0.5 sec of simulation running time also reference value is changed from 250V to 230V it is changed at a instant of 0.5 sec of simulation running time. Now the intent is to check reliability of voltage controller when the capacitor voltages are supposed to change its value instantly and to check the controller whether it is working properly or not for that K_p and K_i values of controller are tuned with this one can conclude the reliability of the voltage controller.

3.3 Balanced Capacitor voltages:

After voltage control loop connected in cascade with current control loop we have obtained output rated voltage and inductor rated current. Now we are concerned about balancing the output capacitor voltages, this is achieved by implementing a algorithm for one of the capacitors [?][?]i.e, V_{C2}. The algorithm implemented for balancing capacitor is very much similar to the technique implemented for voltage and current controllers. Following are the waveforms obtained before and after balancing[?] both the capacitors i.e in the Fig. 3.9

Vol-curr-vol bal.pdf

Figure 3.8: Balanced capacitor voltages with rated voltage and inductor currents

capacitor voltages before and after balance.pdf

Figure 3.9: Balanced capacitor voltages with rated voltage and inductor currents

3.4 Hardware circuit and results of TLBC:

TLBC hardware circuit has been implemented, monitored and recorded results are showned in the Fig.3.10, along with the step reference change responses. All colored waveforms are shown in the Fig.3.10 after step at the instant of t_o as shown, green waveform is an output voltage has the value of approximately 87V, Meroon waveform is an inductor current has the value of 2.76A, blue waveform is a capacitor voltage which has the value of 43V, gold colored waveform is a input voltage which has the value of 31V constant throughout the time period without change. This hardware circuit has the power rating of 85.56W and value of capacitors used at the output are 470 μF each and inductor value of 1mH, load resistance of 84Ω.

STEP CHANGE.pdf

Figure 3.10: TLBC hardware setup picture and reference step change responses of input voltage, output voltage, capacitor voltage, inductor current

3.5 Conclusion:

The document describes a design for a controller for a three-level boost converter (TLBC) used in a solar panel system. The controller maintains the output voltage and inductor current at desired levels. It achieves this by using cascaded PI controllers. The document also presents simulation and hardware results that verify the effectiveness of the controller design.

Chapter 4

DC - AC Converter

4.1 Introduction

Inverters are the power electronic converters which converts DC power to AC power with the help of power electronic switches, they are used where there is requirement of uninterrupted power supply and also for driving mechanical loads or for any other stand alone applications. At the output of this converter it is very much easier to control the output voltage magnitude and frequency depending upon the requirement. In input it takes energy from either battery or from any chopper and can convert DC power into AC power at desired magnitude and frequency.
These inverters are classified as voltage source inverters(VSI) and current source inverters(CSI), due to limited applications of CSI's it is not explored in this thesis, VSI's are further classified into categories based on their output voltage control they are (a) single pulse modulation (b) multiple pulse modulation (c) sinusoidal pulse width modulation.

Here are the certain applications where inverters are employed such as where there is an uninterrupted power supply is requirement such as house hold appliances, UPS,etc further in high voltage DC power transmission systems at the receiving end side, and in electric drives where AC motors are used.

`inverter block diagram.pdf`

Figure 4.1: Block diagram of rectifier and inverter in series

(a)Single Pulse Modulation: In this modulation technique reference signal is square wave and triangular signal repeating signal which repeats at higher frequency. In this inverter only one pulse is produced per half cycle.

(b)Multiple Pulse Modulation: In this modulation technique also reference signal is square wave and two triangular signals will be repeating which repeats at higher frequency. In these inverters multiple pulses of equal width are produced per half cycle.

(c)Sinusoidal Pulse Width Modulation: In this modulation the reference signal is sinusoidal and traingular signal is repeating at higher frequency value. In these inverters if there one reference signal then it is Bipolar PWM, where as if there are two referece signals then it is Unipolar PWM. In these inverters switches should operate at higher frequencies for controlling the output waveforms.

SPWM,UPWM.pdf

Figure 4.2: unipolar pulse width modulation

In this thesis work it is concerned more on 1-phase full bridge inverter connection in series with TLBC in order to avail sinusoidal signals for supply and utilization of loads. This system could feed stand alone loads or support power to the grid.

4.2 1ϕ - Full Bridge Inverter

A single- phase full bridge is showned in the Fig. 4.3 which consists of four switches and diodes antiparallel to switches responsible for inverting the input DC power available at desired frequency, output voltage magnitude depends upon the input voltage available at the inverter. When the switches S_1 & S_2 are turned on appeared voltage would be v_{in} and when S_3 & S_4 are on output voltage would be $-v_{in}$ operation of S_1, S_2 & S_3, S_4 are in complementary mode. Anti parallel diode doesn't effect output voltage but allows the reverse current to flow through. Output voltage equation is as follows

INVERTER.pdf

Figure 4.3: (a) full bridge inverter circuit (b) output voltage

$$v_o(t) = \sum_{n=1,3,5..}^{\infty} \frac{4v_{in}}{n\pi} sin(nwt)$$

The inverter output voltage has voltage components of odd integral multiples of fundamental component due to its half wave symmetricity. Other than fundamental component all other remaining are called as harmonics due to which fundamental sinusoidal component is getting distorted so to mitigate this issue its feasible to adapt unipolar technique to control output voltage of a inverter.

Amplitude Modulation Ratio(m_a):

$$m_a = \frac{\hat{v}_{ref}}{\hat{v}_{tri}}$$

Frequency Modulation Ratio(m_f):

$$m_f = \frac{f_{tri}}{f_{ref}}$$

4.2.1 Unipolar PWM:

In UPWM switching, devices in the both legs are not operated simultaneously, both the legs are controlled separately by comparing v_{tri} with v_{ref} and $-v_{ref}$. The switching signals are as follows and also voltage waveforms are also of similar kind

UPWM.pdf

Figure 4.4: Unipolar Pulse width modulation switching waveforms

The logical signals which controls the switches are

$$\begin{aligned} v_{ref} > v_{tri} \ , &\qquad S_1 \text{ is on} \\ -v_{ref} > v_{tri} \ , &\qquad S_3 \text{ is on} \\ v_{ref} < v_{tri} \ , &\qquad S_4 \text{ is on} \\ -v_{ref} < v_{tri} \ , &\qquad S_2 \text{ is on} \end{aligned}$$

4.2.2 Output Voltage and current waveforms of Inverter:

The output voltage and current waveforms of the inverter for which input voltage is supplied by DC-DC converter i.e, DC-DC converter has been cascaded with inverter and waveforms are obtained as follows

OUTPUT VOL AND CURR WITHOUT FILTER.pdf

Figure 4.5: Inverter output voltage and current waveforms without filter (a) voltage waveform (b) current waveform

Inverter along with LC- Filter: The LC filter has been connected at the output of the inverter for filtering out the harmonics that are present in the voltage waveform and the filtered output voltage and current waveforms are in the Fig.4.6

`INVERTER WITH FILTER.pdf`

Figure 4.6: Inverter with LC filter

`inverter output parameters.pdf`

Figure 4.7: Inverter output voltage and currents with LC filter (a) voltage waveform (b) current waveform

Output voltage equation of an inverter is

$$v_o(t) = \sum_{n=1,3,5..}^{\infty} \frac{4v_{in}}{n\pi} sin(nwt)$$

This waveform has fundamental component and integral multiples of odd harmonics, odd harmonics are so because its waveform [**?**] i.e, 4.3(b) has odd half wave symmetricity, in order to mitigate/filter those harmonics LC filters[**?**] has been used. Now after LC filter waveform [**?**]obtained is approximately sinusoidal in nature as shown in figure 4.7(a)

4.2.3 Hardware Implementation:

Hardware circuit has been implemented and tested and all the outputs have been recorded and showned. TLBC and inverter both setup are showned navy blue is inverter and green colored is TLBC in the Fig. 4.8 and waveforms are showned in the Fig. 4.10

hardware_setup.pdf

Figure 4.8: Hardware setup of TLBC & Inverter in cascaded form.

4.2.4 Signal Conditioning Circuit:

In a data acquisition system, the signal conditioning circuit plays a crucial role. This circuit takes the voltage and current outputs from Hall effect transducers, which can reach 5 volts, and scales them down to a range between 0-3 volts. This adjustment ensures compatibility with the analog input channels[?] of the digital signal processor (DSP). The DSP is designed to handle signals within this specific range (0-3V) and cannot exceed it under any circumstances. To achieve[?] this scaling, an operational amplifier (op-amp) based circuit is used for signal conditioning. The signal conditioning circuit acts as an

Signal conditioning Circuit.......pdf

Figure 4.9: Signal conditioning circuit

intermediary between the sensors and the data processing unit. It ensures the sensor signals are compatible with the Digital Signal Processor (DSP). Here's a breakdown of its stages:

Unity Follower: This initial stage acts like a buffer, offering high input impedance. This prevents the circuit from affecting the sensor's output (loading effect).

Attenuator: This stage reduces the signal strength (attenuation) without significantly changing its shape. However, it introduces a 180-degree phase shift, which might need further correction.

Level Shifter: This stage introduces a DC offset voltage of -1.5V, effectively shifting the entire signal down to a range between 0 and 3V. This makes it compatible with the DSP's input range.
Adjustable Negative Voltage Regulator: Provides a stable -1.5V reference for the level shifter.
Precision Rectifier: Prevents any negative voltage spikes from reaching the DSP by allowing only positive voltage to pass through.

Zener Diode: Acts as a safety valve at the output, clamping any voltage exceeding 3.3V to protect the circuit from overvoltage.

TLBC_HARWARE_RESULTS.pdf

Figure 4.10: Voltage and current waveforms of a cascaded system

In the Fig. 4.10 obtained waveforms of voltage and current waveforms depicts the cascaded system in which TLBC and Inverter are connected in series.

4.3 Controller values and specifications:

The transfer function of a PI controller is $(k_p + \frac{k_i}{s})$, k_p value controls the gain and k_i value controls the steady state error. Tuning of the controller is very much important for proper operation of the system improper tuning leads to bad results. Controller receives error signal and produces modulating signal this is what brief definition of a controller. Inner current control loop is designed first and then voltage control loop is connected in series with this current loop and modulating signal of the voltage loop behaves as a reference signal the current loop. Current loop modulated signal is given to switch(S_1)comparator and compared with repeating signal and pulses are produced. Similarly a voltage balancing loop is also designed and its modulation signal is given to the switch(S_2).

0.5

Table 4.1: Specifications of simulated circuit

Parameters	Value
DC link voltage	250V
Power converter power handling capacity	500W
UPWM carrier frequency	10 kHz
Grid/reference frequency	50Hz
TLBC switching frequency	10kHz
TLBC inductor	1mH
TLBC capacitors values	1mF
All voltage,current,Voltage balancing loops controllers K_p	0.01
All voltage,current,Voltage balancing loops controllers K_i	10

4.4 Conclusion:

This chapter details a novel system for converting DC power to AC power. The system comprises two key components: a three-level boost converter (TLBC) and a full-bridge inverter. The TLBC efficiently elevates the voltage from a DC source, while the inverter subsequently transforms this boosted DC voltage into AC voltage.

Furthermore, the chapter delves into the design of controllers for both the TLBC and the inverter. These controllers utilize pulse-width modulation (PWM) to meticulously regulate the system's output voltage and current.

The chapter culminates by presenting the outcomes of extensive simulations and real-world hardware tests. These results convincingly demonstrate the system's ability to effectively convert DC power into AC power, delivering a desirable sinusoidal output voltage.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

A three-level boost converter (TLBC) was designed to efficiently increase DC voltage. This design offers advantages over conventional boost converters.

- Detailed simulations of both the TLBC and the inverter were conducted in PSCAD software. Since the software models ideal components (without losses), the simulations provided accurate results.
- Controllers were implemented to regulate the inductor current and capacitor voltages to desired levels within the TLBC.
- The system's response to changes in reference values for both the inductor and capacitor elements was analyzed through step change simulations.
- A specific algorithm was successfully applied to achieve balanced voltages across both capacitors in the TLBC.
- The TLBC was cascaded with a full-bridge inverter to deliver AC power to a load, demonstrating successful system operation.
- Following the simulation phase, the designed hardware was built and tested, and its output responses were captured for analysis. To boost the DC-DC voltage, a three-level boost converter is designed due to it's advantages over the conventional boost converter.

5.2 Future Work

The next stage is real-world testing of the designed hardware. This testing will involve both open-loop and closed-loop operation to assess the system's performance under different control methods. Following these initial tests, we will evaluate the TLBC[?] hardware's response to various load types, including resistive loads, battery charging loads, and different AC loads. Additionally, we will explore the functionality of different inverter topologies. The testing will encompass a range of power supplies, including 100 W, 500 W, and 1 kW options. Finally, we will integrate the hardware with a photovoltaic (PV) system to examine its ability to boost voltage for resistive loads. Furthermore, potential future [?]integration with a Maximum Power Point Tracking (MPPT) control [?]algorithm for efficient AC load feeding with various AC topologies will be investigated.

References