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Design and Simulation of Boost DC - DC Pulse Width Modulator (PWM) Feed-Forward Control Converter

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DESIGN AND SIMULATION OF BOOST DC-DC PULSE WIDTH MODULATOR (PWM) FEED-FORWARD CONTROL CONVERTER

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

by

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Calenia L. Franklin ENTITLED Design and Simulation of Boost DC - DC Pulse Width Modulator (PWM) Feed-Forward Control Converter BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

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ABSTRACT

Franklin, Calenia. L. M.S.E.E, Department of Electrical Engineering, Wright State University, 2020. Design and Simulation of Boost DC - DC Pulse Width Modulator (PWM) Feed-Forward Control Converter

Military aircraft systems' power losses are occurring during the loading operations; loading and unloading causes the aircraft systems to lose power. The primary aircraft power source is provided by a 400Hz Ground Power Units (GPU). This GPU provides power to interior lighting, the aircraft cargo compartment, and other electrical systems (i.e. bus). The issues are during loading and unloading on the aircraft, which causes dropout of aircraft power supplied by the external 400Hz GPU. The majority of the military aircraft require a high voltage and a high current with a 270V power output. This thesis analyzes using Feed-Forward PWM Boost DC-DC Control Converter to help maintain 270V power output.

The Feed-Forward PWM Boost DC-DC Control Converter design equations are operating in Continuous Conduction Mode (CCM) and all theoretical simulation responses were verified using Saber circuit simulator. The design and simulation results are documented in this thesis.

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1. Introduction

The earliest military aircraft designs did not have an electrical power requirement because there were no electronics or electrical equipment that required it. Around early 1920, aircraft started having on board radios and navigation equipment powered by batteries. This change continued with advances leading to creating smaller generators that supplied DC power. As of today, the smaller aviation aircraft tend to use DC electrical systems.

Military aircraft are becoming increasingly complex. The 1950s' era mechanical pressure sensing instruments have been replaced with "Glass" cockpits, and more specialized mission equipment added to meet operational requirements. These aircraft require large amounts of electrical power to operate. On these aircraft are radars, sensors, and sophisticated cockpit displays [7]. Faleiro [16] states, "electricity to operate military aircraft flight instruments, actuators, avionics, and internal and external lighting, and other aircraft," the direct current power supplies cannot keep up with the growing demands.

The demands for more electrically powered aircraft will help reduce military aircraft systems' structural and fuel use significantly [23]. For example, reducing one pound of weight from the aircraft can reduce the weight by at least five pounds. The reason the aircraft will lose the weight is that the additional structure and fuel are no longer needed to carry it over the range the aircraft can fly [24]. Some of these challenges led to standardization advancements in military aircraft electrical power systems.

1.1 Military Aircraft Power

Today, military aircraft power is mission critical to safely support and secure military operations. Depending on the nature of the military operations, the few seconds between power going down and standby generators kicking in, could mean the difference in successfully completing the mission, or losing the competitive edge, and our military interests adversely affected. Lives can be depending on those few seconds.

Aircraft power supply problems are difficult to predict. To achieve the required level of reliability, and avoid aircraft supply problems, military aircraft power supplies must be built to comply with military standards. These standards describe specific requirements for the type and quality of parts, design, and applications for use. The purpose for these standards and requirements is to provide guidance and power characteristics for military aircraft before installing the electrical equipment to ensure military standards are met, and to ensure the aircraft is airworthy after undergoing these modifications and parts replacements.

The power supply system plays an important part of the overall performance of the aircraft system. The power capacity index should meet the requirements of the onboard electrical equipment; according to Zhang et al. [1], "it should also have the power supply characteristics which meet the prescribed requirements under various aircraft operating conditions, including the steady state, transient performance of the power supply, conversion performance and system compatibility."

Military aircraft upgrades are requiring more modifications to what is already there in older aircraft, making these modifications more electrical. The purpose is to replace many of the outdated mechanical systems that are being used on aircraft today with a more robust electrical power distribution system to enhance performance or functionality while delaying the costs associated with replacing the aircraft.

1.2 Power Electronics for Aircraft Systems

Today's aircraft manufacturers are losing profits and cutting operating cost due to low cost carriers for commercial airlines, and power electronic systems [2]. The aircraft manufacturers are increasingly trying to meet industry demands by placing more emphasis on the use of technology that could lower the maintenance and fuel usage operating costs.

Industry is moving in the direction of more power electronic systems for aircraft. The older the aircraft systems the more mechanical power dependent. For instance, hydraulic power [23], pneumatic power [23], which were the standard for conventional aircraft power [3]. The concept of using more electrical energy has advantages such as reducing the need for support equipment and improving reliability.

To achieve more power electronics on aircraft systems, studies and analysis show DC-DC power converters such as buck and boost, designs incorporate the variable frequencies at the input using control techniques [2]. Taha [3] stating, "Advanced power electronics converters, such as the buck and boost converter within aircraft equipment, are a possibility to operate this variable power to provide system level benefits." While power electronic converters will improve the control voltage at the load, electromagnetic interference (EMI) noise is unavoidable due to the switching actions of the semiconductor devices and resulting discontinuous currents, and its effects must be considered for the performance and the design phase of the system. These specialized capabilities underscore many of the imaginative engineering concepts and solutions that can be employed to enhance power electronics for aircraft systems.

1.3 Military Aircraft Standards for Electrical Power Supply Characteristics

The Department of Defense (DoD) MIL-STD-704 intent is to provide guidance and defines "electric power quality requirements" for all military aircraft systems. The DoD [3], has provided guidance and standards to follow during system design that are essential to achieving interoperability and ensuring any new designs meet certain requirements, commonality, and reliability to mitigate system risks. MIL-STD-704 aircraft power supply characteristics' that cover the aspects of load measurement, the steady limits, the voltage phase difference, the voltage transient, the frequency transient, and the power failure for the entire aircraft electrical system [1],[2],[3],[4].

The electrical power supply aircraft characteristics' standard is an essential system design criterion for military aircraft systems. The electrical power supply interfaces with multiple sources on the aircraft, such as the avionics bus. Military aircraft systems must implement these standards during the process of development in accordance with MIL-STD-704. This guidance covers production, procurement, acceptance, use, maintenance and repair [4]. The handbook guidance is the foundation for technical inspection and coordination for modified systems and new technical equipment for the user.

Military aircraft, electrical power systems must meet compliance to MIL-STD-704 for the aircraft to meet airworthiness standards to perform its missions. The handbook is updated on a periodic basis. These updates provide revisions that must be met before the electrical equipment installation can be certified to military standards. The MIL-STD-704 covers multiple power supply types such as: single phase 115V/400Hz AC, the three phase 115V/400Hz AC, the signal phase 115V/60/Hz AC, the 270 VDC and the 28 VDC.

Zhang et al. [1], “the performance and quality of the aircraft power supply system impacts significantly on the overall performance of aircraft.” As the power of the aircraft measures the ability of a production process to produce parts within a given tolerance, the aircraft power supply shall meet the requirements of all electrical equipment and power supply characteristics that are in MIL-STD-704. The characteristics of the power supply in aircraft systems provide exacting requirements for the generation and distribution systems, and also have corresponding limitations on the power equipment.

MIL-STD-704 is designed to ensure the aircraft functions whether or not the power supply system of the aircraft has the power supply characteristics that satisfy all the requirements under steady state a and transient performance of the power supply working conditions. All military aircraft systems must meet the criteria for MIL-STD-704.

1.4 Motivation for Thesis

Modern military aircraft systems are moving away from mechanical systems and toward electrical components and more electrical power aircraft systems. Some military aircraft systems draw 165 kilo-watt power, which is divided across the electrical loading through the electrical power system. Almost all of the aircraft that require more power need a standard voltage of 270V.

Military aircraft systems fall short when transitioning from ground power to engine power. The issue is during offloading of the aircraft; the aircraft's forward winch operations cause the dropout of aircraft power supplied by the external 400Hz GPU with DC voltage at 270V.

The United States Air Force has created a patent using an "open loop" control arrangement for the avionics bays in military aircraft systems [5]. US Patent 5,982,156, Kazimierczuk et al. [5], states controlling circuit coupling will control the electrical energy flow, the DC voltage source is a super capacitor [10] to bus voltage. This concept uses feed-forward PWM boost converter circuit design. Using the "open loop" design concept and modifying it to meet the current and voltage requirements can reduce the power loss in military aircraft systems.

Ideally, it is better to have power that is free of interruptions and transient free to provide better power to the aircraft [5].

1.5 Thesis Objective

The general objectives of this work are:

Learning Objective:

- Understanding Feed-Forward “open loop” concept.

Research Objective:

- To design a Feed-Forward pulse – width modulator boost converter. To meet desired specifications and improve the power quality to military aircraft systems.
- To simulate the design of Feed-Forward converter and present the characteristics
- To present final results of the Feed-Forward converter to maintain 270V and validate the change in the comparator.

Contributions

The main contributions consist of:

- A design method for military aircraft power loss using Feed-Forward “open loop” concept.
- An improved perturbation technique using the simple Feed-Forward concept to identify the accuracy of maintaining 270 V, voltage output.

2 DC-DC Power Supply

2.1 Introduction

Power supply sources are being used in, telephones, radios, computers, aerospace, medical, and defense electronics to name a few [23]. The dc-dc converter is one type of power supply. The dc-dc converter circuitry is not a simple or an easy solution. The design of a good dc-dc converter may seem tremendous, or over powering, however, if all the logical concepts are being done correctly, the design is successful.

2.2 Power Supply

The power supply is defined as a constant voltage source with maximum current capacity [24]. There are two types of power supply; regulated and unregulated. The regulated power supply output voltage is to maintain a range to 1% - 2% of its nominal value, without being affected by line voltage, load current and temperature variants. The unregulated power supply is to produce a particular voltage at particular current. Thus, this means to supply a constant amount of power.

Traditional power supply is “step-down” transformers which are a bulky and expensive part of the power supply. The bulkiness of the transformer is due to low line frequency (60Hz). What’s more, the low line frequency requires large filter capacitors, which reduces the output ripple, and adds up the cost and physical dimensions of the power supply [1], [2]. As well, the power transistor is operating in the active region and is continuously on, which dissipates considerable power. These three factors combined make the traditional power supplies bulky, more expensive and less efficient [1], [2], [3].

2.3 DC-DC converter

Maximum states [7], “the dc-dc converter” circuit shares one thing with other electronic designs, in that there is a small possibility of it working satisfactorily when first powered [7]. The technology design for this converter has shown that the circuit is very complicated. The dc-dc converter design technology tries to simplify its circuit by using highly rated integrated circuits (ICs). Adding these ICs to the design technology did simplify the design considerably, however, they still require component calculations and carefully choosing the correct integrated circuit controller. There are few books that provide guidance on what it is, what it isn't, and how to design a dc-dc converter. Studying this converter in engineering courses only discuss dynamical systems in engineered processes and machines, but do not cover the details of designing the dc-dc converter. Manufacturers of dc-dc converters provide additional detailed information in their data sheets [21].

For the initial specifications for dc-dc converter design, one must select input voltage range, output voltage, output current, then, select a converter IC. The power supply ICs are categorized into two types; linear regulators and switching regulators. The linear regulators only focus on one output voltage, which is the buck converter (step-down) [7]. With this design, the input voltage goes high, while the output voltage is low. The switching regulators focus on multiple output voltages, which are boost converter (step-up,). In this design, the input voltage goes low and while the output voltage is high [8], [9].

2.3.1 Switching Power Supply

A switching power supply is also referred to as a dc-dc converter that takes an unregulated DC and converts it efficiently up or down to a desired level of fixed and regulated DC output. The larger the duty cycle, D, the larger the average DC voltage is at the output. This technique is used to control and regulate the output DC level in switching power supply [1], [2].

Switching power supplies provide huge improvements in many areas by utilizing a technique called Pulse Width Modulation (PWM) [1], [2].

2.3.2 Pulse-Width Modulation (PWM)

The PWM converters retain a constant switching frequency over a range of loads. The switching frequency performance is important when switching; the reason is due to noise that may interfere with the system. General rule is for switching frequencies to avoid frequencies that work under 100 kHz. Older devices working under these frequencies have poor power efficiency [7]. Thus, when using a PWM converter, it is important to choose devices with the correct power criteria and that provide the correct switching frequencies that will not affect other components [7].

The PWM produces an analog signal that generates periodic square waveform using a digital source. The signal will produce a wave at any given time that will either be high or low. In circuit digest [6], if the signal stays high, it is called “on time,” and if the signal stays low, it is called “off time.” The PWM signal time is determined by the duty cycle shown below in figure 2.

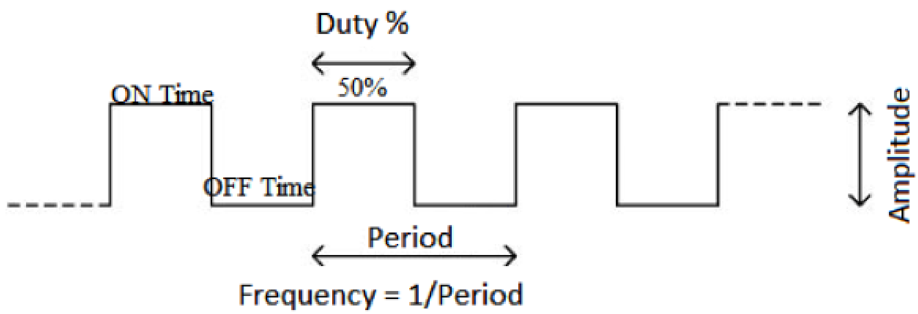

Figure. 2.1 Duty Cycle of PWM

Duty cycle = Switch On time/ (Switch On time + Switch OFF time).

Thus, controlling the duty cycle can control the PWM. The rule of thumb, the widest PWM should not exceed 80% of maximum; the narrowest pulse width should not be less than 20% of maximum [6]. In this thesis the dc-dc converter design considered is the PWM boost converter implementing feed-forward “open loop” control concept.

3 Proposed Feed-Forward "Open Loop" Concept

3.1 Introduction

As discussed in chapter 1, the proposed feed-forward "open loop" concept has been proven in smaller applications of military aircraft systems. This thesis will show the feed-forward concept could be applied on the entire aircraft. Thus, the proposed open loop concept is the input voltage "feed-forward" to the input PWM boost converter in a steady state continuous conduction mode (CCM). The feed-forward design was modified to meet special conditions for military aircraft systems.

3.2 PWM Boost Converter Design

In the early 1960's, the boost converter was designed to power aircraft electronics [13]. The boost converter's job is to "Boost" the input voltage [2]. This means the boost converter has an output voltage greater than the input voltage for steady state analysis [2]. The boost converter contains four major components, which include the capacitor, inductor, diode and MOSFET [14], [15]. The boost converter is considered to be the most efficient converter as it operates at its max of 99% for input and output energy [13].

There are four assumptions to consider: according to [15], the first assumption is the MOSFET, and the diode, are considered ideal switches. The second assumption is the transistor output capacitor; the diode capacitor and lead inductor are zero [2]. The third assumption is the passive components that never change; linear, and frequency independent. And, the fourth assumption is the output impedance is zero [15].

3.2.1 Circuitry

The circuitry for the PWM boost converter consists of four major components. The first is the transistor switch, which is a MOSFET. The second is a diode. The third is an inductor. And, the fourth is a filter capacitor.

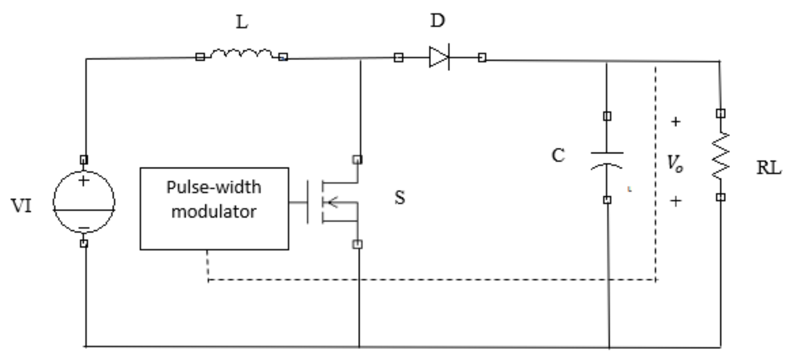

Figure. 3.1 Equivalent Circuit for the PWM Boost Converter

The PWM boost converter operates in two intervals. The first interval is when the switch is ON, $0 \leq t \leq dT$ and, the second interval is when the switch is OFF $dT \leq t \leq T$ [8], [9].

3.2.2 Transfer Function

The transfer function equation comes from the volt-second balance principle [8], [9]. Thus, controlling the control voltage is dependent to the transfer function.

$$V_I = V_o(1-d) \quad 3.1$$

$$M_{vdc} = \frac{V_o}{V_I} = \frac{1}{1-D} \quad 3.2$$

The transfer function is M_{vdc} [8]. Transfer functions generate the duty cycle which is based on the voltage controller. The change in the voltage controller, the duty cycle will change relative to the amount of the PWM, given in figure 3.2. The duty cycle is the portion of time during which the system is staying active [9].

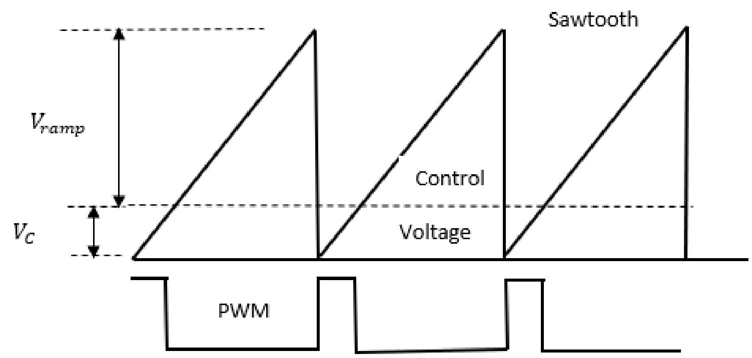

Figure. 3.2 Sawtooth Voltage Control PWM

3.2.3 Continuous Conduction Mode (CCM)

CCM is the power in the inductor flows continuously during the operation of the converter. To make sure the converter is in a steady state, the inductor energy increases while the switch is ON, which is equal to the output discharge while the switch is OFF. The CCM operation of the boost converter is dependent upon the inductor waveform [9].

When the switch is ON, the inductor is powered. When the switch is OFF, the inductor power is transferred to the output through the diode. The switch current is a fix steady state, sawtooth, is ON. The inductor voltage is more or less equal to both the capacitor and input voltage. The output is the voltage across the switch.

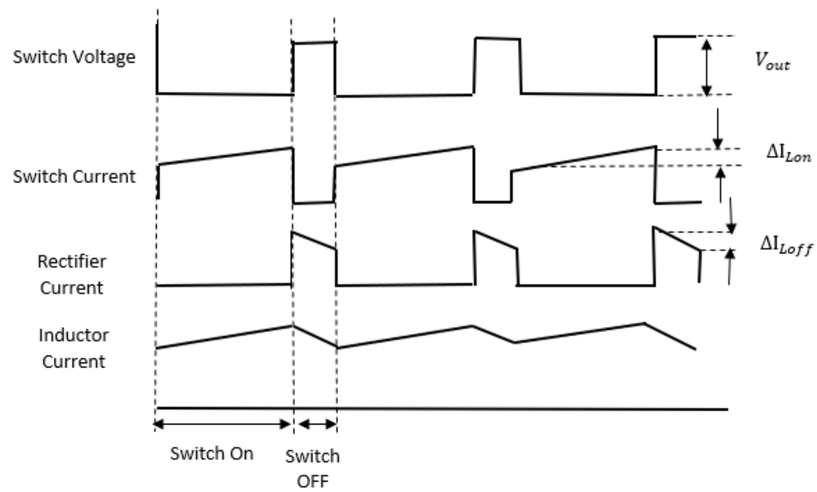

Figure. 3.3 CCM Waveform

3.2.4 Component Selection in CCM

Inductor Selection

Choosing the correct inductor, the peak current should be higher than the peak current of the converter. The winding resistance should be low to avoid overheating. To limit EMI, the makeup of the inductor should have low inter-winding capacitance.

MOSFET Selection

The MOSFET focuses on the breakdown voltage and power dissipation. Breakdown voltage of the MOSFET is approximately 1.5 times the output voltage. To make sure the converter is operating correctly, the drain voltage should not be higher than the 1.5 times the output voltage. The power dissipation has three elements; the switch loss, conduction loss and gate loss. Therefore, to lower the switching loss, choosing a MOSFET with low capacitance is best. Or, select a MOSFET with both the switching and conduction loss equals, and the converter operates at its max load.

Diode Selection

The diode should be able to support the capacitor's peak input current. Diode voltage drops times the load current. The diode breakdown voltage must be greater than the output voltage. The Schottky diode is the most popular used diode. The Schottky has low output voltage and low capacitance.

Capacitor Selection

The capacitor should have very good filtering performance and ripple current; calculating the ripple current into the capacitor and the capacitor ESR. The capacitor ripple current provides "smooth" voltage to the load. This occurs when at the switching frequency and ESR is low, to maintain the ripple voltage across the capacitor.

3.3 Feed-Forward Converter

The feed-forward technology uses the input voltage and the load current. Bao, et al. [13], describes feed-forward technology has an advantage to attain better "disturbance rejection and tracking performance" in these situations. The feed-forward design is a DC voltage at the input of the boost converter that will decreases with time, but the boost converter DC output voltage should remain constant [8],[10]. The feed-forward circuit is shown in figure 3.4.

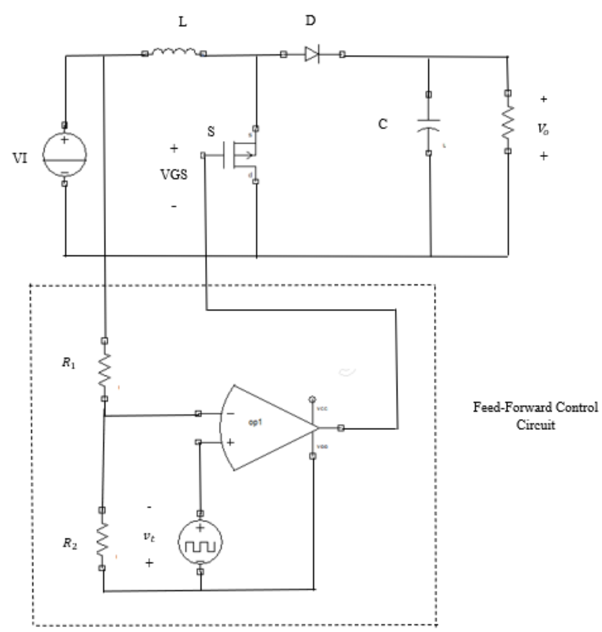

Figure. 3.4 Feed-Forward Circuit

The feed-forward PWM concept uses an amplitude or the PWM slope, which is a linear function of the two voltages [28]. This method proposed by Kazimierczuk et al. [3], is placing the voltage divider in parallel at the input voltage of the converter, which in turn feeds the signal to the input of the comparator.

The comparator takes two voltages or current and outputs signal specifying which is larger. The two input terminals are positive and negative [29]. The PWM signal is providing the output of the comparator, and drives the switch. [3], [30]. The comparator circuit is shown below in figure 3.5.

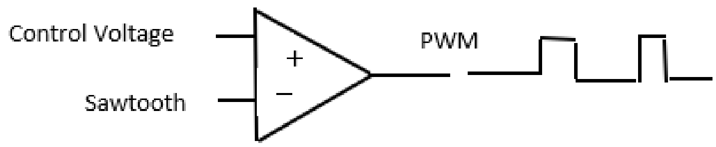

Figure. 3.5 Comparator Circuit

4 Simulation and Results Obtained from the Proposed Feed-Forward “Open Loop” Concept

4.1 Introduction

For any design to be successful, it must meet the theoretical design requirements. This means it must be tested to ensure the real-life assumptions are correct. The feed-forward “open loop” designed discussed in the previous chapter was a model and simulated to guarantee the design requirements for military aircraft systems.

4.2 Circuit Modeling Simulation

The feed-forward schematic design was modeled and simulated in the Saber modeling program. Saber is a modeling and simulation for applications in power electronics. SABER simulation measures axes for plotting and simulate single or iterative experiments.

Saber simulation uses time domain analysis, which is the most common analysis tool in Saber. Time domain analysis is also known as transient analysis. The Saber analysis tool is set to transient analysis/time domain analysis, powering up a circuit for a certain amount of time, and providing output. The simulation results are obtained from SABER sketch. SABER Sketch is an engineering software tool that is used on many industry platforms and by educational institutions.

4.3 Special Condition for Military Aircraft Systems

Discussed in previous chapters, earlier military aircraft variants with 1950s’ era mechanical pressure sensing instruments and lower power requirements have been retired from the inventory, while the later variants with upgraded “Glass” cockpits and equipment, with increased power requirements, are in service today. Most of the military aircraft variants, with the exception of special mission aircraft, can be reconfigured rapidly to augment the tactical portion of the airlift mission. To meet these requirements, the proposed feed-forward "open loop" circuit design must be modified. The proposed design uses one MOSFET and diode. The modified design uses fifteen MOSFET placed in parallel. Then, adding additional FIVE diodes. The reason for the modification is to meet military aircraft's high current and voltage systems.

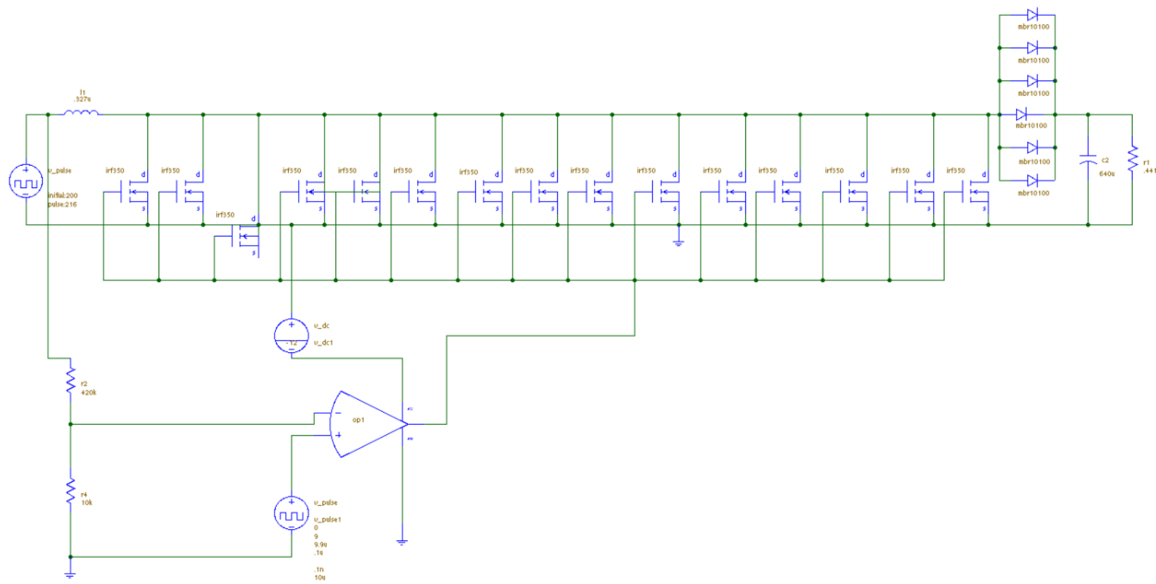

Figure 4.1. Military Aircraft Systems Feed-Forward Circuit

4.4 Circuit Diagrams to Simulate

The feed-forward converter design is a boost converter CCM, comparator (op-amp) and voltage divider composed of two resistors [10], shown in figure 4.1.

A single voltage is supplied to the comparator. The sawtooth wave voltage is at the non-inverting side of the comparator. The peak value voltage is a fix value V_{Tm} = 5-10, the inverting-input is the V_{Reff} the equation given by [5], [10].

$$V_{Reff} = \frac{R_2}{R_1+R_2} V_I = \alpha V_I \qquad (4.1)$$

$$\text{Where } \alpha = \frac{R_2}{R_1+R_2} \qquad (4.2)$$

The rectangle waveform is the output voltage of the comparator [5], [10], which drives the gate-source voltage of the MOSFET. Thus, the principle to operate a feed-forward circuit is when V_{Reff} is higher at the inverting input rather than the at the non-inverting input side of the comparator [10], then the gate-source voltage goes low turning the power transistor OFF. Changing V_{Reff} to low, then gate-source voltage is high. The MOSFET switch is ON. Hence, figure 4.2 shows the duty cycle is ON, as the switch increases the converter input decreases [10].

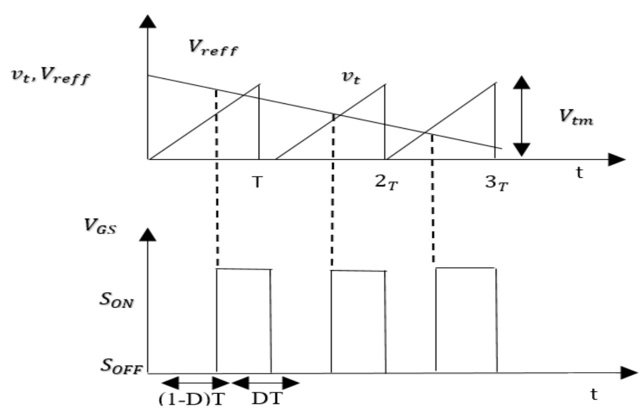

Figure 4.2. Feed-Forward Circuit Waveform

4.5 Specifications and Parameters

Efficiency is one of the key dc-dc converter performance parameters. Choosing the correct inductor, capacitor, and power MOSFET components for the feed-forward converter are extremely important. Selecting incorrect components can comprise the efficiency of the converter.

4.5.1 Specifications for Power MOSFET and Diode

The IRF 350 is a HEXFETs power MOSFET and provides the best combination of the fast switching devices.

I_D = 16A Continuous Drain Current

I_{DM} = 64A Pulsed Drain Current

V_{Dss} = 400V

ON Semi Schottky Rectifier Diode MBR 01000

The MBR10100 is a Schottky Rectifier Diode with molded plastic body, metal silicon junction, nearly all carrier conduction and lead-free pure tin-plated terminals.

V_{RRM} = 100V

I_F = 10A

Table 4.1 Feed-Forward "Open Loop" Parameter

Parameter	Notation	Value
Minimum DC Input voltage	V_I	216V
DC Output Voltage	V_o	270V
Switching Frequency	F_s	100kHz
Maximum DC Output Current	I_o	612A
Peak-Peak Voltage	V_{tm}	10V
Load Resistance	R_L	.4418Ω
Input Power	P	165 kW,

4.6 Calculations

The circuit designed is to deliver input voltage = 216 V to maintain an output voltage = 270 V. The output current = 612.2 A and a switching frequency = 100 kHz with output ripple voltage, = 20 V and load resistor .441 Ω. The MOSFET is IRF 350 n channel has data requirement gate-source = 10 and drain current = 64A. Fairchild diode Part Number MBR 0100. Note: Military aircraft systems requirement for output voltage varies between 260 and 270.

The max of the load current

$$I_o = \frac{Vo}{R} = \frac{270}{.441} = 612.2\text{A} \quad (4.3)$$

The transfer function in CCM, the efficiency is assumed at η= 99%

$$Mvdc = \frac{V_O}{V_I} = \frac{270}{216} = 1.25 \quad (4.4)$$

The duty cycle, D

$$D = 1 - \frac{\eta}{Mvdc} \quad (4.5)$$

$$1 - \frac{.9}{1.25} = .28$$

The V_{tm} = 10 peak-peak, voltage at $V_{I=}$ 216.

$$V_{reff} = (1 - D)V_{tm} \quad (4.6)$$

(1-.28)10= 7.2V

Where the V_C is the control voltage ≈ the reference voltage

$$V_c = V_{reff}\left(\frac{R_2}{R_2+R_1}\right) = V_I\left(\frac{R_2}{R_2+R_1}\right) \quad (4.7)$$

Assuming R_2 = 10K

$$R_1 = \left(\frac{216}{7.2} - 1\right)\times 10^3 = 3.3\times 10^6 = 300\text{k}$$

4.7 Results from Simulation

After all circuits were modeled in Saber, the transient analysis was performed using the circuit schematic shown in figure 4.1. Transient analysis is performed, setting an end time of 20 milliseconds and a time step of .1 microseconds. The gate-source voltage, sawtooth voltage and reference voltage waveforms are plotted. The average value and the maximum value are measured for the output voltage, output current and the output power. The duty cycle and the peak value are measured from the sawtooth voltage. The voltage controller is measured

4.7.1 Transient Analysis Waveforms

The feed-forward converter uses the input voltage load current to control the output voltage. The input voltage is given in figure 4.3.

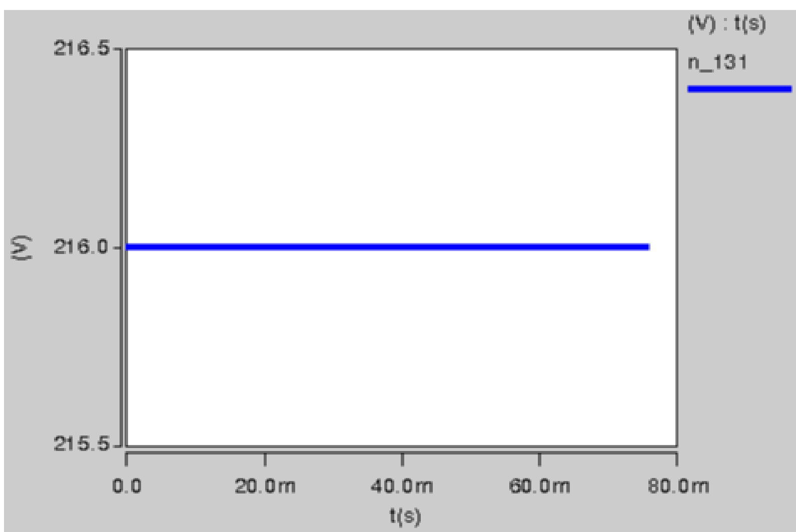

Figure. 4.3. Input Voltage Load Current

Gate-source output is a rectangular wave of the comparator and is used to drive the MOSFET. Thus, if the comparator output current is not high enough it will not drive the MOSFET at the high frequency. The gate-source voltage simulation is given in figure 4.4.

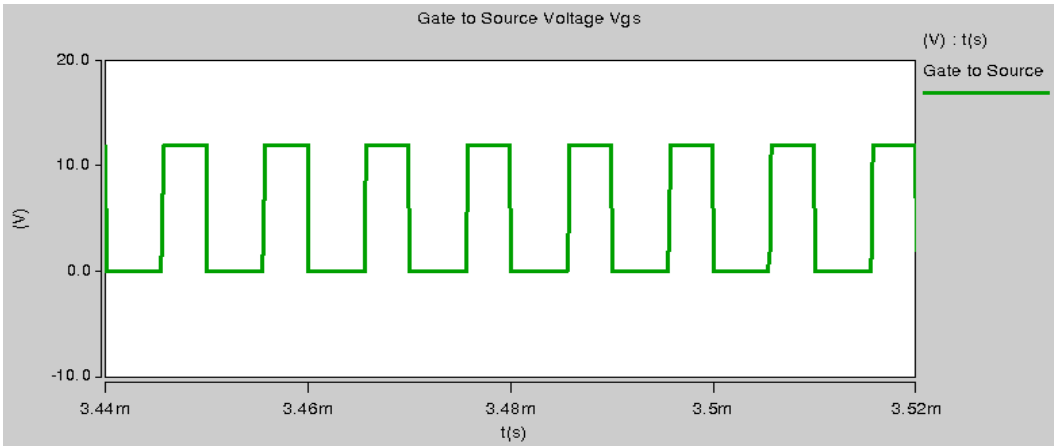

Figure. 4.4. Gate-Source Voltage

The sawtooth voltage is at the inverting side of the PWM and remains constant. Peak of the sawtooth signal is fixed with a voltage V_{tm} that varies from 5 to 10 Volts. The duty cycle is measured to be .5. The sawtooth voltage simulation is given in figure 4.5.

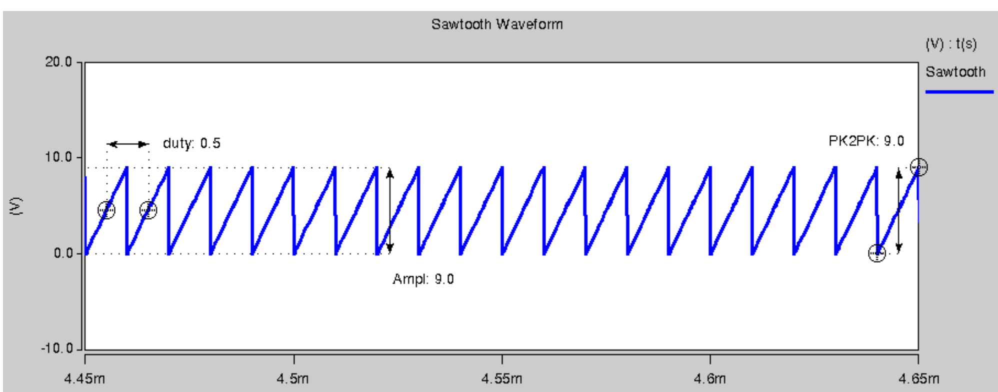

Figure.4.5. Sawtooth Voltage

Voltage controller source output is control by input voltage. The input voltage decreases and the voltage controller increases. Voltage controller is measured at 7V. The voltage controller simulation is given in figure 4.6.

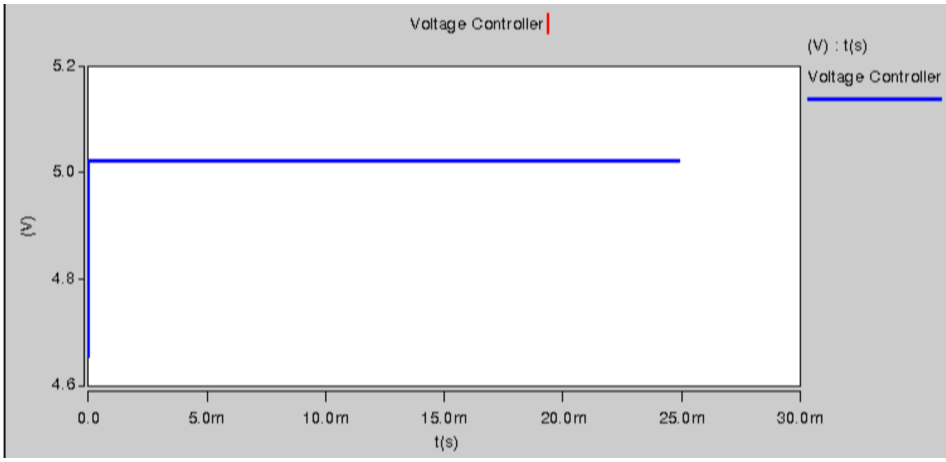

Figure.4.6. Voltage Controller

The output current, output power and output voltage calculations were verified by simulation. The average values were measured output 264.98W, output voltage 264.98V, and output current 600.86A. The output current, output power and output voltage simulation are given in figure 4.7.

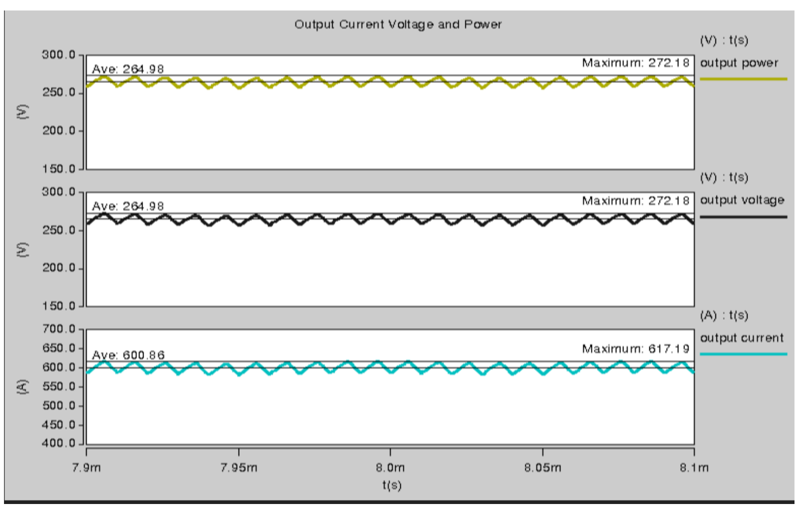

Figure.4.7. Output Power, Output Current and Output voltage

The output voltage is measured at 270.58. The output voltage simulation is given in figure 4.8.

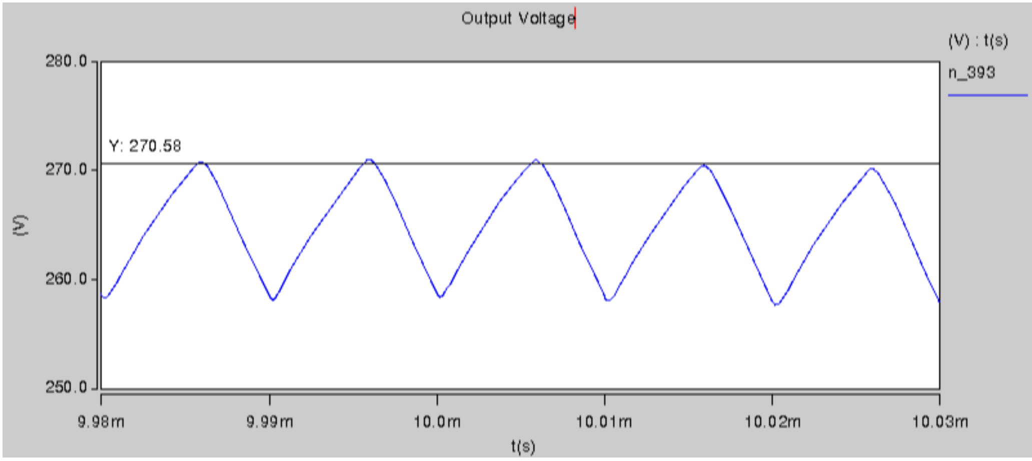

Figure.4.8. Output Voltage

5 Simulation and Results Obtained from the Proposed Feed-Forward "Open Loop" Concept Incorporating Step Change.

5.1 Introduction

In chapter 4, the simulation and results were obtained for feed-forward "open loop" concept. Now, this chapter will provide simulation and results, utilizing step change response. The step change response is the one of the most common tests to use at the input voltage (load). Applying the step change response proves the feed-forward "open loop" concept is working correctly.

5.2 Circuit Modeling Simulation

The feed-forward "open loop" concept with a step change response use Saber the same simulation as in chapter 4. The input voltage was removed and replaced with piecewise- linear voltage source. The circuit shown in figure 5.1 is analyzed during a steady state; this is when the input voltage of the feed-forward converter slowly changes with time. The voltage profile, values for Time (ms), is 0 and 6 respectively. The input voltage is 216 for both time values.

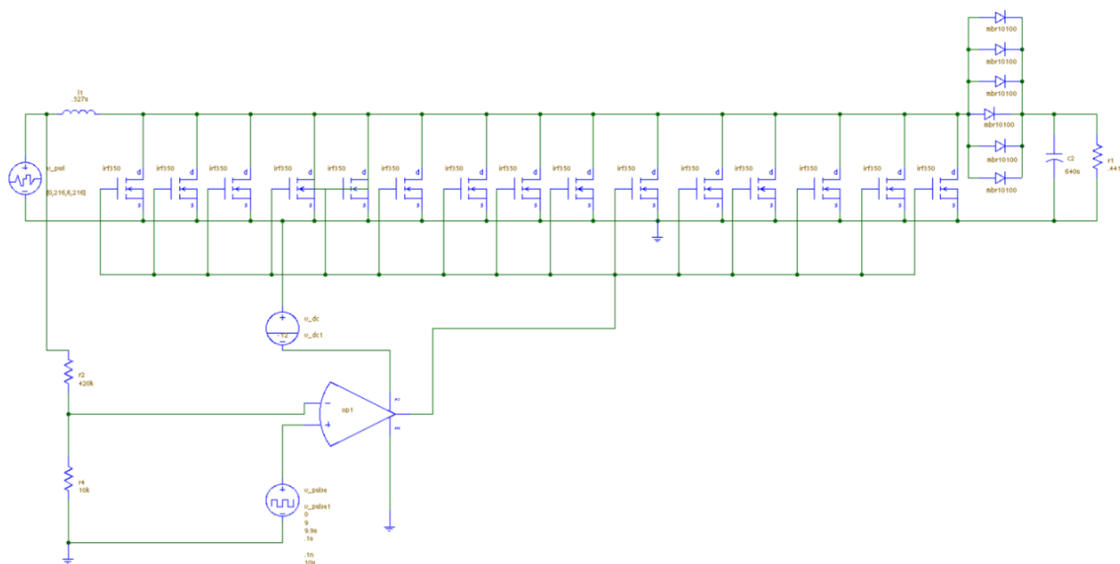

Figure 5.1 Military Aircraft Systems Feed-Forward Circuit with Step Change

5.3 Results from Simulation

The same simulation process that was done in chapter 4, section 4.3; was done for this section.

5.4 Transient Analysis Waveforms

The square waveform shows the input voltage from 200 volts and reaches its peak value of 216 after about 12ms, given in figure 5.2.

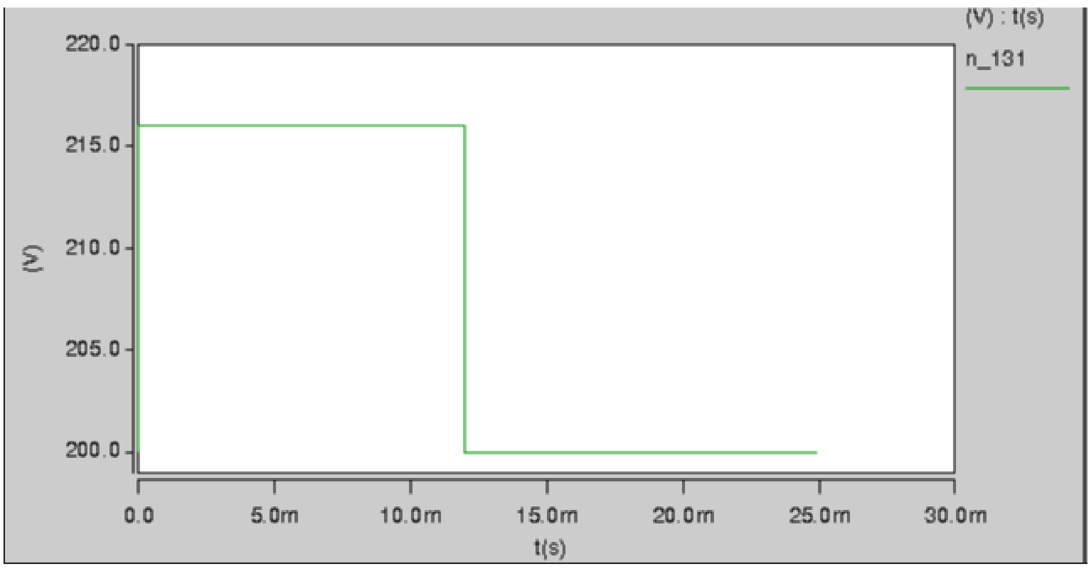

Figure. 5.2. Input Voltage with Step Change

The voltage controller is a square-wave. Square-wave voltage controller with step change, the drop input voltage, drops controls voltage causing increase in duty cycle.

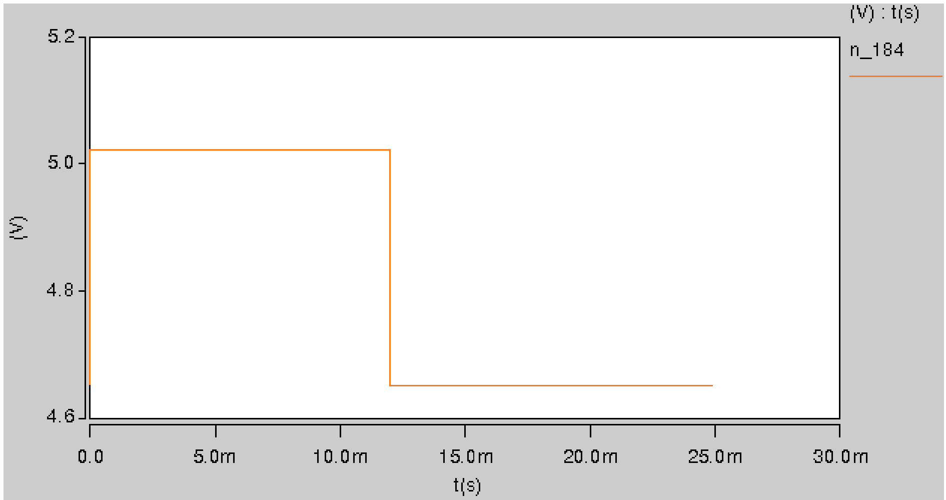

Figure. 5.3. Voltage Controller with Step Change

The gate-source voltage will go high, then turning the transistor ON with step change, given in figure 5.4.

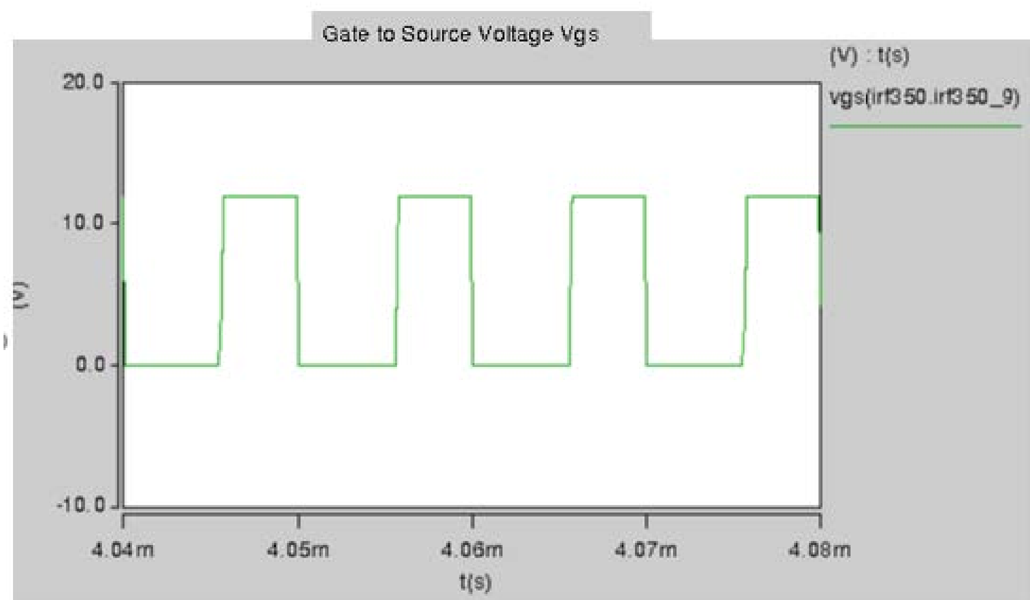

Figure.5.4. Gate-Source Voltage with Step Change

The sawtooth voltage at the input of the inverting side of the PWM remains constant. The duty cycle was measured at .5 given in figure 5.5.

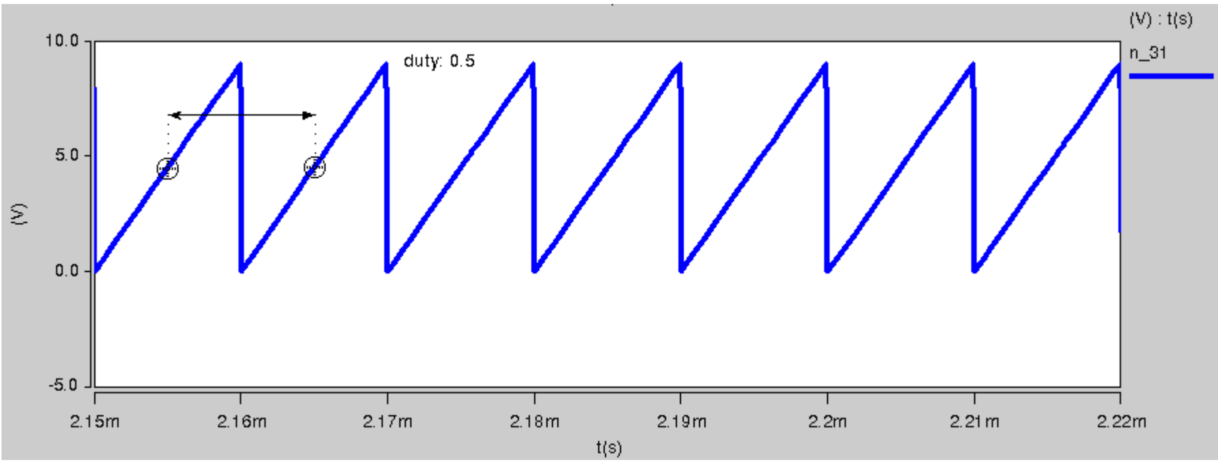

Figure. 5.5. Sawtooth Voltage with Step Change

The input current remains constant as it changes in time shown in figure 5.6.

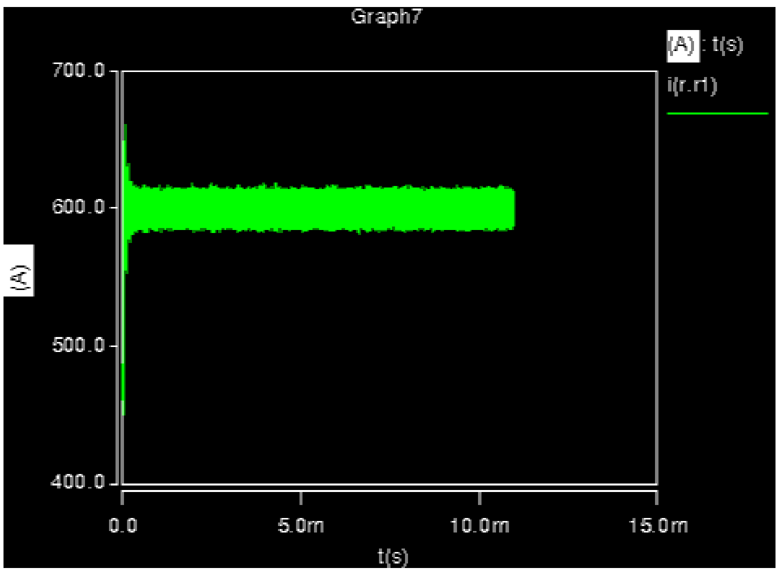

Figure. 5.6. Input Current with Step Change

The output power is maintained at 264V.

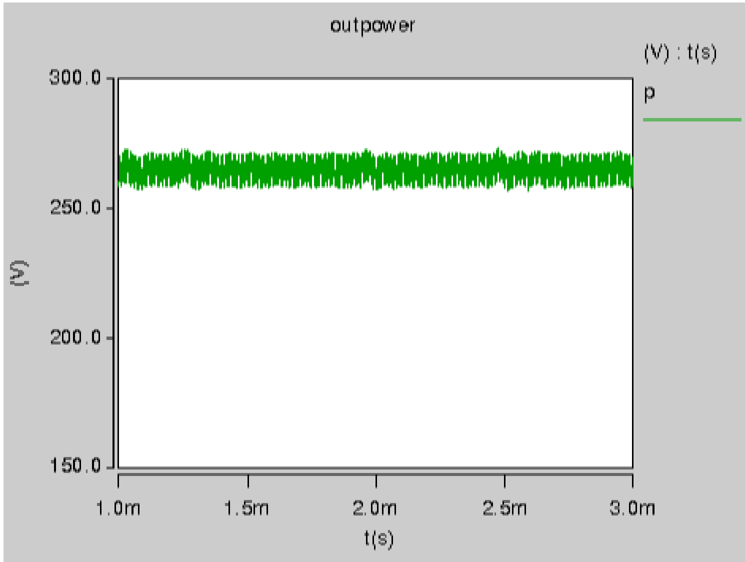

Figure. 5.7. Output Power with Step Change

The output voltage is maintained with the step change at 270 Volts.

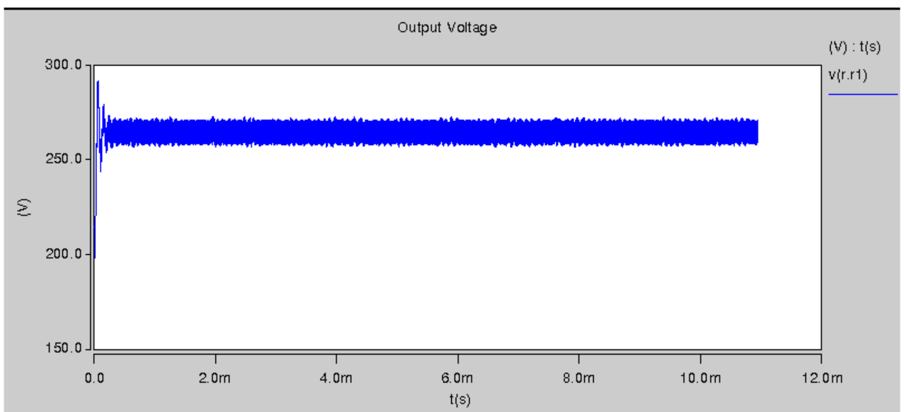

Figure. 5.8. Output Voltage with Step Change

6 Conclusions

6.1 Summary

Most of the military tactical transport aircraft variants, with the exception of special mission aircraft, can be reconfigured rapidly to augment the tactical portion of the airlift mission. The Loading and unloading can result in the aircraft losing power, delaying turnaround times, and immobilizing aircraft availability for critical missions. The feed-forward control is a powerful technique for improving the fast response of switching converters to input voltage and the output voltage.

The feed-forward circuit design discussed was simulated with two different input voltages. The first circuit was designed with a DC input voltage. The second circuit was designed using a piecewise-linear voltage source. The piecewise linear voltage provides a step change at the input voltage and the results showed how the output voltage changed.

In order to meet military aircraft standards for aircraft power loss, the original feed-forward circuit was modified. The original design uses one MOSFET to drive the power to the comparator and the output voltage. MOSFET is a low voltage, low current and high switching frequency. Thus, one MOSFET did not produce the necessary high power and current. The modification changes consist of placing fifteen IRF350 MOSFET in parallel at pulsed drain current current 60A and 400 volts to produce the output current of 900A. Also, four additional diodes in a series were added. Making these modifications to the original design supplied enough power and current to meet the 600A output current at and 270 V output voltages.

The results from the feed-forward design included the theory and how the design works. The circuit simulations were performed for the feed-forward design and waveform results are presented.

Finally, the feed-forward "open loop" design, proved, Kazimierczuk et al. [5], "the open loop control arrangement", shown it could work on the entire aircraft system for power loss. However, the design was difficult to achieve high efficiency because the load resistance is very low, below 1 ohm or 0.5 ohm.

6.2 Contribution

The feed-forward design has been important in the industry and military research. The U.S. Air Force can continue using the feed-forward patent for additional research and testing. The theoretical design presented for the feed-forward PWM boost converter operating in CCM structural design can be replicated. The circuit can be constructed with a few components at low cost. As discussed in previous chapters, the feed-forward simulation helped to understand and prove the workings of the design.

Understanding the feed-forward design enables the military to expand its research and work closely with industry to continue to maintain military tactical transport aircraft for mission readiness without loading and unloading power losses.

6.3 Future Work

The feed-forward PWM Boost Converter design could be improved by using Insulated-Gate Bipolar Transistor (IGBT) for high current and high voltage requirements; replacing the MOSFET with an IGBT. The IGBT combines the MOSFET characteristics (gate drive) with high current low saturation voltage of the Bipolar Junction Transistor (BJT) [20]. This concept is using the Field Effect Transistor (FET) to control the input and the BJT as a switch. The advantages of using the IGBT is that it will be able to handle the high power, high current and high voltage of military aircraft systems [20], [27].

This thesis helped identify this finding, and the need for replacement. Further, expanding on the work performed is possible working with Air Force Research Laboratory (AFRL). The recommendation of substitute MOSFET with IGBT can be pursued to determine if the results are the same. Investigating this new design will further assist the military with future modifications to tactical transport aircraft, preventing power losses during the loading and unloading operations, assuring mission readiness.

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