22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024

ISBN: 978-84-09-60656-6

A Road Map for the Design, Simulation, and Analysis of Switch Mode Universal Power Supply Adapters

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Abstract. The primary objective of this paper is to present a road map plan for the design, simulation, and analysis of a universal switch-mode supply adapter. This adapter can be used to connect AC or DC power supplies to AC or DC loads. There are adapters available for various household appliances, laptops, and other electronic devices. The need for a universal power supply adapter comes when the electrical power supply needs to be converted in order to meet input the requirements of the load.

This paper focuses on the design and simulation of a universal power supply adapter with the primary aim of powering DC and AC loads using a solar cell to charge a 24V battery as a primary source and the AC line voltage as a secondary source. In order to achieve the desired result, this design requires the universal power supply adapter to have three main design components: a switch-mode power supply, a switch-mode DC to DC regulator, and an inverter. Photovoltaic panels are used as the primary DC power sources of the system with a battery for energy storage, and the DC to AC inverter to feed AC loads. This paper focuses of the design, simulation, and analysis of these three components.

Key words: Regulator, switch mode, adapter, and Inverter.

1. Introduction

The design topology presented in this paper handles AC or DC input and AC or DC output. The block diagram for the universal power supply adapter presented in this paper is given in figure 1 where a 28-32 volts DC input from PV panels requires the design of a DC-to-DC regulator to provide a stable DC source for the adapter. A 120v/60HZ AC input represents the AC line from the utility requires the design of a switch-mode power supply to supply a stable DC input for the adapter.

An inverter needs to be designed for the AC output of the adapter to provide a 120v/60Hz output for the standard AC outlet power. The focus of this paper is on the switch-mode inputs of the universal power supply adapter. This design was verified using PSPICE simulation [1].

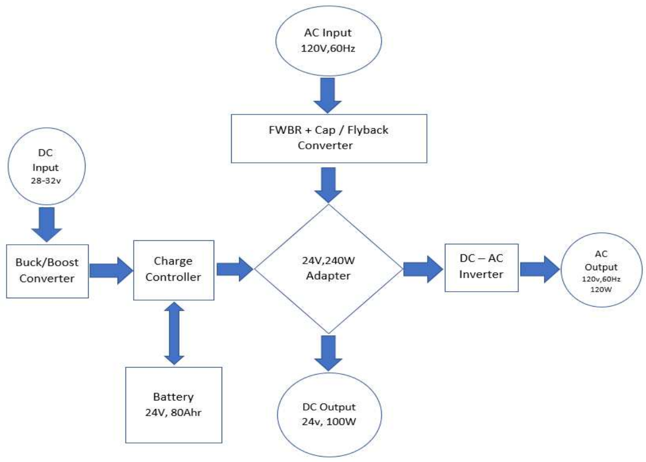

Figure 1: Universal Power Supply Adapter Block Diagram

The AC-to-DC switch-mode input part of the design takes a United States standard 120V single phase AC input and uses a Full Wave Bridge Rectifier circuit with a smoothing capacitor to convert the voltage to about 170V DC with a maximum of a 1% ripple factor. Then, the 170V DC voltage is fed through a Flyback Regulator, an Isolated Switch-Mode Power Supply, to reduce this DC voltage to 24V DC using a switching frequency of 100kHz to control the MOSFET switching.

In the DC-to-DC input part of the design, the 28V-32V DC output from the PV panels is regulated using a switch-mode Buck-Boost converter and fed into the adapter through a charge controller that regulates the charging and discharging of the 24v adapter battery.

The Charge Controller regulates the charging and discharging of the battery depending on the solar input and the demand of loads. In this design the charge controller will determine from where the load will get powered. Power on this side of the adapter will either come from the output of the Buck/Boost Regulator directly when the PV cell is active or from the charge reservoir of the battery. This design of adapter would be a good fit to be used for modern hybrid LED illumination systems [2].

In the DC-to-AC output part of the design, the 24V DC output from the adapter is fed into a Full wave H-Bridge Square Wave DC-to-AC inverter, and then a boost transformer with a 1:5 turns ratio is used to convert the voltage to 120V, 60 Hz AC output [3]. A Square Wave Inverter, on its own, will have noise so a capacitor shall be installed in parallel to smooth it into a standard sine wave.

2. Switch Mode AC-to-DC Regulated Input

A Full Wave Bridge Rectifier and an Isolated Switched-Mode Power Supply are used in the design to convert the AC input from an electrical outlet or standard single-phase connection to a DC voltage that the system requires to function. An AC supply voltage of 120V at 60Hz is connected to a Full Wave Bridge Rectifier with a parallel capacitor to create a 170V DC voltage. Then, this voltage is reduced to 24V DC using a Flyback Converter [4].

Figure 2 shows a standard configuration of a Flyback Converter circuit. The isolated switched-mode Flyback Converter is the most often used topology found in off-line converters. The circuit operation is based on a single switch topology. Energy taken from the input is stored in the transformer's primary windings while the switch is closed and transferred to the secondary windings when the switch is opened.

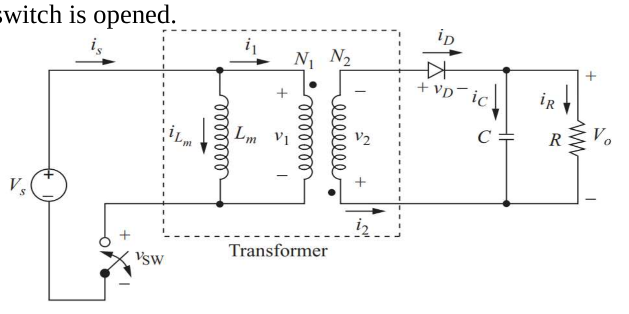

Figure 2: Flyback Converter Schematic [5]

The first step of design for this section was to size the capacitor meant to smooth the rectified waveform out to resemble a DC voltage. The capacitor and inductor were determined using the following calculations:

C = (IL)/(VL*f), so C = (10A)/(170V*60Hz) = 980uF

Design specifications: V_O = 24V, P_O = 240W, Ripple (r) = 0.01, f = 100kHz

Source (line) Voltage: $V_{S(RMS)}$ = 120V,

$V_{S(peak)}$ = 120V*sqrt(2) = 169.7V

$V_S \approx$ 170V

Load Resistance: $R = (V_O)^2 / P_O = (24)^2 / 240W = 2.4\Omega$

Turns Ratio (N_1/N_2): [Assume D = 0.5]

$(N_1/N_2) = (V_S/V_O) * (D/(1-D))$

(N_1/N_2) = (170V/24V) * (0.5 / (1-0.5))

$(N_1/N_2) = 7.083 \approx 7$

Duty Ratio (D):

$D = ((N_1/N_2) * (V_O/V_S)) / (1+(N_1/N_2)*(V_O/V_S))$

D = ((7) * (24V /170V)) / (1+(7) * (24V/170V))

D = 0.497

Magnetizing Inductance:

$I_{Lm} = (V_O)^2 / (V_S*D*R)$

$I_{Lm} = (24V)^2 / (170V*0.497*2.4\Omega)$, so I_{Lm} = 2.84A

$\Delta i_{Lm} = 0.4* I_{Lm}$ = 0.4* 2.84A

Δi_{Lm} = 1.136A

$L_m = (V_S*D) / (\Delta i_{Lm}*f)$

L_m = (170V*0.497) / (1.136A*100kHz)

L_m = 0.74 mH. With a 25% safety factor, L_m = 929.6mH

Capacitance:

$C = D / Rrf$

C = 0.497 / (2.4Ω) *(0.01) * (100kHz)

C = 207.08 µF. With a 25% safety factor, C = 258.85mH

In order to fully design the AC Input Adapter, the Full Wave Bridge Rectifier (FWBR) would need to be combined with the Flyback Converter. The full schematic circuit diagram is found in Figure 3 with calculated values identified. An op-amp was added between the two circuits to create a buffer to help regulate the voltage.

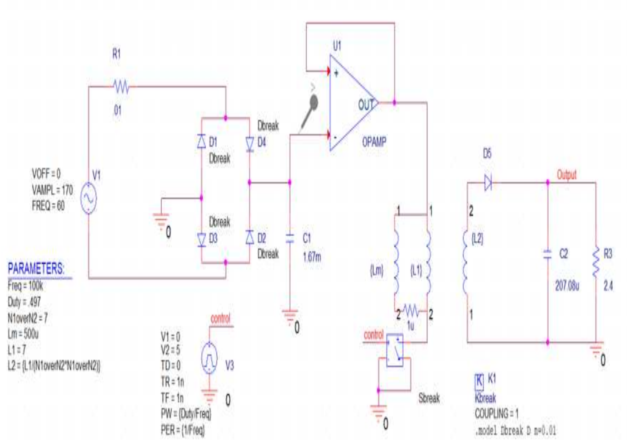

Figure 3: AC to DC Schematic Circuit in PSPICE

After calculating the correct values for all the circuit components, the circuit was simulated using PSPICE. Figure 4 presents the voltage output waveform of the Full Wave Bridge Rectifier without the parallel capacitor. The waveform is slightly less than 170V due to the voltage drop over the diodes and is exactly what was expected. The design parameters can also be verified using MATLAB using the procedure presented in [6].

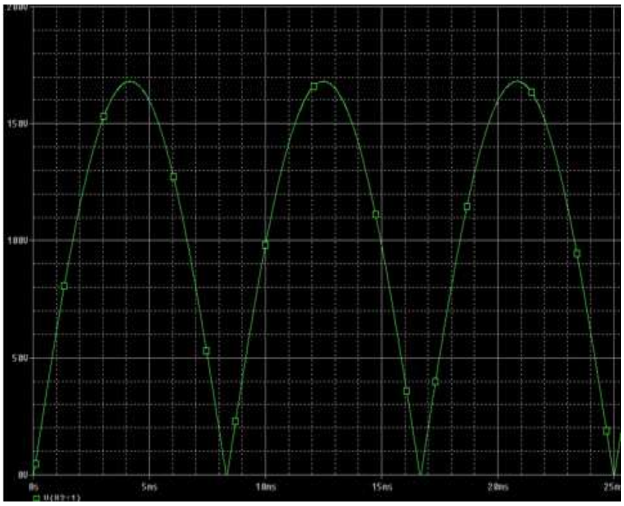

Figure 1: Output Voltage of the FWBR without Capacitor

Then, the capacitor was added in parallel with the bridge diode configuration and the simulation was run again. The resultant voltage output waveform is given in Figure 5.

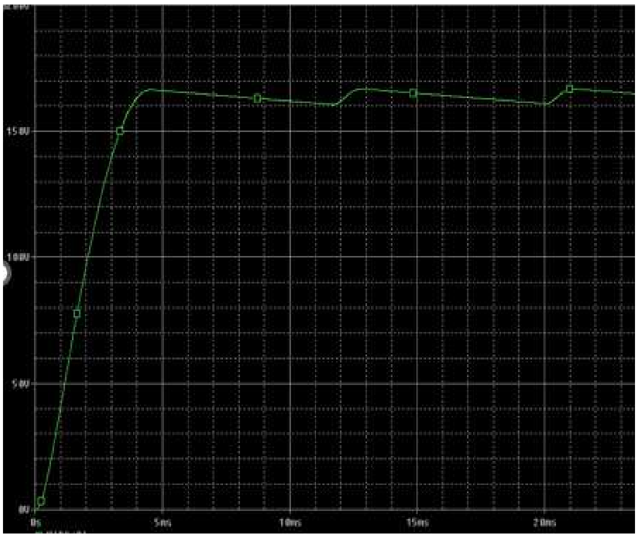

Figure 2: Output Voltage of the FWBR with Capacitor

Again, the peak of the waveform is just short of the 170V line as expected and the capacitor discharges voltage between peaks to create a smoother waveform resembling the desired DC voltage due to losses in the PWBR diodes.

Finally, the Full Wave Bridge Rectifier was connected to the Flyback Converter circuit, and the simulation was run again to trace the output voltage. The output voltage waveform for the AC input of the adapter is shown in Figure 6. Initially, the voltage is unsettled at start-up, but evens out after only a few milliseconds. Then, the waveform stays steady at 24V DC since the system was designed for a 1% ripple factor, so if you were to zoom in on the waveform you would see that the small fluctuations in voltage do not exceed 0.2V.

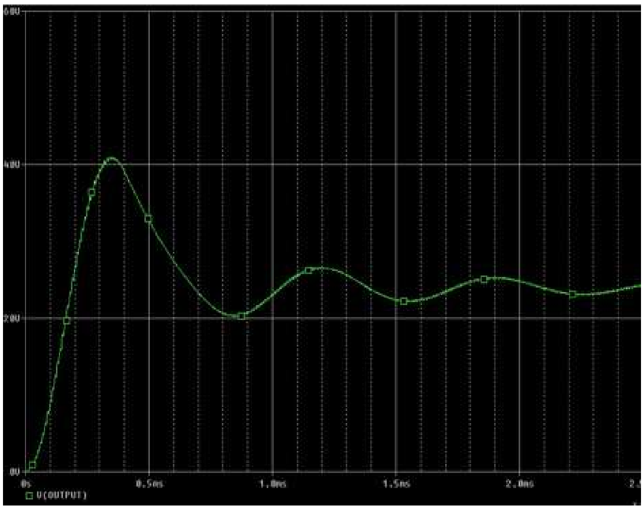

Figure 3: Output Voltage of Flyback Converter

3. Switch Mode DC-to-DC Regulated Input

The DC-to-DC portion of the design takes a variable source voltage of 28-32V DC from photovoltaic panels and uses a Buck-Boost Regulator, a non-isolated switch-mode DC-DC Regulator, to reduce the voltage to a steady 24V DC. The circuit was designed using a 100kHz switching frequency and a maximum of a 1% ripple factor for a 240W load. The output of the Buck-Boost Regulator is then connected to the charge controller.

The charge controller regulates the charging and discharging of the battery depending on the solar input and the demand of loads. In this design the charge controller determines from where our 240W load will get powered. Power on this side of the adapter will either come from the output of the Buck/Boost Regulator directly when the PV cell is active or from the charge reservoir of a 24V, 80 AHr DC battery. Refer to Figure 7 for the Buck-Boost circuit diagram. The Buck-Boost Regulator allows the adapter to perform properly by ensuring a stable 24VDC signal is fed into the DC input side of the adapter.

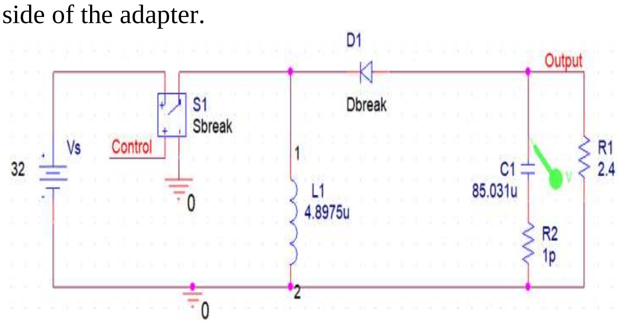

Figure 7: Buck-Boost Converter Schematic Diagram

The values for the resistor, capacitor, and inductor in the PSPICE circuit were determined using the following calculations:

Given Values: V_S = 28 to 32V, V_O = -24V, P_O = 240W, Ripple (r) = 0.01, f = 100kHz

Source Voltage: Assume V_S = -32V to calculate for a lower Duty Ratio

Resistance:

$R = (V_O)^2 / P_O = (24V)^2 / 240W = 2.4\Omega$

Duty Ratio (D):

$D = ABS(V_O) / (V_S + ABS(V_O))$

$D = ABS(-24V) / (32V + ABS(-24V))$

$D = 0.429$

Minimum Inductance:

$L_{min} = ((1-D)^2 * R) / (2*f)$

$L_{min} = ((1-0.429)^2 * 2.4\Omega) / (2*100kHz)$

$L_{min} = 3.912\mu H$

With a 25% safety factor added - $L_{min} = 4.891\mu H$

Capacitance:

$C = D / Rrf = 0.429 / (2.4\Omega) * (0.01) * (100kHz)$

$C = 178.75mF$

With a 25% safety factor added - C = 223.44mH

The simulation results matched expectations. The output voltage stabilizes at -24VDC, which is exactly where the circuit was designed to stabilize. The stabilization occurs around 1ms into the simulation. Both of these results can be observed in Figure 8.

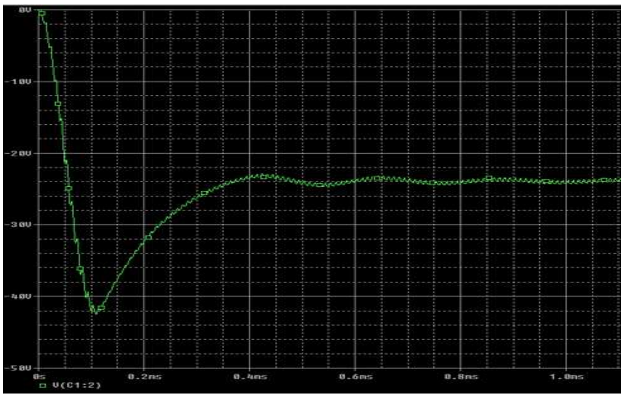

Figure 8: Buck-Boost Regulator Output graph in PSPICE

4. Switch Mode DC-to-AC Inverter Output

The last stage of designing a Universal Power Supply Adapter was to invert the steady 24V DC voltage out of the Adapter Controller to a 60 Hz, 120V AC signal. To achieve this goal we used a Full H-Bridge Square Wave Inverter with diode protection. The primary purpose of an Inverter is to convert a DC voltage into AC output voltage. After the voltage is converted to AC, a boost transformer can be used to significantly increase the voltage. This is what is intended for this project design. The standard configuration for a Full H-Bridge Square Wave Inverter is shown in Figure 9 with an Input of V_b from the Adapter Controller and the output is measured across the load given by voltage V_L. The square wave inverter makes use of a switching circuit to produce an alternating square wave voltage. The most common method is the use of an Inverter Bridge, also known as Full-Bridge or H-Bridge.

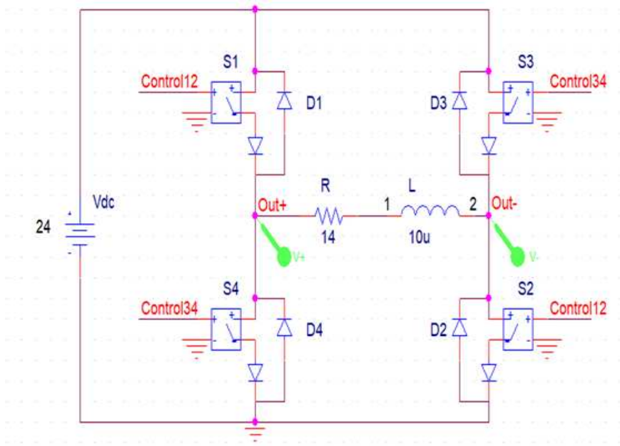

Figure 9: Full H-Bridge Square Wave Inverter Schematic

The diagram of a Physical Transformer Model is shown in Figure 10.

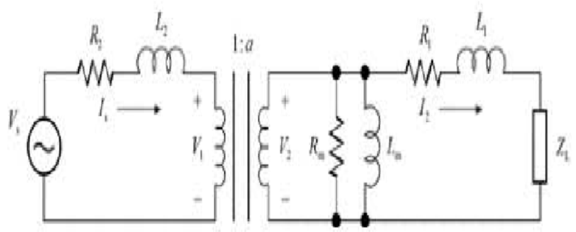

Figure 10: Physical Transformer Model

The voltage source in Figure 9 is representative of the Square Wave Inverter and the impedances of each of the components is as follows:

$R_1 = 0.1\Omega$, $L_1 = 50\mu H$, $R_m = 1K\ \Omega$, $L_m = 0.8H$, $R_2 = 0.02\ \Omega$, $L_2 = 10\ \mu H$, $a = 5$, $Z_L = 14 + j5\ \Omega$,

$V_S = 24V_{AC}$, f = 60Hz

Design:

$Z_{L1} = j\omega L_1 = j2\pi*(60)*(50\ \mu H) = j0.019\ \Omega$

$Z_{L2} = j\omega L_2 = j2\pi*(60)*(10\ \mu H) = j0.004\ \Omega$

$Z_{Lm} = j\omega L_m = j2\pi*(60)*(0.8H) = j301.593\Omega$

$Z_1 = 0.1 + j0.019\ \Omega$

$Z_2 = 0.02 + j0.004\ \Omega$

$Z_{sec} = Z_2 + Z_1 = 14.02 + j5.004\ \Omega$

$Z_r = (1/5)^2\ (14.02+j5.004) = 0.561 + j0.2$

$Z_{eq} = (1/Z_r) + (1/Z_{Lm}) + (1/R_m) = 0.56 + j0.2\ \Omega$

$Z_T = Z_1 + Z_{eq} = 0.66 + j0.219\ \Omega$

$V_1 = (V_s * Z_{eq})/Z_T = 20.518 + j0.465V$

$V_2 = V_1 * a = 102.59 + j2.325V$

$V_{out} = V_L = (V_2*Z_L)/Z_{sec} = 102.45 + j2.342V$

$P_{out} = (V_{out})^2/Z_L = 675.415 – j206.943W$

MATLAB can be used to analyze the inverter circuit design [6&7]. For this work it was used to analyze the inverter design without the transformer, with a blanking interval of 30º with the results shown in Figure 11. The waveform looks relatively the same, except for the small gap between the positive and negative sides of the square wave. The gap is representative of the blanking interval needed to provide overlap when the switches are turned on and off.

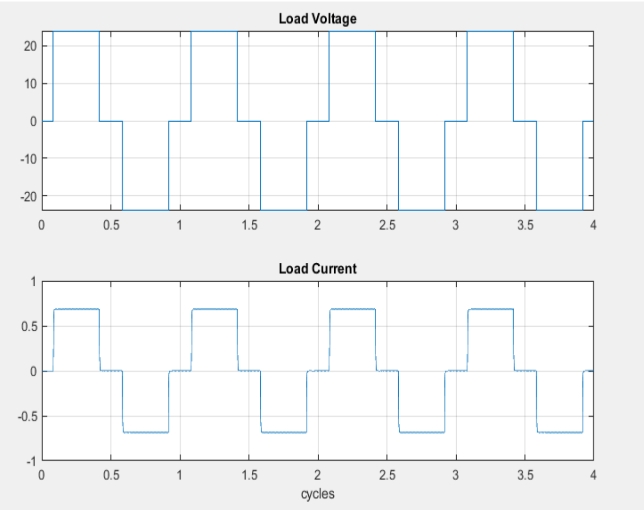

Figure 11: Matlab Results for Inverter Circuit Only

When a capacitor is added in parallel with the square wave inverter, it smooths out the edges and produces a more accurate representation of a sine wave. Then, it is fed into a transformer with the results as shown in Figure 12.

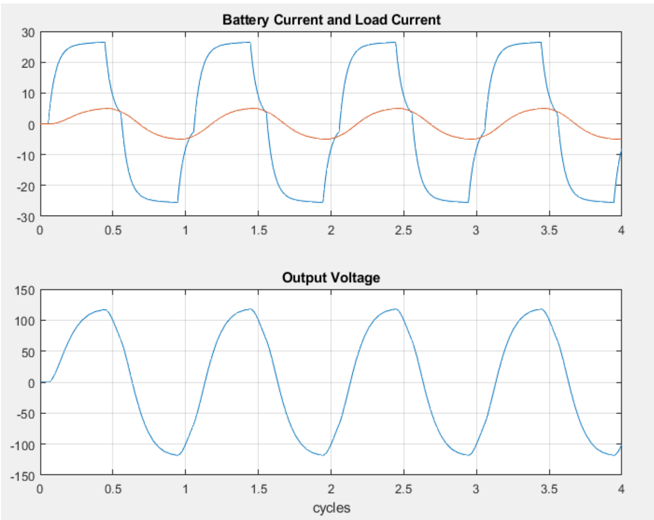

Figure12: Matlab Simulation Results for a Square wave inverter Circuit with Transformer and Capacitor

5. Switch Mode AC-to-DC and DC-to-DC Regulation Circuit Design

The DC-to-DC Buck-Boost Converter produces an output of 24V DC, but it does not remain constant due the varying DC input from the photovoltaic cell and the load conditions. In order to stabilize the output at 24V we place the Buck-Boost converter inside a closed-loop control system called a regulator. This closed loop control system design in detailed in [7]. The primary purpose of the charge controller is to stabilize the system output at 24V regardless of the varying input and load conditions in the design.

In general, a closed loop control system includes a set of electronic or mechanical devices that automatically regulates a process variable to a desired state. The charge controller unit used in the design of the universal power supply adapter consists of error amplifier, oscillator, and PWM circuits. The control loop adjusts the duty cycle of the PWM circuit to maintain the output voltage as per the reference voltage. An example of an Error Amplifier Circuit is shown in Figure 13.

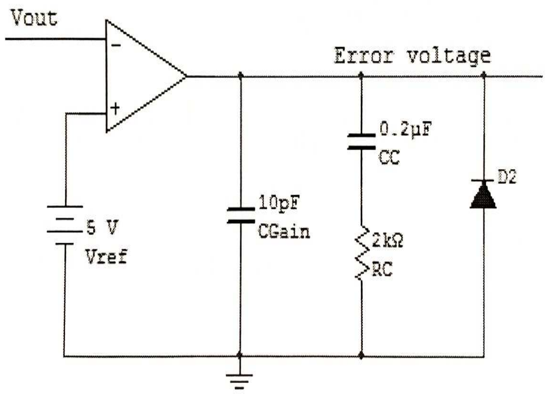

Figure 13: Error Amplifier Circuit

The Error Amplifier Circuit is the most used circuit in feedback unidirectional voltage control. In the design of this project, the Buck-Boost Converter requires stabilization of the 24V DC output due to the variable 28-32V input from the photovoltaic cell.

To accomplish this the output of the Buck Converter is fed into the inverting terminal of the Error Amplifier and the non-inverting terminal is supplied with a DC reference voltage at 5V. The Error Amplifier produces an output that is equal to the difference between the output of Buck-Boost converter and the reference voltage known as Error voltage which is equal to V_{REF} - V_{OUT}

If the $V_{OUT} > V_{REF}$, then, error signal is negative, which reduces the error voltage output and PWM Duty cycle. If the $V_{OUT} < V_{REF}$, then, the error signal is positive, which increases both error voltage output and PWM Duty cycle.

If the duty cycle cannot be adjusted in accordance with the input voltage, then the L and C values of the Buck-Boost Converter cannot be maintained to achieve stabilization. The C-Gain capacitor of the Error Amplifier sets the bandwidth limit, while the capacitor CC and resistor RC maintain the gain. They also decrease the gain when the frequency of the amplifier increases, in order to protect the supply from large oscillations.

This design requires the error voltage out of the ERR to be approximately equal to zero, which means that the output is stabilized regardless of varying input and load conditions. To accomplish this, the output terminal of the error amplifier is directly connected to the non-inverting terminal of the PWM Comparator circuit. The other terminal of the PWM comparator circuit is connected to the output of Oscillator circuit, which is the next stage of closed loop control system.

The next step in stabilizing the output of the Buck-Boost Converter, after producing an error voltage, is to compare the error voltage to a Ramp Signal to produce a PWM output that drives the MOSFET in the Buck-Boost converter. To generate a Ramp Signal, a Triangular wave Oscillator is designed, and it is presented in Figure 14.

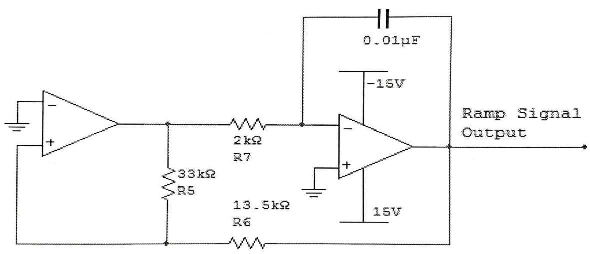

Figure 14: Oscillator Circuit [5]

The circuit in figure 15 uses two Op Amps. The first Op Amp functions as a square wave generator, producing a square wave output. The second Op Amp works as an integrator, which generates a triangular waveform, known as the Ramp Signal, required for the design.

The oscillating frequency for this oscillator is given by:

$f = (1/ (4*R_7 * C)) * (R_5/R_6) = 30,56$ Hz. Since the comparator output is +/-12V the peak-to-peak value of the comparator output becomes 24V.

$V_{PP} = (R_6/R_5) * 24V = (13.5/33) * 24 = 9.82V$

The circuit above uses two Op Amps. The first Op Amp functions as a square wave generator, producing a square wave output at resistor R_5. The second Op Amp works as an integrator, which generates a triangular waveform, known as the Ramp Signal, required for the design of this project. The Final stage of the closed loop voltage control system is the PWM Comparator.

In the PWM stage of the regulator we need to compare the outputs generated from the Error Amplifier Circuit and the Oscillator Circuit to produce a Pulse Width Modulated Output that is directly connected to the gate terminal of the Switch (MOSFET) in the Buck-Boost Converter. This concept is shown in Figure 15.

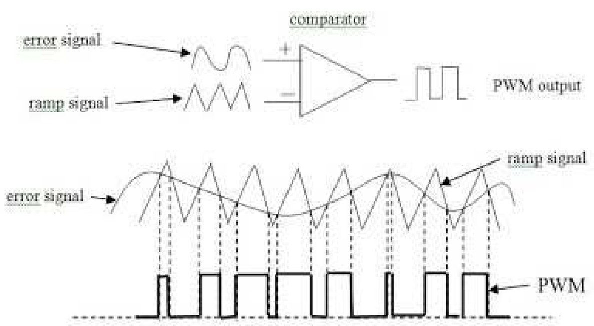

Figure 15: Output of the closed-loop voltage control system

6. Conclusion

The design, simulation and analysis of a switch mode AC input Adapter, a switch mode DC input adapter, and a switch mode inverter were presented in this paper.

Both the AC and DC switch mode input Adapters were designed to meet the design specifications. and the design parameter values were verified using PSPICE. The AC output adapter was designed using the square wave inverter topology and the design parameters were verified using MATLAB. The design presented meets the specs. And simulation results of each section of the power supply adapter were identical to the calculated design values.

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