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Solar PV Integration with Grid: Designing Buck, Boost Converter and Inverter

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ABSTRACT:

This research proposes a novel approach to the integration of solar photovoltaic (PV) systems into the electrical grid is an important step in advancing sustainable energy solutions. Solar power generation, while abundant and renewable, generates direct current (DC) electricity that must be converted to alternating current (AC) to meet the power grid's voltage and frequency needs. To efficiently integrate solar PV systems with the grid, important power electronics components such as buck converters, boost converters, and inverters need to be designed and optimized. This study investigates the design concepts and operational features of these critical components, which play an important role in solar energy optimization, regulation, and conversion. A buck converter steps down the voltage from the solar panels, ensuring that it is suitable for charging batteries or flowing into the grid. In contrast, a boost converter is used to increase the voltage, assuring compliance with higher voltage levels required for grid integration, especially when the solar panel output is less than what is required for grid connection. Inverters, the heart of PV integration, convert solar panels' DC output into AC power appropriate for grid synchronization.

Keywords: Solar PV system, PV Module Characterization, DC-DC Converter, DC-AC Converter, Power Converter Design.

Introduction:

The fast development of solar photovoltaic (PV) systems as a clean and sustainable energy source has considerably aided the global transition to renewable energy. However, integrating solar PV systems with the electrical grid brings unique issues due to solar energy's intrinsic fluctuation and the necessity for efficient power conversion and control. This review study is focused on the crucial function of power electronic components specifically buck converters, boost converters, and inverters—in enabling seamless and efficient grid integration of solar PV systems. These components not only ensure that solar energy is efficiently converted and transferred, but also that the entire system is safe, stable, and meets grid criteria.

Solar PV systems generate direct current (DC) electricity, which must be converted into alternating current (AC) to match the grid's requirements. This conversion process involves multiple stages, including voltage regulation, maximum power point tracking (MPPT), and synchronization with the grid. DC-DC converters (buck and boost) and inverters are essential components that ensure optimal energy harvest, stable operation, and compliance with grid standards.

Buck Converter is a dc-to-dc converter that performs step- down conversion of applied dc input. In a buck converter, the applied fixed dc input is lowered to a set dc output voltage, hence the buck converter's output voltage is always lower than the input voltage. The Buck converter is also known as the step-down converter or step-up chopper. Bulk converters' effective power conversion lowers heat production and prolongs battery life. Therefore, it is primarily chosen for the manufacturing of tiny devices. There are many interesting uses for it. It is frequently utilized in switched-mode power supplies (SMPS) when the desired output DC voltage is lower than the input DC voltage.

Buck converter circuits use a variety of semiconductor devices as switches, including power MOSFETs, power BJTs, IGBTs, and GTOs. Since thyristors require an additional external communication circuit, they are typically not utilized in dc-dc converters. However, by keeping the voltage between the gate and the IGBT's collector terminal or the gate and the power MOSFET's source terminal at zero, either device can be switched off.

A boost converter is a DC-DC converter that steps up the input voltage to produce a greater output voltage. It is extensively utilized in applications where a higher voltage is required than that provided by the power source. These converters are essential in a variety of applications, including solar power systems, battery-powered electronics, power supplies, and electric vehicles.

An inverter is a vital component of a solar photovoltaic (PV) system that converts the direct current (DC) electricity produced by solar panels into alternating current (AC), which is utilized by most domestic appliances and the power grid. A battery in a solar photovoltaic (PV) system stores excess electricity produced by solar panels. It allows for energy use when solar generation is minimal or unavailable, such as at night or on cloudy days. Batteries are critical components of off-grid, hybrid, and backup power systems, increasing energy independence and system resilience.

Solar PV System

An overview

A solar photovoltaic (PV) system uses photovoltaic cells to directly convert sunlight into electricity. As a clean, sustainable, and eco-friendly substitute for fossil fuels, these systems are an essential part of renewable energy solutions. Large-scale solar farms and commercial, industrial, and residential settings all make extensive use of solar photovoltaic systems. They play a significant role in decreasing greenhouse gas emissions and addressing climate change. key Components of Solar PV Systems Solar panels (PV modules) convert sunlight into direct current electricity. Inverters convert direct current (DC) electricity into alternating current (AC) for usage in homes and businesses. Mounting Structure - Supports and places the solar panels for maximum sunshine exposure. Battery (optional): Stores surplus energy for use at night or during power shortages. Charge Controller (For Off-Grid Systems) - Regulates power to batteries to prevent overcharging. Metering and Monitoring System- Monitors system performance and energy generation.

Buck and Boost converter:

The dc-dc converter is a tiny, lightweight, and highly efficient power supply that utilizes a semiconductor switching element. It responds fast and appropriately to variations in input voltage within normal operating conditions, returning to the typical operational state. The system consists of two components: (i) a switching power supply unit that operates at high frequency to convert a dc input voltage VIN to a dc output voltage VOUT, and (ii) a control unit that regulates the switching operation of the power supply unit. The dc input voltage to the converters is considered to have zero internal

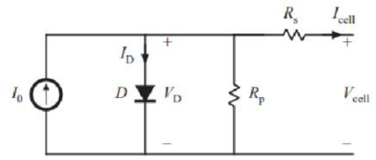
Sr. No.	Parameters	Value
1	Rated Maximum Power	75W
2	Rated Operating voltage (Vmp)	17.5V
3	Rated Operating Current (Imp)	4.29A
4	Open Circuit Voltage (Voc)	21.5V
5	Short Circuit Current (Isc)	4.69A

Impedance. The output stage includes a tiny filter as an integrated part of the dc-to-dc converter. The output is supposed to supply a load with similar resistance. For years, power-electronics circuits have been analyzed and simulated using computer techniques.

Inverter

An inverter converts a direct current voltage (DC) to an alternating current voltage (AC). In most circumstances, the input DC voltage is lower, while the output AC voltage is equivalent to the grid supply voltage, which is either 120 volts or 240 volts depending on the country. The inverter can be built as standalone equipment for uses such as solar power or as a backup power source using batteries that are charged separately .The opposite arrangement occurs when it is part of a larger circuit, such as a power supply unit or a UPS. In this situation, the inverter input DC comes from the rectified mains

$$I_{pv} = K_i(irr) - I_{D0}\left(\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_t}\right) - 1\right) - \frac{V_{pv} + I_{pv}R_s}{R_p} = f(I_{pv}, V_{pv}) \quad (1)$$



$$I_D = I_{D0}\left(e^{V_D/V_T} - 1\right)$$

$$I_0 = I_D + \frac{V_D}{R_p} + I_{pv,cell}$$

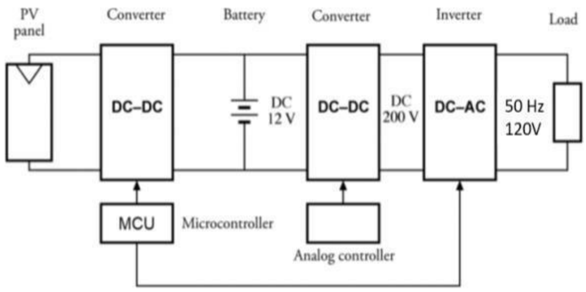
$$V_{pv,cell} = V_D - R_s I_{pv,cell}$$

$$I_0 = k_i(\text{irradiance})$$

AC in the PSU, or from the rectified AC in the UPS while there is power, and from the batteries when there is a power outage. Inverters are classified into distinct categories based on the shape of the switching waveform. These have varied circuit layouts, efficiency, benefits, and downsides. An inverter converts dc power sources into ac voltage, which is helpful for powering electronics and electrical equipment rated at the ac mains voltage. Furthermore, they are commonly utilized as inverting stages in switched mode power supply. The circuits are classed based on the switching technology and switch type, the waveform, the frequency, and the output waveform.

Battery

A solar battery is a device that you may install in your solar power system to store surplus electricity generated by your solar panels. You can utilize the stored energy to power your home when your solar panels are not producing enough electricity, such as at night, on cloudy days, or during power outages.A solar battery's purpose is to allow you to make better use of the solar energy you generate. If you don't have battery storage, any excess electricity from solar power flows to the grid, which means you're creating power and distributing it to other people without fully utilizing the electricity your panels generate first.



PROPOSED METHODOLOGY

PV Module Characterization

PV Panel Specification

PV Panel Circuit Modeling and Circuit Simulation. Now we need to estimate the parameters of the equivalent solar cell model from the given PV Panel Specification. Note that the panel has 36 cells in series. Therefore, all voltage ratings need to be divided by the same value to get per cell parameters. Now we need to estimate the parameters of equivalent solar cell model from the given datasheet parameters. Note that the panel has 36 cells in series. Therefore, all voltage ratings need to be divided by same value to get per cell parameters. The equation of interest is the following which can be derived from PV cell equivalent circuit.

Equation (1) has 4 unknowns out of which 3 unknowns can be evaluated by assuming the $4th$ variable as a symbolic placeholder. The 3 equations are resulting from the following points –

Equation (1) evaluated at $(Vpv,) = (Voc, 0)$ Equation (1) evaluated at $(Vpv,v) = (0,Isc)$ Equation (1) evaluated at $(Vpv,Ipv) = (V\text{mp},I\text{mp})$

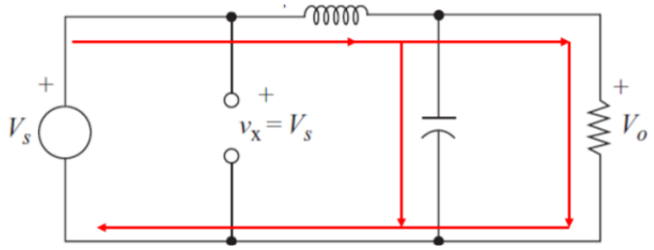
Now we invoke the fourth constraint that the solution needs to deliver maximum power at Vmp and Imp by evaluating –

$$\frac{dP}{dV} = I_{mp} + \frac{V_{mp}\left(\frac{\partial f(I,V)}{\partial V}\right)}{1 - \frac{\partial f(I,V)}{\partial I}} = 0 \qquad (2)$$

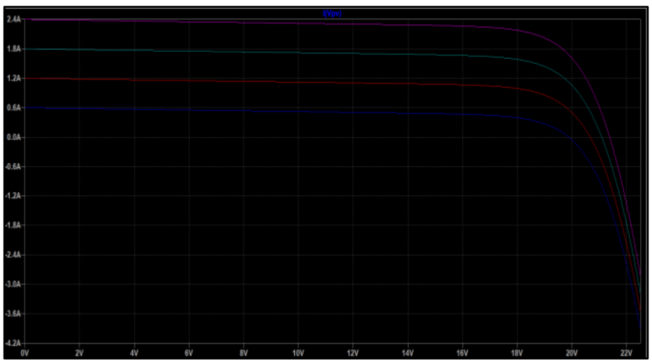
Now we solve for Rs that makes the above equation true using vpa solve function in MATLAB. The solution for Rs is then used to evaluate other three parameters ki, $ID0$ and

Rp.

VI Characteristics of Solar Panel at difference Irradiance level



The Ltspice schematic used to plot the $i- v$ characteristics. Now we find the value of Vmp, Imp, and Pmp at different irradiance levels



VI Characteristics

Vmp (V), Imp (A) and Pmp (W) at different Irradiance level:

DC-DC CONVERTER

Irradiance	Vmp (V)	Imp (A)	Pmp (W)
250W/m2	16.81	0.449348	7.55353
500W/m2	17.64	1.01338	17.876
750W/m2	18.02	1.58067	28.4836
1000W/m2	18.24	2.150349	39.2223

$$T_{ON} = DT$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{Vs - Vo}{L}$$

$$(\Delta i_L)_{closed} = \left(\frac{Vs - Vo}{L}\right) DT \quad (1)$$

Solving for Inductor (L),

$$L = \frac{(Vs - Vo)DT}{(\Delta i_L)_{closed}}$$

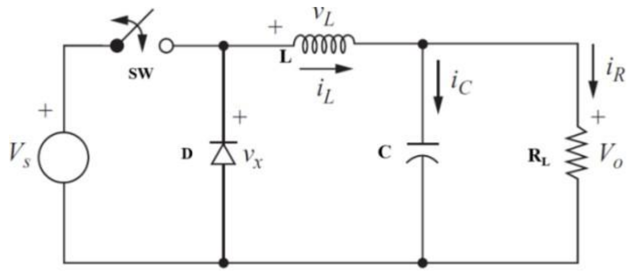
Where, T=1/f

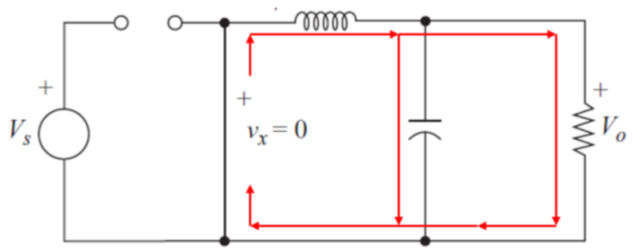
$$L = \frac{(Vs - Vo)D}{(\Delta i_L)_{Closed}\, f}$$

1) Buck Converter:

A Buck Converter is a type of DC-DC power converter that steps down a higher DC input voltage to a lower DC output voltage efficiently. It uses switching elements (like transistors or MOSFETs), along with inductors and capacitors, to regulate the voltage and minimize power loss.

Buck Converter Circuit Diagram





A basic buck converter comprises essential components like a switch (MOSFET or BJT), an inductor, a diode (or a second MOSFET), and a capacitor, as depicted in Fig. The control circuit (typically an integrated circuit) monitors the output voltage, compares it with a reference value, and autonomously adjusts the duty cycle to achieve the desired output voltage.

Operating principle of Buck Converter

The non-synchronous buck converter serves as the foundation of buck converter topologies. Its operation is best understood by analyzing the switch behavior in ON and OFF states separately, ensuring that the input voltage always remains higher than the output voltage.

Switched Closed (ON)

Equivalent circuit for the switch closed

Analysis for the Switch Closed When the switch is closed in the buck converter circuit of Fig. 2, the diode is reverse-biased and Fig. is an equivalent circuit. The voltage across the inductor is

$$v_L = Vs - Vo = L\frac{di_L}{dt}$$

Rearranging,

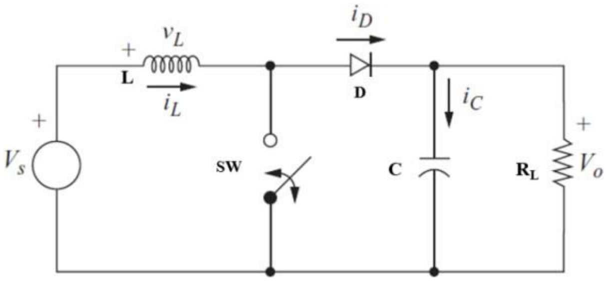
$$\frac{di_L}{dt} = \frac{Vs - Vo}{L} \qquad switch\ Closed$$

Since the derivative of the current is a positive constant, the current increases linearly as shown in Fig. The change in current while the switch is closed is computed by modifying the preceding equation.

Switched Open (OFF)
Equivalent circuit for the switch open

Analysis for the Switch Open When the switch is open, the diode becomes forward-biased to carry the inductor current and the equivalent circuit of Fig. applies. The voltage across the inductor when the switch is open is

$$v_L = Vo = L\frac{di_L}{dt}$$



$$T_{OFF} = (1 - D)\,T$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{Vo}{L}$$

$$(\Delta i_L)_{open} = \left(\frac{Vo}{L}\right)(1-D)T$$

$$L = \frac{Vo(1-D)T}{(\Delta i_L)_{open}}$$

Rearranging,

$$\frac{di_L}{dt} = \frac{Vo}{L} \qquad \textit{switch open}$$

$$L = \frac{Vo(1-D)}{(\Delta i_L)_{open}\,f}$$

The derivative of current in the inductor is a negative constant, and the current decreases linearly as shown in Fig. The change in inductor current when the switch is open is

Solving for Inductor (L),
Where, T=1/f

Buck converter equation and duty cycle Steady-state operation requires that the inductor current at the end of the switching cycle be the same as that at the beginning, meaning that the net change in inductor current over one period is zero. This requires

$$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

Using Eqs. (1) and (2)

$$\left(\frac{Vs - Vo}{L}\right)DT + \left(\frac{Vo}{L}\right)(1-D)T = 0$$

Solving for Output Voltage (Vo),

$$[Vo = VsD]$$

Where,

$$Duty\ Cycle\ (D) = \frac{Vo}{Vs}$$

$$v_L = Vs = L\frac{di_L}{dt}$$

Boost Converter:

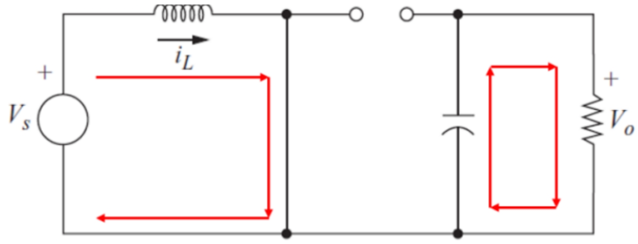
A Boost Converter is a type of DC-DC power converter that steps up a lower DC input voltage to a higher DC output voltage. It uses a switching device (typically a MOSFET), inductor, diode, and capacitor to efficiently increase voltage.

Boost Converter circuit diagram

Operating principle of Boost Converter

A Boost Converter increases the input voltage to a higher output voltage using an inductor, switch, diode, and capacitor. When the switch is ON, the inductor stores energy. When the switch is OFF, the stored energy is released, adding to the input voltage and supplying power to the output. The switching duty cycle controls the voltage boost, making this converter ideal for applications requiring efficient voltage step-up.

Switched Closed (ON)



Equivalent circuit for the switch closed

Analysis for the Switch Closed: When the switch is closed, the diode is reverse biased. Kirchhoff's voltage law around the path containing the source, inductor, and closed switch is

Rearranging,

The rate of change of current is a constant, so the current increases linearly while the switch is closed, as shown in Fig. The change in inductor current is computed from

$$T_{ON} = DT$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{Vs}{L}$$

$$(\Delta i_L)_{closed} = \frac{VsDT}{L} \qquad (3)$$

$$\frac{di_L}{dt} = \frac{Vs}{L} \qquad switch\ Closed$$

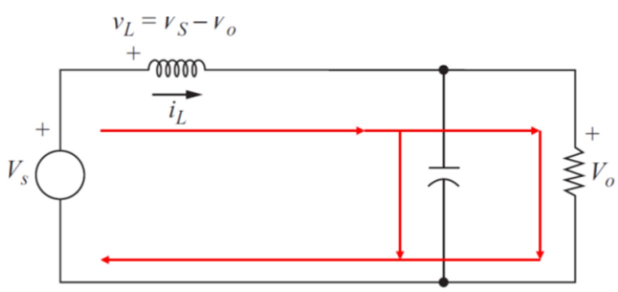
Solving for Inductor (L),

$$L = \frac{VsDT}{(\Delta i_L)_{closed}}$$

Where, T=1/f

$$L = \frac{VsD}{(\Delta i_L)_{Closed}\, f}$$

Switched Open (OFF)



Equivalent circuit for the switch open

Analysis for the Switch Open: When the switch is opened, the inductor current cannot change instantaneously, so the diode becomes forward-biased to provide a path for inductor current. Assuming that the output voltage Vo is a constant, the voltage across the inductor is

$$v_L = Vs - Vo = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{Vs - Vo}{L} \quad \textit{switch open}$$

Rearranging,

The rate of change of inductor current is a constant, so the current must change linearly while the switch is open. The change in inductor current while

$$\mathbf{T_{OFF} = (1 - D)\ T}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{Vs - Vo}{L}$$

$$(\Delta i_L)_{open} = \left(\frac{Vs - Vo}{L}\right)(1-D)T \qquad (4)$$

the switch is open is

Solving for Inductor (L),

$$L = \frac{(Vs - Vo)(1-D)T}{(\Delta i_L)_{open}}$$

$$L = \frac{(Vs - Vo)(1-D)}{(\Delta i_L)_{open}\, f}$$

Where, T=1/f

Boost converter equation and duty cycle For steady-state operation, the net change in inductor current must be zero. Using Eqs. (3) and (4),

$$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\frac{VsDT}{L} + \frac{(Vs - Vo)(1-D)T}{L} = 0$$

Solving for Vo,

$$\left[Vo = \frac{Vs}{1-D}\right]$$

Where,

$$Duty\ Cycle\ (D) = \frac{Vo - Vs}{Vo}$$

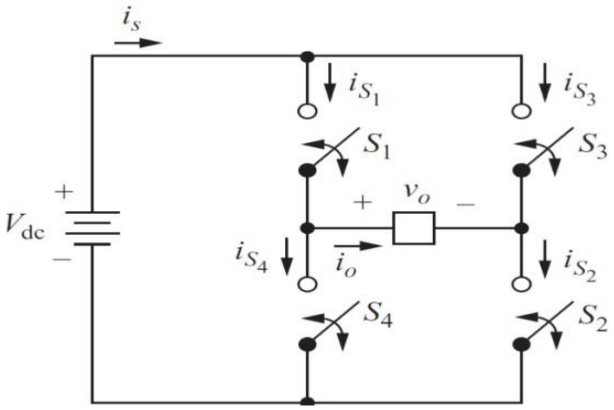
DC-AC CONVERTER

1) Inverter

An Inverter is an electronic device or circuit that converts direct current (DC) into alternating current (AC). It is essential in applications where the power source (like a solar panel or battery) provides DC, but the load or utility grid requires AC. Inverter circuit diagram

The output voltage (Vo) can be +Vdc, -Vdc, or zero, depending on which switches are closed. Figure 9b to e shows the equivalent circuits for switch combinations.

Sr. No.	Switch Closed	Output Voltage Vo
1.	S1 and S2 _Vdc	+Vdc
2.	S3 and S4 _Vdc	-Vdc
3.	S1 and S3 0	0
4.	S2 and S4 0	0



The Square-Wave Inverter

The simplest switching scheme for a full-bridge converter generates a square wave output voltage. When switches S1 and S2 are closed, the load connects to +Vdc, and when S3 and S4 are closed, it connects to -Vdc. This periodic switching creates a square wave voltage across the load.

While this alternating output is nonsinusoidal, it may still be suitable for certain AC applications. The load's current waveform depends on its components. A resistive load produces a current waveform identical to the output voltage, whereas an inductive load smooths the current into a more sinusoidal shape due to the filtering effect of inductance. Designing switches for an inductive load requires consideration of bidirectional current flow in the full-bridge circuit.

Power Converter Design

Buck Converter(Topology)

Synchronous Buck Converter: A Synchronous Buck Converter is a DC-DC power converter that steps down voltage efficiently using two MOSFET switches instead of a diode, reducing conduction losses. The high-side MOSFET controls energy delivery, while the low-side MOSFET ensures continuous current flow, minimizing power dissipation and improving efficiency. This topology is ideal for applications requiring high efficiency, low voltage ripple, and precise voltage regulation in modern power management systems.

Design Calculation (Design Input)

Power (Pbatt)	75W
Output Voltage (Vbatt)	12.55V
Output Current (Ibatt)	5.97A
Switching Frequency (Fsw)	100 kHz
Ripple Voltage (ΔVo)	0.5V
Ripple Current (Δi)	20% of Ibatt

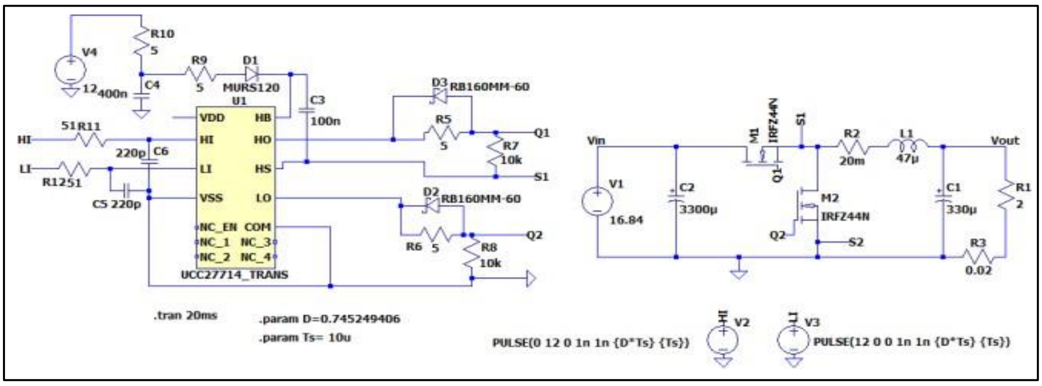
Theoretical Calculation

Duty Cycle	Avg. Ind. Curr.	Ripple Current	Min. Ind. Curr.	Max. Ind. Curr.	Inductance	Avg. Diode Curr.	Max.Diode Curr.
D	$I_{L(IND)}$	ΔI_L	$I_{L(MIN)}$	$I_{L(MAX)}$	L	I_D	I_{D_MAX}
0.729411765	3.47826087	1.391304348	2.782608696	4.173913043	3.01452E-05	0.941176471	4.173913043
0.717647059	3.333333333	1.333333333	2.666666667	4	3.09485E-05	0.941176471	4
0.704705882	3.187250996	1.274900	2.549800797	3.824701195	3.17833E-05	0.941176471	3.824701195

Pbatt=Pmpp	75	W		Δi	1.195219124		dut cycle (D)=	Vbatt/Vmpp
Vbatt/V_o	12.55	V		f_{sw}	1,00,000	0.00001	I_s	1.998900948
Iout/Ibatt	5.976095618	A	2.100033333	ΔVo	0.005		$\Delta V_o/V_o$	0.000398406

Irradiance	Vmp (V)	Imp (A)	Pmp (W)	Iout	Δi	Duty Cycle (D)	Inductor	Capacitor (Cout)	Capacitor (Cin)
250W/m2	16.84	0.969709	16.3299	1.301187251	0.26023745	0.745	2.67492E-05	1.70E-04	2.93E-05
500W/m2	17.3	2.0767	35.9269	2.862701195	0.572540239	0.725	2.88299E-05	1.83E-04	6.59E-05
750W/m2	17.42	3.18266	55.4419	4.417681275	0.883536255	0.720	2.93547E-05	1.87E-04	1.02E-04
1000W/m2	17.4	4.28898	74.6282	5.94647012	1.189294024	0.721	2.92677E-05	1.86E-04	1.37E-04

Simulation of Buck Converter



Boost Converter(Topology)

Cascade Boost Converter, The Cascade Boost Converter topology operates in two stages. In the first stage, the battery voltage is stepped up to 42V, and in the second stage, this 42V is further boosted to 150V DC, achieving efficient voltage conversion across two distinct steps.

Design Calculation (Design Input)

Input Power	P_{IN}	40	W
Suuply Vltg_Min.	V_{in_MIN}	11.5	V
Supply Vltg_rated	V_{in}	12	V
Suuply Vltg_Max.	V_{in_MAX}	12.55	V
Supply Current	I_S	3.47826087	A
Pout	P_{OUT}	40	W
O/P vltg	V_{OUT}	42.5	V
O/P current	I_{OUT}	0.941176471	A
Load Resistor	R_{OUT}	45.15625	Ω
SW frequency	f_{SW}	1,00,000	Hz
Time	T	0.00001	sec

Design input Stage-1

Input Power	P_{IN}	40	W
Suuply Vltg_Min.	V_{in_MIN}	42	V
Supply Vltg_rated	V_{in}	42.5	V
Suuply Vltg_Max.	V_{in_MAX}	43	V
Supply Current	I_S	0.952380952	A
Pout	P_{OUT}	40	W
O/P vltg	V_{OUT}	150	V
O/P current	I_{OUT}	0.266666667	A
Load Resistor	R_{OUT}	562.5	Ω
SW frequency	f_{SW}	1,00,000	Hz
Time	T	0.00001	sec

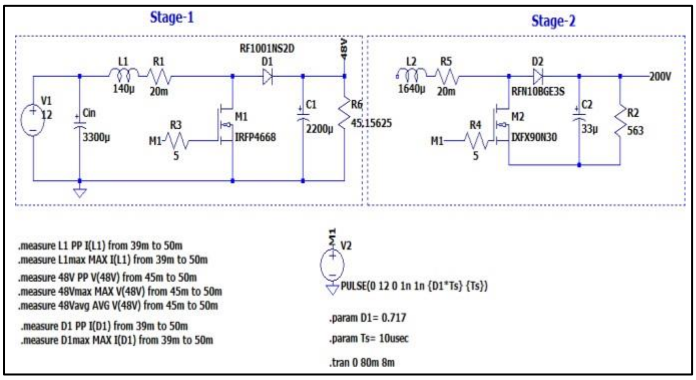
Design Input Stage-2

Stage-1 Calculation

Duty Cycle	Avg. Ind. Curr.	Ripple Current	Min. Ind. Curr.	Max. Ind. Curr.	Inductance	Avg. Diode Curr.	Max.Diode Curr.
D	$I_{L(IND)}$	ΔI_L	$I_{L(MIN)}$	$I_{L(MAX)}$	L	I_D	I_{D_MAX}
0.72	0.952380952	0.380952381	0.761904762	1.142857143	3.97E-04	0.266666667	1.142857143
0.716666667	0.941176471	0.376470588	0.752941176	1.129411765	4.00E-04	0.266666667	1.129411765
0.713333333	0.930232558	0.372093	0.744186047	1.11627907	4.03E-04	0.266666667	1.11627907

Stage-2 Calculation

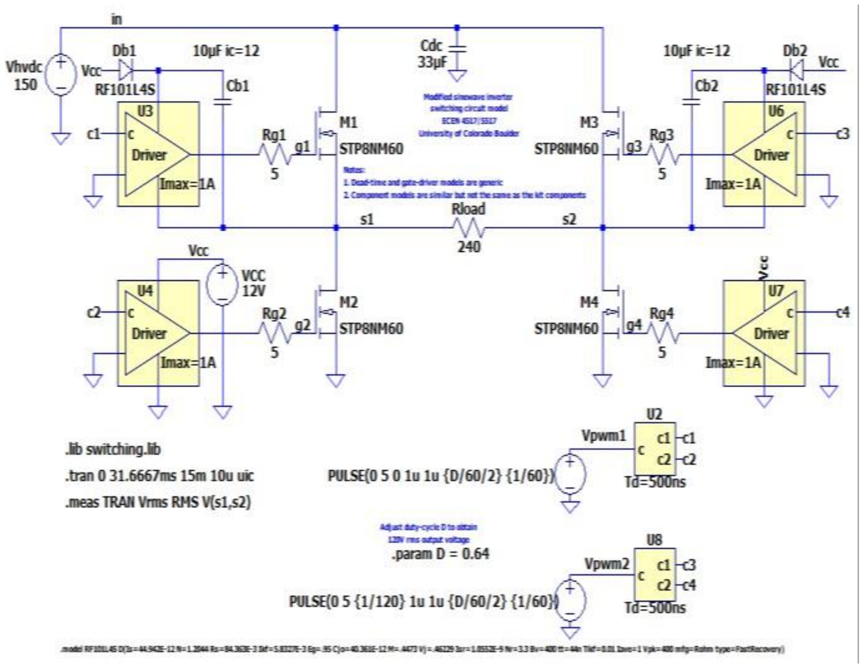
Simulation of Boost Converter



Inverter Design(Topology)

The Full-Bridge Inverter Topology utilizes an H-bridge configuration to convert DC into AC efficiently. It employs four switches (MOSFETs or transistors) to alternate the polarity of the DC input, producing an AC waveform. The output can be a square wave, modified sine wave, or pure sine wave, depending on the control technique. This topology is widely used in motor drives, UPS systems, and renewable energy applications due to its ability to handle bidirectional current flow and deliver stable AC power.

Simulation of Inverter (DC to AC)



Conclusion

The Solar PV Integration project successfully demonstrates the design and implementation of Buck, Boost, and Inverter converters for efficient solar energy conversion and utilization. Each converter plays a crucial role:

The Buck Converter steps down voltage for optimized low-power applications.

The Boost Converter elevates voltage for better energy utilization. • The Inverter converts DC to AC, enabling compatibility with standard electrical systems. Through careful design, component selection, PCB layout optimization, and testing, the converters achieved high efficiency, reduced losses, and reliable operation. The inclusion of control circuits and protection mechanisms ensures system stability, safeguarding against overvoltage, overcurrent, and thermal fluctuations. This project highlights the feasibility of solar PV power integration with advanced conversion technologies, reinforcing its role in sustainable energy solutions. Future work could explore MPPT (Maximum Power Point Tracking), real-time monitoring, and scalability to enhance system performance and adaptability in smart energy grids and industrial applications.

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