5kW Smart Solar Inverter and Charging System

Solar Panel Brand and Specifications

The photovoltaic system for the building will be placed on the roof in order to have access to the most sun during the day. The solar panels that we will use are the Tesla Photovoltaic Module model T420S. The spec sheet for the solar panel is shown in the following tables.

Power Class	T420S	
Test Method	STC	NOCT
Max Power, P_{MAX} (W)	420	313.7
Open Circuit Voltage, V_{OC} (V)	48.5	45.47
Short Circuit Current, I_{SC} (A)	11.16	9.02
Max Power Voltage, V_{MP} (V)	40.90	38.08
Max Power Current, I_{MP} (A)	10.27	8.24
Module Efficiency (%)	19.3	

Table 1: Electrical Characteristics of the Solar Panel

Operational Temperature	-40°C - +85°C
Power Output Tolerance	-0 /+5 W
V_{OC} & I_{SC} Tolerance	+/- 3%
Max System Voltage	DC 1000 V (IEC/UL)
Max Series Fuse Rating	20 A
NOCT	45.7 +/- 2°C
Safety Class	Class II
Fire Rating	UL Type 1 or 2

Table 2: Operation Parameters of the Solar Panel

Cell Orientation	144 (6 x 24)
Junction Box	IP68, 3 diodes
Cable	4 mm² | 12 AWG, 1400 mm | 55.1 in. Length
Connector	Staubli MC4 or EVO2
Glass	3.2 mm ARC Glass
Frame	Black Anodized Aluminum Alloy
Weight	25.3 kg | 55.8 lb
Dimension	2094 mm x 1038 mm x 40 mm 82.4 in x 40.9 in x 1.57 in

Table 3: Mechanical Parameters of the Solar Panel

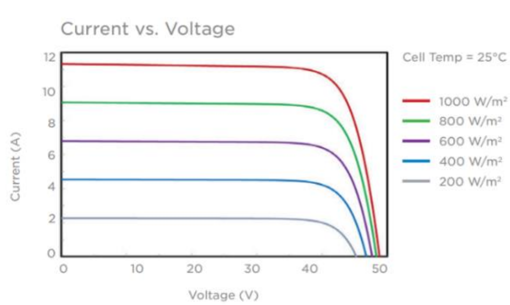

Figure 1: Current-Voltage Characteristics for Solar Panel

In order to be able to produce 5kW power we will need 12 solar panels. A solar panel costs $2.31/Watt which will cost 420*2.31 = $991.2 per panel. To produce 5kW using 12 panels will cost 991.2*12 = $11894.4.

The solar panels will be placed in a combined parallel-series configuration. The rating of each solar panel voltage is 48.5 volts. We are going to place 3 of them in series to get a voltage of 145.5 volts and then each series connected panels will be connected in parallel.

EV Brand and Technical Specifications

The brand of the electric vehicle that we will be using is Chevrolet EUV which has the specifications in the table below. The voltage of the battery of this vehicle is 220V.

Type:	Rechargeable energy storage system comprising multiple linked modules
Mass (lb / kg):	947 / 430
Battery chemistry:	Lithium-ion
Cells:	288
Energy:	65 kWh
Warranty^:	8 years / 100,000 miles of battery and electric components coverage

Table 4: Battery System Spec of Chevrolet EUV

Diode and the MOSFET Specifications

The MOSFET that will be utilized for the system is APTM50UM09FAG which costs about $638.44333. In the whole system, there will be 6 MOSFETs which in total will cost $3830.65998. It has a max operating frequency of 350kHz. The specifications of this MOSFET can be found in the following tables and figures.

Symbol	*Parameter*		*Max ratings*	*Unit*
V_{DSS}	Drain - Source Voltage		500	V
I_D	Continuous Drain Current	$T_c = 25°C$	497	A
		$T_c = 80°C$	371	
I_{DM}	Pulsed Drain current		1988	
V_{GS}	Gate - Source Voltage		±30	V
R_{DSon}	Drain - Source ON Resistance		10	mΩ
P_D	Power Dissipation	$T_c = 25°C$	5000	W
I_{AR}	Avalanche current (repetitive and non repetitive)		71	A
E_{AR}	Repetitive Avalanche Energy		50	mJ
E_{AS}	Single Pulse Avalanche Energy		3000	

Table 5: MOSFET Ratings

Symbol	*Characteristic*	*Test Conditions*	*Min*	*Typ*	*Max*	*Unit*
I_{DSS}	Zero Gate Voltage Drain Current	$V_{GS} = 0V, V_{DS} = 500V$			600	µA
$R_{DS(on)}$	Drain – Source on Resistance	$V_{GS} = 10V, I_D = 248.5A$		9	10	mΩ
$V_{GS(th)}$	Gate Threshold Voltage	$V_{GS} = V_{DS}, I_D = 30mA$	3		5	V
I_{GSS}	Gate – Source Leakage Current	$V_{GS} = \pm 30\ V, V_{DS} = 0V$			±450	nA

Table 6: MOSFET Electrical Specifications

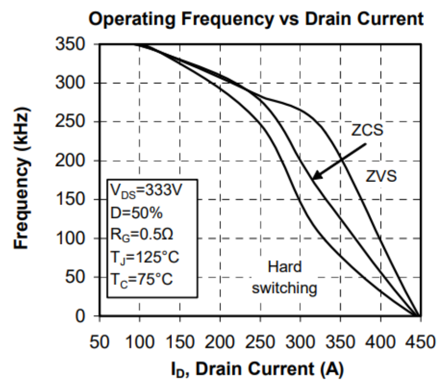

Figure 2: Operating Frequency vs Drain Current Graph of the MOSFET

The diode that will be utilized is HS24515E3. It is a Schottky type diode with a low voltage drop of 370mV. It can handle a very high current of 240A, which is what we need. The specifications of this diode can be found in the table below.

Electrical Characteristics			
Average forward current	$I_{F(AV)}$	240 Amps	T_C = 78° C, Vr = 5V
Average forward current	$I_{F(AV)}$	240 Amps	T_C = 69° C, Vr = 15V
Maximum surge current	I_{FSM}	3500 Amps	8.3ms, half sine, T_J = 125°C
Maximum repetitive reverse current	$I_{R(OV)}$	2 Amps	f = 1 KHZ, 25° C, 1us square wave
Max peak forward voltage	V_{FM}	0.37 Volts	I_{FM} = 240A: T_J = 25° C*
Max peak forward voltage	V_{FM}	0.30 Volts	I_{FM} = 240A: T_J = 100° C*
Max peak reverse current	I_{RM}	4000 mA	V_R = 5V, T_J = 100°C*
Max peak reverse current	I_{RM}	6500 mA	V_{RRM}, T_J = 100°C*
Max peak reverse current	I_{RM}	75mA	V_R = 5V, T_J = 25°C
Max peak reverse current	RM	150mA	V_{RRM}, T_J = 25°C
Typical junction capacitance	C_J	21,700pF	V_R = 5.0V, T_C = 25°C

*Pulse test: Pulse width 300 usec, Duty cycle 2%

Table 7: Schottky Diode Electrical Specifications

Boost-Buck Converter Analysis

Know parameters:

$$Vo = 120V$$
$$Vin = 145.5V$$
$$P = 5kW$$
$$I_{load} = \frac{P}{V} = \frac{5000}{120} = 41.6A$$
$$I_{ripple} = 0.3 \times 41.6\ (30\%\ of\ the\ load\ current)$$
$$\Delta I_L = I_{ripple} = 12.5A$$

The calculations for the inductance and capacitance of the boost converter are as follows

$$L = \frac{Vin}{\Delta I_L} T_{ON}$$
$$\frac{Vo}{Vin} = \frac{D_{ON}}{1 - D_{ON}}$$
$$\frac{120}{145.5} = \frac{D_{ON}}{1 - D_{ON}}$$
$$120\ (1 - D_{ON}) = 145.5 D_{ON}$$
$$D_{ON} = \frac{120}{265.5}$$
$$D_{ON} = 0.452$$

$$D_{ON} = \frac{T_{ON}}{T}, \text{ where } T = 12\mu s$$
$$T_{ON} = D_{ON} \times T$$
$$T_{ON} = 0.452 \times 12 \times 10^{-6}$$
$$T_{ON} = 5.4237\mu s$$
$$L = \frac{145.5}{12.5} \times 5.4237 \times 10^{-6}$$
$$L = 63\mu H$$
$$C = \frac{I_o T_{ON}}{\Delta V_o}$$
$$\Delta V_o = 0.1 \times 120 \ (10\% \ of\ the\ output\ voltage)$$
$$\Delta V_o = 12V$$
$$C = \frac{41.67 \times 5.4237 \times 10^{-6}}{12}$$
$$C = 19\mu F$$

The calculation for the inductance of the buck converter is as follows

$$\Delta I_L = \frac{(V_i - V_o)}{L} DT$$
$$L = \frac{(V_i - V_o)}{\Delta I_L} DT$$
$$L = \frac{(145.5 - 120)}{12.5} (0.452)(12 \times 10^{-6})$$
$$L = 11\mu H$$

DC/AC Inverter

The inverter system utilizes a 60 Hz PWM system with a 50 percent duty cycle since the output of the inverter requires to be 60Hz. This is modulated using a saw circuit attached to a comparator.

LC Filter Analysis

The calculation of the cut-off frequency is as follows

$$w(t) = \sum_{n=0}^{n=\infty} a_n \cos(nw_o t) + \sum_{n=1}^{n=\infty} b_n \sin(nw_o t)$$

The output voltage waveform of the inverter is a square wave which is non-sinusoidal.

$$a_1 = 0$$
$$b_1 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} V_{dc}\ \sin(wt)\,dt + \int_{\frac{T}{2}}^{T} -V_{dc}\ \sin(wt)\,dt\right]$$
$$b_1 = \frac{2V_{dc}}{T}\left[\int_0^{\frac{T}{2}} \sin(wt)\,dt - \int_{\frac{T}{2}}^{T} \sin(wt)\,dt\right]$$
$$b_1 = \frac{2V_{dc}}{T}\left[-\cos\left(w\frac{T}{2}\right) + \cos(0) + \cos(wT) - \cos\left(w\frac{T}{2}\right)\right]$$
$$b_1 = \frac{2V_{dc}}{T}\left[-2\cos\left(w\frac{T}{2}\right) + \cos(wT) + 1\right]$$
$$b_1 = \frac{2V_{dc}}{T}\left[-2\cos\left(\frac{2\pi}{T}\cdot\frac{T}{2}\right) + \cos\left(\frac{2\pi}{T}\cdot T\right) + 1\right]$$
$$b_1 = \frac{2V_{dc}}{T}\left[-2\cos(\pi) + \cos(2\pi) + 1\right]$$
$$b_1 = \frac{2V_{dc}}{T}(4)$$
$$b_1 = \frac{8V_{dc}}{T}$$
$$w(t) = b_n \sin(nw_o t)$$
$$w(t) = b_1 \sin(w_o t)$$

$w(t) = \frac{8V_{dc}}{T} \sin\left(\frac{2\pi}{T}\right)$
$f_c = \frac{2\pi}{T}$
$f_c = \frac{2\pi}{\frac{1}{f}}$
$f_c = 2\pi f$
$f_c = 2\pi(60)$
$f_c = 120\pi$

The calculations of the inductance and the capacitance of the low pass filter is as follows
We picked the inductance as $L = 30\mu H$

$C = \frac{1}{4\pi^2 f_c^2 L}$
$C = \frac{1}{4\pi^2 (120\pi)^2 (30 \times 10^{-6})}$
$C = 6mF$

PWM with Voltage Mode Control Analysis

The peak-to-peak voltage of the ramp generator is 2V. Therefore, the output of the amplifier V_E which then feeds into the comparator is 0.5. The resistors R1, R2, R3, and R4 from the circuit in figure 2 are calculated as follows

$V_E = V_{in}\left(\frac{R_2}{R_1+R_2}\right)$, where $R_2 = 1k\Omega$
$0.5 = 120\left(\frac{1000}{R_1 + 1000}\right)$
$0.5(R_1 + 1000) = 120000$
$0.5R_1 = 119500$
$R_1 = \frac{119500}{0.5}$
$R_1 = 240k\Omega$
$R_2 = 1k\Omega$

Control System Design

The control system is going to utilize an integrated circuit programmable logic controller to change the values of R1 and R2 to modulate the PWM parameter Don = Ton/T. This is going to be accomplished using a three-step process.
There are three stages in the charging process. The three stages are the Bulk Stage, the absorption stage, and the float stage.

Bulk Stage:
The control algorithm should ensure that the battery current is constant at the maximum value. This is done by making the PWM Don constant for a particular period of time according to the formula shown in the following figure.

$$I_b = \frac{1-\alpha}{\alpha} I.$$

Figure 2: Calculating Battery Current (alpha = Don)

This will be done until the voltage of the battery reaches its maximum setpoint value as determined by the spec sheet.

Absorption Stage:
When this occurs, the voltage of the system is held constant while the current is slowly decreased. This can be accomplished again by modulating the value of Don for the Buck-Boost converter until the current reaches the float value.

Float Stage:
During this stage, the charge current will be held constant at the float value which is determined by the battery spec sheet. In addition to this, the voltage will also be held constant. This will be accomplished by having the control system modulate Don so it's min value.
In addition to this, there will also be an MPPT mode that will be adopted before the bulk stage. This mode will track and charge the battery with the maximum power generated by the battery. The MPPT mode will be accomplished using the following flow chart.

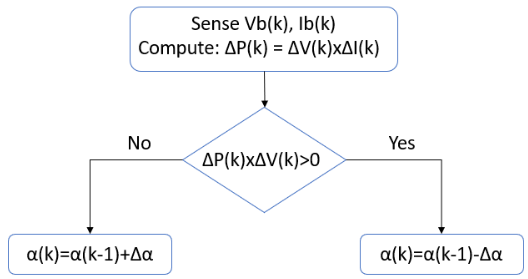

Figure 3: Flow Chart of the MPPT Mode

This shows that if the product of the change in voltage and power is greater than 0 you have to decrease the duty cycle; else you are going to increase it. This is done until the current reaches it max value.