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Modeling, Simulation and Control Issues on Standalone Photovoltaic System

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Abstract

For application in the design and implementation of standalone PV solar electric application, as well as, control of its output characteristics and performance, to meet particular electric application requirements, different PV system models and corresponding control approaches are derived, built and tested in MATLAB/Simulink. The models and approaches were tested. For a given PV system design parameters with variable output from PV subsystem and under specific given PV system working conditions, all to control outputs characteristics of overall PV system, as well as, each subsystem output characteristics, all to meet overall PV system desired output characteristics, performance and meeting desired values of voltage and current.

Keywords: Photovoltaic, renewable energy, DC-DC converter, DC-AC inverter, Modeling and Control.

1. INTRODUCTION

The solar energy is a clean, inexhaustible, green, environmentally friendly energy. Photovoltaic solar energy is most used form of solar energy to generate electricity. The amount of generated electric power, current and voltage by a given PV module is not constant all the time, it is a function of Photovoltaic cell voltage V, solar irradiance β, ambient temperature T, the PV cell's series-parallel configuration, shading, applied control approach, the load voltage or current at which the attached load is drawing power (voltage or current) from the PV module and more other factors. Due to this PV complex behavior, and to help designers in the design and selection process to meet desired PV system design requirements. It is of need to develop mathematical and various simulation overall PV system and subsystems' models, to investigate, test and evaluate the effect of all these factors on PV system power, current and voltage characteristics. This work presents Photovoltaic overall and subsystems' system modeling, simulation and control issues for utilizing in design and implementation of solar electric application.

This work is organized as follows; section 2 provides an overall PV system, subsystems and components modeling and simulation. In section 3, subsystems testing and evaluation are provided. Section 4 presented control algorithms design, testing and evaluation. Finally, section 5 provides results and conclusions.

2. OVERALL PV SYSTEM AND SUBSYSTEMS MODELING AND SIMULATION

The Overall PV system can be considered consisting of the next main subsystems and components; PV array, DC-DC converter, charge controller, batteries, DC-AC inverter, load and control units with control algorithms. The overall PV system's circuit and control models are shown in Figure 1. The system parameters applied in testing and evaluation are listed in table-1. In the next parts of this section, for each of these subsystems, mathematical and MATLAB/Simulink models will be built, tested and evaluated.

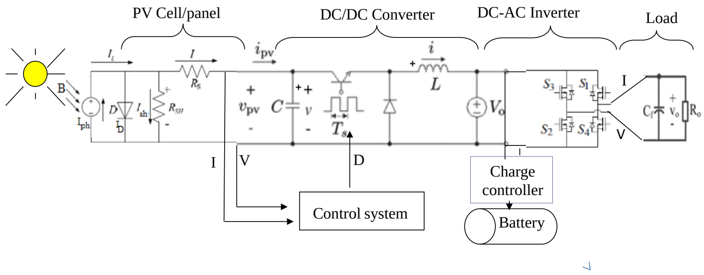


Figure 1: Circuit diagram of overall PV system consisting of; PV array, Converter, charger, inverter, and control subsystems.

2.1 PV Panel/Array Subsystem Modeling, Simulation and Testing

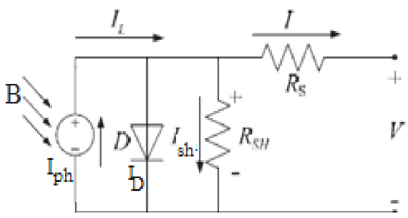
There exist different models of PV system. The simplest one to be applied in this work is the single diode exponential circuit model shown in Figure 2 (a). As noted, the amount of generated electric power, current and voltage of a given PV module are not constant all the time and instead it is a function of PV parameters such as PV cell voltage V, ambient temperature T, solar irradiance β, the PV cell's series-parallel configuration, shading, applied control approach, any or both load's voltage or current at which the attached load is drawing power (voltage or current) from the PV module and others.

For a given PV module, the maximum generated output voltage and current can be expressed mathematically as given by Eqs. (1) and (2). Utilizing these two equations and referring to [1,2,3,4], MATLAB Simulink model with two mask blocks shown in Figure 2(b) and (c) are developed. This model is designed and built, such that it returns all the needed visual, graphical and numerical, data for PV system design, analysis, and evaluation under a given working conditions and parameters.

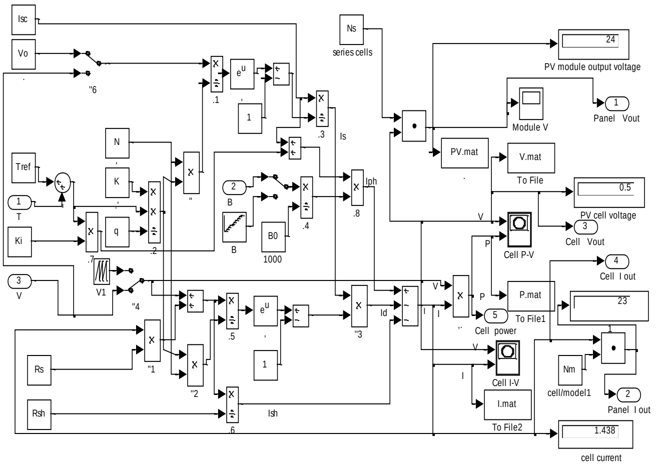
$$I = N_P I_{ph} - N_P I_s \left(e^{\frac{q\left(\frac{V}{N_S} + \frac{IR_S}{N_P}\right)}{NKT}} - 1 \right) - \frac{\frac{N_P V}{N_S} + R_S I}{R_{sh}} \qquad (1)$$

$$V = \frac{NKT}{q} \ln\left(\frac{I_{ph} + I_s + I}{I_s} \right) - IR_s \qquad (2)$$

Testing this PV model for the parameters listed in Table 1 with cell surface area A=0.005 m^2 , N_P=30, N_S=36, at sun irradiance β=200 and temperature, T=50, will return all the required data for PV system design and analysis process. This will reflect on both characteristics V-I and P-I curves shown in Figure 2(d) and (e), as well as, visual results shown in Figure 2(c), and numerical data listed in Table 2.



(a)



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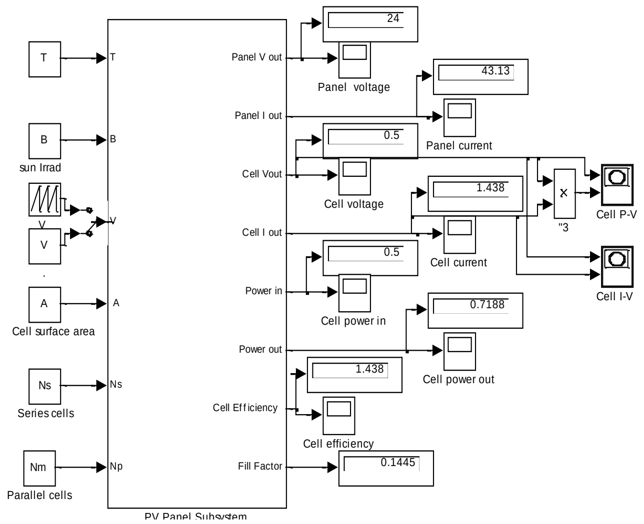

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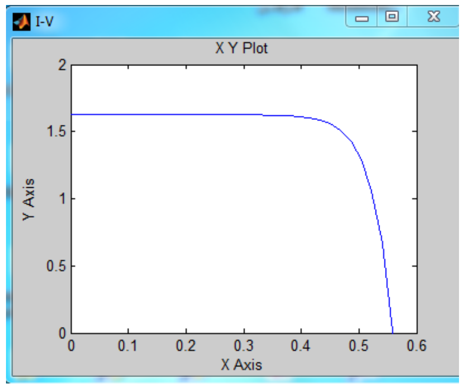

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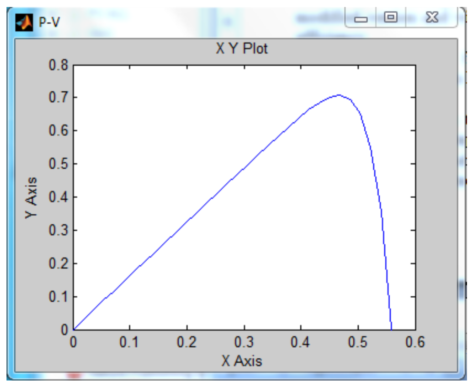


(e)

Figure 2 **(a)** the exponential single diode model of the PV cell; **(b)** PV cell /array MATLAB/Simulink subsystem model [1-3]; **(c)** A PV Cell/array Simulink mask model with visual data results; **(d)** V-I Characteristics curve for sun irradiance β=200 and temperature, T=50; (e) P-V Characteristics curve for sun irradiance β=200 and temperature, T=50.

2.2 DC/DC Converter Subsystem Modeling, Simulation and Testing.

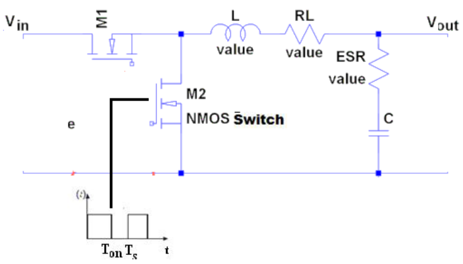
Since the amount of generated electric power, current and voltage by a given PV module is not constant all the time and are function of different variables. The DC/DC converters are applied in PV system to transform variable input DC voltage from one level to another desired stabilized constant output voltage level. Also, they are applied to match the loads to the power supply. There are three types of DC/DC Converters; step-up, step-down and step up and down, (Buck, Boost and buck-boost converters). In this section of the work, step-up Boost DC/DC converter shown in figure 3(a) is applied in overall PV system. In the second part a buck converts is also applied.

2.2.1 Step-up Boost DC/DC Converter

A closed loop control, as separately shown in Figure 3(b) and in Figure 1, is applied to control the PV parameters during sudden changes in the input power of boost converter coming from the PV array. The exact control of converter's outputs is achieved utilizing pulse width modulation. A PWM signal is generated to control the converter's MOSFET-switch ON or OFF by controlling the switching duty cycle D. Therefore the output voltage of the boost converter is related to the input voltage by the expression given by Eq. (3). Where, D refers to the duty cycle ratio and is given by Eq. (4)

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad \Rightarrow \quad V_o = \frac{V_{in}}{1-D} \quad \Rightarrow \quad D = 1 - \frac{V_{in}}{V_o} \qquad (3)$$

$$k = \frac{t_{on}}{T} \qquad (4)$$



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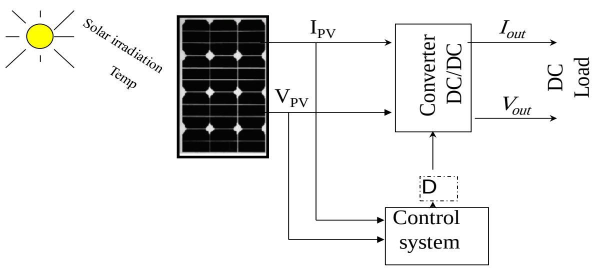


(b)

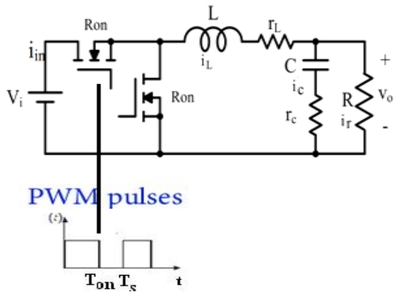
Figure 3. (a) Circuit diagram of a step-up Boost DC/DC converter; **(b)** Closed loop control approach for Boost converter.

2.2.2 Step Dawn DC/DC Buck Converter

The circuit diagram of the step dawn DC/DC Buck converter is shown in Figure 4(a). The output voltage of the Buck converter is related to the input voltage by the expression given by Eq. (5). Referring to [5], the Simulink model shown in Figure 4(b) is built and the duty cycle D is calculated as given by Eq. (5). Corresponding to this, the output voltage of the buck converter is as given by Eq. (6).

$$\frac{V_{out}}{V_{in}} = D = \frac{I_{in}}{I_{out}} \Rightarrow V_{out} = D * V_{in} \Leftrightarrow D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T}$$
$$\Rightarrow (V_{in} - V_{out}) T_{on} = V_{out} (\mathrm{T} - \mathrm{T}_{on}) \qquad (5)$$

$$V_{out} = D V_{in} \qquad (6)$$



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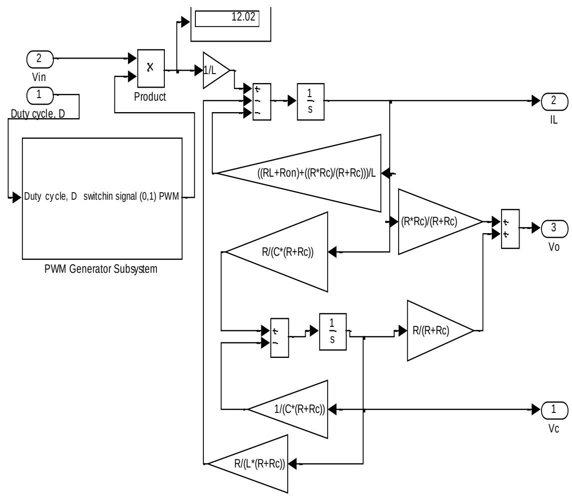

(b)

Figure 4: (a) Circuit diagram of the Buck converter circuit diagram; **(b)** The buck converter subsystems model and PWM generating model

2.3 DC/AC Inverter Subsystem Modeling and Simulation.

In [6], authors developed a DC-DC Boost converter-inverter system. Both mathematical and Simulink model were developed. The system model consists of two main parts; single-phase DC/AC inverter and DC/DC boost converter.

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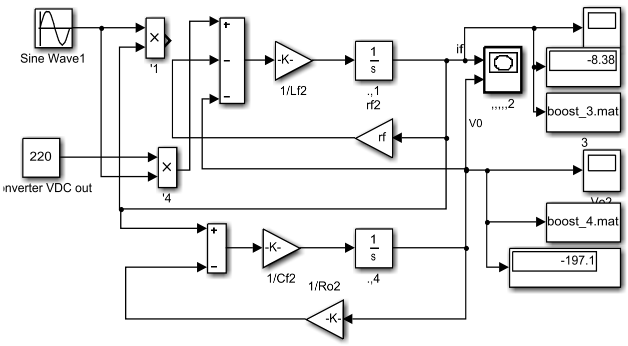
This overall system model is improved for further application and applying control algorithms in this work. The developed DC-AC inverter Simulink model is shown in Figure 5.

2.4 The Overall Photovoltaic System and Mask Models

The overall Photovoltaic system and mask models consisting of PV array, control unit, PI control algorithm and one DC-DC boost converter-inverter Simulink model is shown in Figure 6. This overall PV Simulink system model is built to provide the designers with a maximum visual, numerical and graphical data required to test, analyze and evaluate a given design of a whole PV system characteristics and performance in terms of each and all subsystems.



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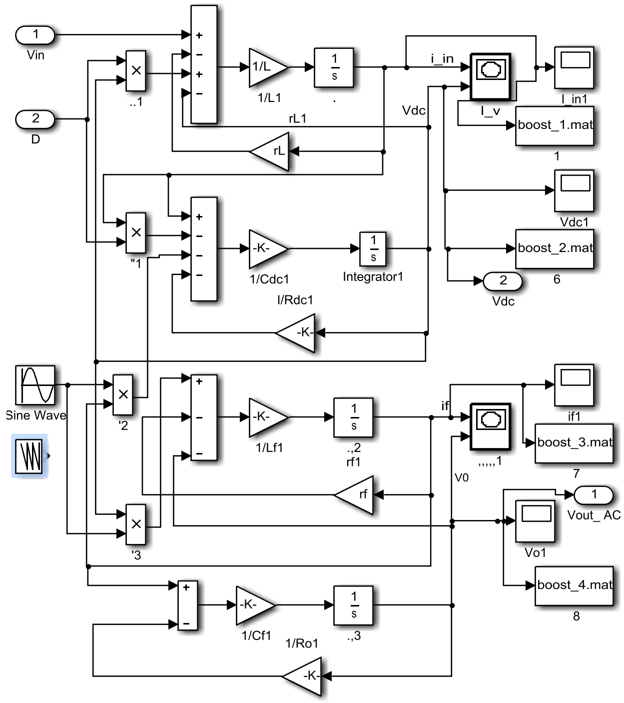

(b)

Figure 5: (a) DC-AC Inverter Simulink model; **(b)** DC-DC Boost converter-inverter single Simulink model system

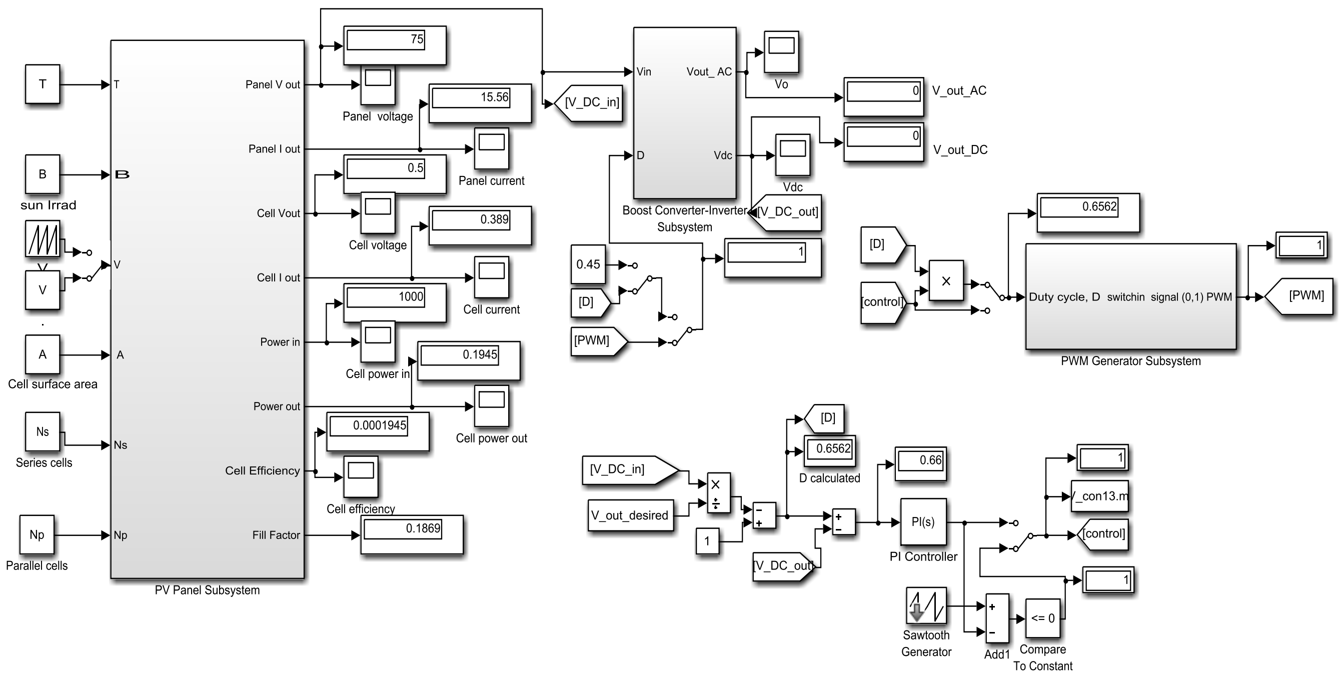

Figure 6. Overall PV system model and masks consisting of PV array, controls, DC-DC Boost converter-inverter Simulink models

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3. DETAILED TESTING OF OVERALL PV SYSTEM

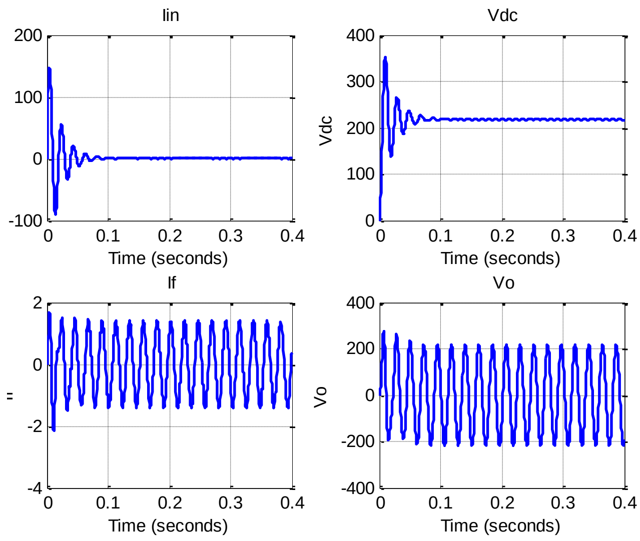
3.1 Testing the Overall PV System Using Boost DC/DC converter

Table 1 shows the parameters used in testing the overall PV system Simulink model. The AC-DC inverter to generate output voltage of 220 V (rms), with load resistance R_o=5 Ohm; DC link resistance, R_{dc}=1000 Ohm, output voltage from PV array of 120 VDC and desired output voltage of boost converter of 160VDC, will return data listed in Table 3 that is also shown in Figure 7(a). Running this model for the desired output voltage of 110VAC with output voltage of PV array is 75VDC using load resistance $R_{o=}$20 and DC link resistance R_{dc}=15, will result in data listed in table 3 and Figure 7(b).

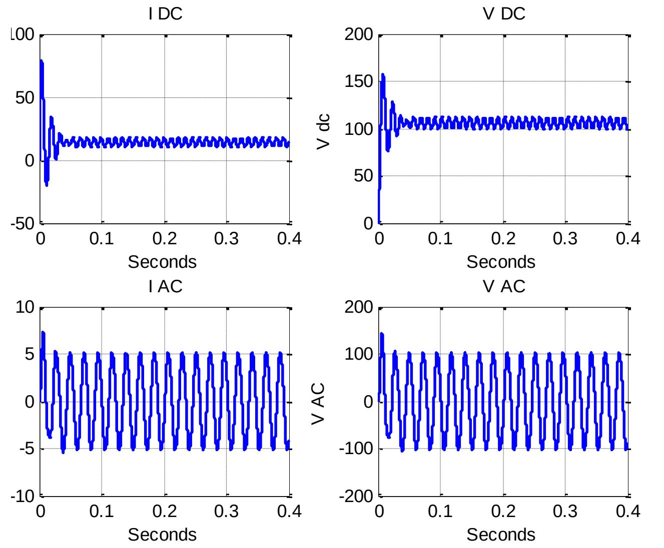
3.2 Testing Overall PV System with Buck DC/DC Converter

Testing the overall PV system Simulink model with buck converter, can be done by replacing the boost converter with buck converter Simulink model. Testing the overall system model for defined Parameters in Table 1, for desired converter's output voltage of 60 VDC, with PV array output of 120 VDC**,** will return, shown in Figure 7 (c), visual and numerical readings, and data listed in Table 4.

The results of these three tests with buck and boost converters, show that the overall system achieves the desired outputs under the given operating conditions. Results also show that in terms of DC voltage the system exhibit overshoots and some oscillations before reaching steady state of desired output. Control unit with algorithm are required to control overall PV system's both output characteristics and performance to meet particular solar electric application requirements.



(a)



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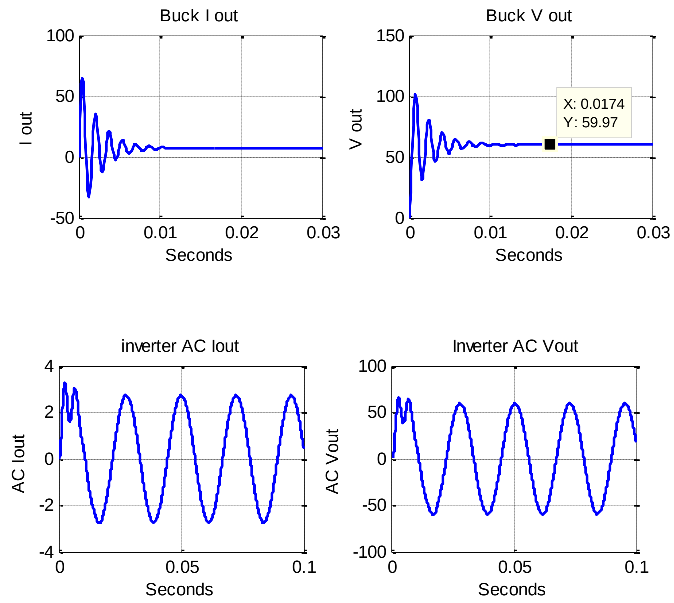

(c)

Figure 7. (a) Boost converter results for test (1) using D=0.45, desired output voltage 220, load resistance R_o=5 Ohm; DC link resistance, R_{dc}=1000 Ohm; **(b)** Boost converter results of test (2) using desired output voltage 110AC, D=0.45,load resistance R_o=10 Ohm; DC link resistance, R_{dc}=15 Ohm; **(c)** Buck converter results for test (1) using desired Converter's and inverter's output voltage 60V, D=0.5, and PV array output voltage of 120VDC.

4. CONTROL ISSUES UTILIZING DC-DC BUCK CONVERTER

4.1 Matching PV Array and Converter's Output Voltages

This target can be accomplished by assigning the duty cycle D as given by Eq. (7). In this setup, the duty cycle is the ratio of the converter's output voltage to PV array output voltage and the classical proportional integral (PI) control scheme is applied to update the duty cycle D. In this setup, the error is

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the difference between converter's output voltage and PV array output voltage. Testing this control approach for parameters listed in Table 1 and PV array output voltage using 30VDC will return the numerical data values listed in table 5 and graphical data shown in Figure 8. These results show that, the target is reached with acceptable response characteristics and nearly without overshoots or oscillations.

$$D = \frac{V_{Conv\_\_out}}{V_{Panel\_out}} \quad (7)$$

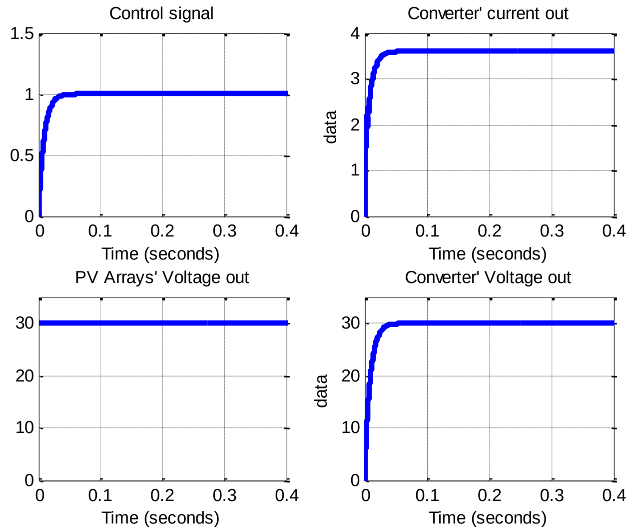
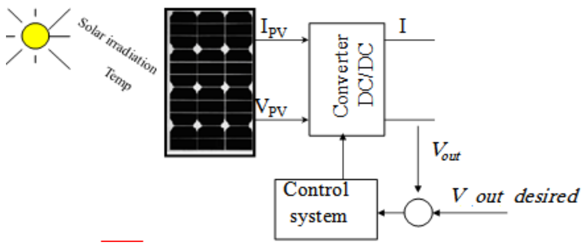
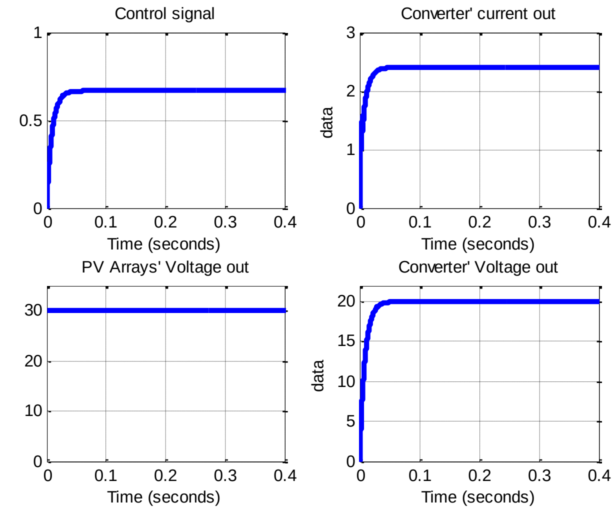


Figure 8 results of the overall system testing with PI controller to match both PV array and converter's output voltages



(a)



(b)

Figure 9. (a) Schematic converter's and its control system; **(b)** results of overall system testing to meet converter's desired load's DC voltage

4.2 Meeting Converter's Desired Output (load's) DC voltage

The converter's desired voltage can be accomplished as shown in Figure 9(a) by assigning the duty cycle D given by Eq. (8). The error for the PI control scheme is the difference between two voltages values; the converter's desired and actual output voltages. Testing this control approach for PV system parameters listed in Table-1 and for desired output voltage of 20 VDC will return the graphical data shown in Figure 9(b) and numerical data listed in table 6. These testing results show the converter's desired output (load's) DC voltage is reached with acceptable response characteristics.

$$D = \frac{V_{Conv\_\_out\_desired}}{V_{Panel\_out}} \quad (8).$$

4.3 Meeting converter's desired output (load's) Current

In this setup, feedback control is applied to control and fix the converter's desired output (load's) Current. The load current, I_{load}, is calculated by applying the well-known Ohm's law. The load is represented as a pure resistor R_{Load}. The resistor value is multiplied by the desired converter's output voltage to calculate the load current. This current is feedback to the converter to be compared with the converter actual output current I_{conv}. The difference between the two currents values is applied to match the desired output load's Current. Testing this approach using parameters listed in Table 1 with duty cycle of D=0.5, load resistance R_{load} = 10 Ohm, and desired load I_{out} =1.449A, will results in data listed in table 7. These results show that the desired load current of I =1.449A is achieved.

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Table 1: Nomenclature and system parameters applied in testing and evaluation

Solar cell parameters	
Isc=1.7A	Short circuit current at reference temperature 25°C
A=0.005	Cell surface area m^2
I A	PV cell Output net current *(the current of PV module)*
I_{ph} *A*	Light generated *photocurrent* (at 25°C and 1000 W/m^2),
E_g *: =1.1*	The semiconductor's band gap energy
$V_t = KT / q$	Cell's thermo voltage. For array($V_t = N_s KT / q$)
I_s *,A*	The leakage current or reverse saturation current of the diode
V	The voltage across the diode
Rs=0.001 Ohm	PV cell's series resistor
Vo= 30.6/50 V	Open circuit voltage
q=1.6e-19 C	charge of the electron
T_{ref}*=273 Kelvin*	The nominal reference temperature
Ki=0.0017 A/◦C	PV cell's short circuit current temperature coefficient
V	The voltage across the diode
Rsh=1000 Ohm	The PV cell's shunt resistors
B_o*=1000 W/m*^{2}	Sun irradiation
N=1.2	The diode ideality factor, takes the value between 1 and 2
β = 200 W/m^2	The irradiation on the given PV surface
T= 50 Kelvin	Working temperature of the *p-n* junction
Ns= 48 , 36	The series connections of PV cells in a module
K=1.38e-23 J/oK;	The Boltzmann's constant
Np= 1 , 30	The Parallel connections of PV cells in a module
Buck converter parameters	
R=8.33; 5 Ohm;	Resistance
T_t*=0.1 , 0.005*	The time constant of the Low pass Pre-filter
V_L	Voltage across inductor
RC=100e-3= rc	ESR of C, Capacitor equivalent series resistance
V_{in}*= 24 V*	Input voltage
Rl=RL=7e-3	Inductor series DC resistance
Ron=1e-3;	Transistor ON resistance
D= 0.5, 0.2,	Duty cycle
C=300e-6;40e-6 F	Capacitance
I_C	Current across Capacitor
L=225e-6 ;.64e-6 H	Inductance
Converter –Inverter parameters	
L = 1.5, 2 ,m H,,	Inductor
F= 2000 ,Hz,	Boost converter frequency
C_{dc} *=1.41 ,m F,*	DC link capacitance
r_L*=0.2*	Inductor resistance
Rdc= 1000 Ω	DC link resistance
L_f *=2 mF;*	Output filter inductance
Ro=22 Ω	Load resistance
R_f *=0.2*	Resistance of output filter inductor
P_o	Output power
C_f*=22 , m F*	Output filter capacitance
F=50 [Hz]	Inverter output frequency

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Table 2: numerical data results of testing PV panel/Array subsystem

Module voltage	Module current	Cell voltage	Cell current, I	Cell output P	Fill factor	Cell efficiency
24 V	*43.13 A*	0.5	1.438 A	0.755Watt	0.1445	1.438

Table 3: Testing with boost converter

Desired output VAC	load resistance R_o	DC link resistance R_{dc}	PV array V_out	R_load	Duty Cycle, D	Boost output current, I_in	Boost output voltage, V_dc	Inverter output voltage, V_O	Inverter output Current, I_f
218.1818	5	1000	120	5	0.45	1,12 ±	217.2 ±	218 ±	1.5 ±
110	20	15	75	10	0.3182	5,4 ±	119.3 ±	118.9±	17.7±

Table 4: testing with buck converter

Desired converter's output VDC	load resistance R_o	PV array V_out	Duty Cycle, D	Buck output current,	buck output voltage,	Inverter output voltage, V_O	Inverter output Current, I_f
60	5	120	0. 5	7.169	59.94	59.6±	2.72±

Table 5: Results of Matching PV array and converter's output voltages

Duty cycle , D	Array V_{out}	Array I_{out}	Converter's V_{out}	Converter's I_{out}	Control signal	Overshoot M_P	Settling time, T_S
1	30	11.69	30	3.601	1	0	0.08s

Table 6 Meeting converter's desired load's DC voltage

Duty cycle , D	Array V_{out}	Array I_{out}	Converte's V_{out}	Converte's I_{out}	Control signal	Overshoot M_P	Settling time, T_S
0.6667	30	11.69	20	2.401	0.6667	0	0.04S

Table 7 Meeting converter's desired load's Current

Duty cycle , D	Array V_{out}	Array I_{out}	Converter's V_{out}	Load R_{load}	Converter's output I_{out}	Desired Load I_{out}	Overshoot M_P	Settling time, T_S
0.5	30	11.69	20	10 Ohm	1.449	1.449	14.831	0.015s

5. CONCLUSIONS

This paper presents issues and applications in the design and implementation of a standalone PV solar electric system, as well as, control of its output characteristics and performances, to meet particular electric application requirements. The PV system and its subsystems have been studied in details. Different PV system models and corresponding control approaches have been derived and verified using MATLAB/Simulink. The models and approaches were verified and tested for different PV parameters changes to control their output voltage and power. Moreover, each subsystem parameters are verified and tested for a given PV system design parameters, with variable output from PV subsystem and under specific given PV system working conditions, all to control outputs characteristics of overall PV system, as well as, each subsystem output characteristics, all to meet overall PV system desired output characteristics, performance and meeting desired values of voltage and current.

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