New Generalized Photovoltaic Panel-Converter system model for Mechatronics design of solar electric applications

Farhan A. Salem

Abstract— To help in facing challenges in Mechatronics design of solar electric applications, including; early identifying system level problems and ensuring that all design requirements are met, this paper proposes modeling, simulation and dynamics analysis issues on PhotoVoltaic Panel-Converter (PVPC) system and proposes a new generalized and refined model for PVPC system. The proposed PVPC system model consists of three subsystems, differently, each subsystems is mathematically described and corresponding Simulink sub-model is developed and tested, then an integrated generalized model of all subsystems is developed, to allow designer to have maximum output data to design, tested and analyze a given PVPC system for desired overall and either subsystem's outputs under various PV system input operating conditions, to meet particular solar electric application requirements. Mathematical and Simulink models of all subsystems and overall system were derived, developed and tested in MATLAB/Simulink.

Index Terms—Mechatronics, Photovoltaic (PV) Cells, Converter, Modeling, simulation.

I. INTRODUCTION

The essential characteristic of a Mechatronics engineer and the key to success in Mechatronics is a balance between two sets of skills modeling/analysis skills and experimentation/hardware implementation skills. Modeling, simulation, analysis and evaluation processes in Mechatronics design consists of two levels, sub-systems models and whole system model with various sub-system models interacting similar to real situation, the subsystems models and the whole system model, are tested and analyzed, for desired system requirements and performance [1].This paper extends writer's previous work, [2] and presets Photovoltaic Panel-Converter (PVPC) system modeling and simulation issues for Mechatronics design of solar electric applications. Based on desired accuracy and particular application, different models of both PVPC system subsystems and generalized refined model are to be derived and developed, to allow designer to have the maximum output data to tested and analyze the PVPC system output characteristics and performance , under given input operating conditions, for desired outputs to meet specific application requirements.

PVPC system consists of three main subsystems; PV panel, DC/DC converter with battery and control subsystems, block diagram of PVPC system is shown in Figure 1. In this paper, only the PVPC system with two main converter and PV-module subsystems will be considered, represented mathematically and corresponding Simulink models developed, where each subsystem will be separately, mathematically modeled and simulated in MATLAB/Simulink, then an integrated generalized and refined model that returns the maximum output data, for design and analysis, will be developed and tested. As a future work control system is to be selected and designed to control inputs and output of either or both subsystems to meet the desired output characteristics and performance (see Figure 1(b))

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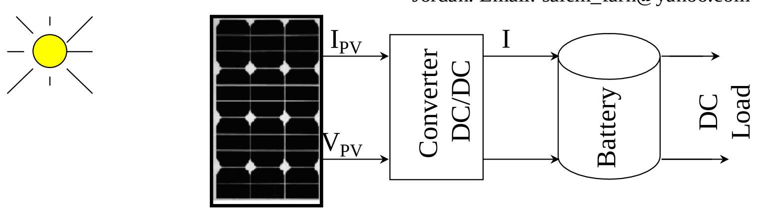


Figure 1(a) proposed PVPC system to be modeled and simulated

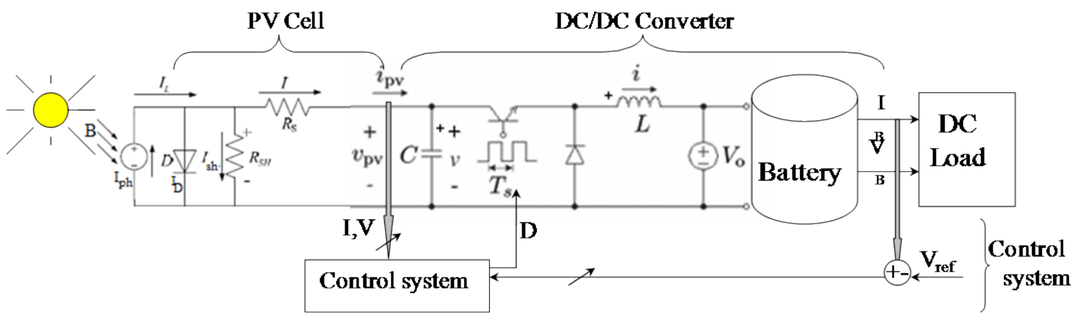


Figure 1(b) with proposed control subsystem added

Figure 1(a)(b) proposed PVPC system.

2. Photovoltaic panel-Converter system modeling

2.1 Modeling the PV cell subsystem

PV system is a whole assembly of solar cells, connections, protective parts, supports etc. The basic device of a PV system is the single PV cell, it consists of a p-n junction fabricated in a thin wafer or layer of silicon semiconductor (Mono-crystalline and multi-crystalline silicon). Cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be warranted for up to 25 years. The output power of PV cell vary as functions of solar irradiation level *β*, the temperature of the module *T*, (output decreases as temperature rises) and load current or the voltage at which the load is drawing power from the module. The power produced by a single PV cell is not enough for general use, where, each solar cell generates approximately *0.5V*, therefore the PV cells are connected in series-parallel configuration on modules (see Figure 2) which are the fundamental building block of PV systems, or a panels consisting of one or more PV modules. To produce enough high power, series connections for high voltage requirement and in parallel connections for high current requirement, finally, panels can be grouped to form large photovoltaic arrays. [2].

The output characteristics of the PV modules, and hence, the array greatly depends on the environmental factors. Therefore, it is difficult to reproduce and maintain the same environmental conditions for testing and comparing the performance of PV power conditioning systems. A PV emulator can reproduce the desired output characteristics irrespective of the environmental conditions. It gives opportunity to test and analyze different PV systems in intended controlled environment [3].

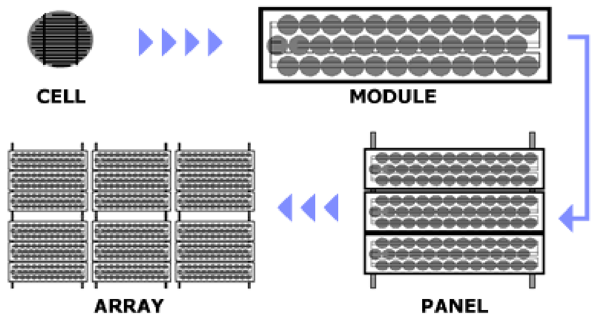


Figure 2 From solar cell to solar array [3]

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the pass four decades and can be found in different resources including [2-18].The mathematical and Simulink models considered are developed in reference to [2]. The simplest equivalent circuit of a PV solar cell consists of a diode, a photo current, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, this all is shown in Figure 3(a). Figure 3 (b) shows typical characteristic I-V and P-V curve of a practical photovoltaic device and the three remarkable points

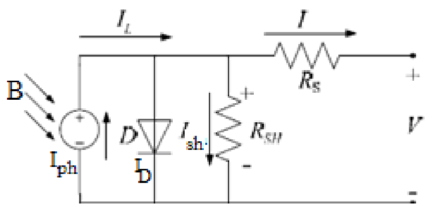


Figure 3(a) Single diode (exponential) model of the PV model

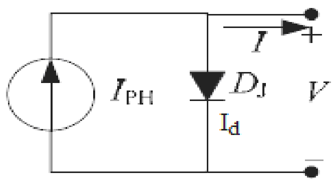


Figure 3(d) *Simplified* single diode model of PV Cell

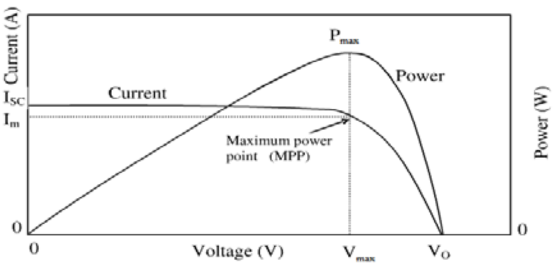


Figure 3(f) Typical characteristic I-V and P-V curve of a practical PV system

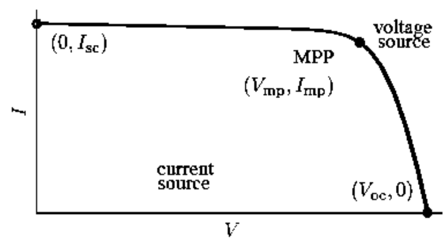


Figure 3(e) Characteristic I-V curve of a PV system and the three *remarkable points*: short circuit *(0, I_{SC})*, MPP *(V_{mp}, I_{mp})* and open-circuit *(V_O, 0)* [15]

The output net current of PV cell I, and the V-I characteristic equation of a PV cell is found by applying the Kirchoff's current law on the equivalent *simplified* single diode circuit model of PV Cell shown in Figure 3 (d), The output net current is the difference of two currents; the light-generated *photocurrent* I_{ph} and *diode current* I_d [2-16] and is given by Eq.(1)

$$I = I_{ph} - I_d \qquad (1)$$

The light-generated photocurrent I_{ph}; is generated by the incident light and directly proportional to the sun irradiation β , and given by Eq.(2).

$$I_{ph} = \left(I_{sc} + K_i \left(T - T_{ref}\right)\right)\frac{\beta}{1000} \quad (2)$$

The cell's short-circuit current I_{SC} ; is the current through the solar cell when the voltage across the solar cell is zero (see Figure 3(e)(f)), it is calculated when the voltage equals to zero *I (at V=0) = Isc*, at a *T= 25°C* and the solar insolation β=1kW/m² , given in datasheet specifications of PV panel.

The diode current I_d ; is given by Eq.(3).

$$I_d = I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) \quad (3)$$

By substituting Eqs.(2)(3) in Eq.(1), the output net current of PV cell I, is given by Eq(4):

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) \quad (4)$$

Because in the real operation of the solar cell some losses exist, this basic Eq. (4) of equivalent *simplified* single diode circuit model , does not represent actual the I-V characteristics of a practical PV module and real operation losses, to get a more real behavior and to pick up these losses in real PV cell, a third current is added to the model as a resistance in series R_s and another in parallel R_{sh} this current is called ***shunt current I_{Rsh}***, and is given by Eq.(5) [17] resulting in correspondingly single diode (exponential) model of the PV shown in Figure 3(a), based on this, *the output net current of PV cell I,* is given by Eq.(6), this model offers a good compromise between simplicity and accuracy, and for simplicity is studied in this paper, Eq.(6), shows that the generated output current of PV cell vary as functions of solar irradiation level *β*, the ambient temperature of the module *T*, (output decreases as temperature rises) and load current or the voltage at which the load is drawing power from the module. Substituting corresponding equations of I_{ph} ,I_d, and I_{Rsh} in Eq.(6) ,the net current of the PV cell can be calculated and represented by Eq.(7).Characteristic I-V of a practical photovoltaic device and the three *remarkable points*, is shown in Figure 3(e).

$$I_{RSH} = \frac{V + R_S I}{R_{sh}} \quad (5)$$

$$I = I_{ph} - I_d - I_{RSH}$$

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

$$I = \left(I_{sc} + K_i\left(T - T_{ref}\right)\right)\frac{\beta}{1000} - I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) - \frac{V + R_S I}{R_{sh}}$$

(6)

$$I = \left(I_{sc} + K_i\left(T - T_{ref}\right)\right)\frac{\beta}{1000} - \frac{I_{sc}}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT}\right]} - 1\right)}\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) - \frac{V + R_S I}{R_{sh}}$$

(7)

2.2 PV subsystem simulation and testing

Based on Eq.(6), Simulink model and masks shown in Figure 4(a) with its different forms, shown in Figure 4(d), are developed in MATLAB/ Simulink to return the following data; cell-panel output currents , voltages, cell power, I-V and P-V characteristics. This model will be used to develop generalized PV panel sub-model in proposed PVPC system and shown in Figure 4(b), with maximum output data for analysis.

The derived equations of I_{ph} ,I_d, and I_{Rsh}, can be used to represent the PV module in MATLAB/ Simulink using user defined function block as shown in Figure 4(b), with four inputs (*β,T,V,I_{PV}*) and two outputs (*V, I_{PV}*), in this function model, where PV module output current is used to calculate output current and voltage, also a low pass filter given by Eq.(8) is added to convert static model into a dynamic model (and to overcome algebraic loop problem)

$$G(s) = \frac{I_{filter}}{I_{PV}} = k\,\frac{1}{Ts + 1} \quad (8)$$

Running proposed model shown in Figure 4 for defined PV system-parameters , shown in table -1 ,will return P-V and I-V characteristics-curves shown in Figure 5(a,b), and visual readings of PV cell–panel outputs including ; current, volt and power, these curves show, this is *3.926 Watt PV cell, I_{SC} = 1.7 A , Vo= 0.587V , I_{max} =1.51 A , V_{max} =0.5 V, (MPP = I_{max} * V_{max} =0.755).*The P-V and I-V curves, show that with *increase* in temperature at *constant* irradiation, the power output *reduces*, also, by increasing operating temperature, the current output increases and the voltage output reduces.

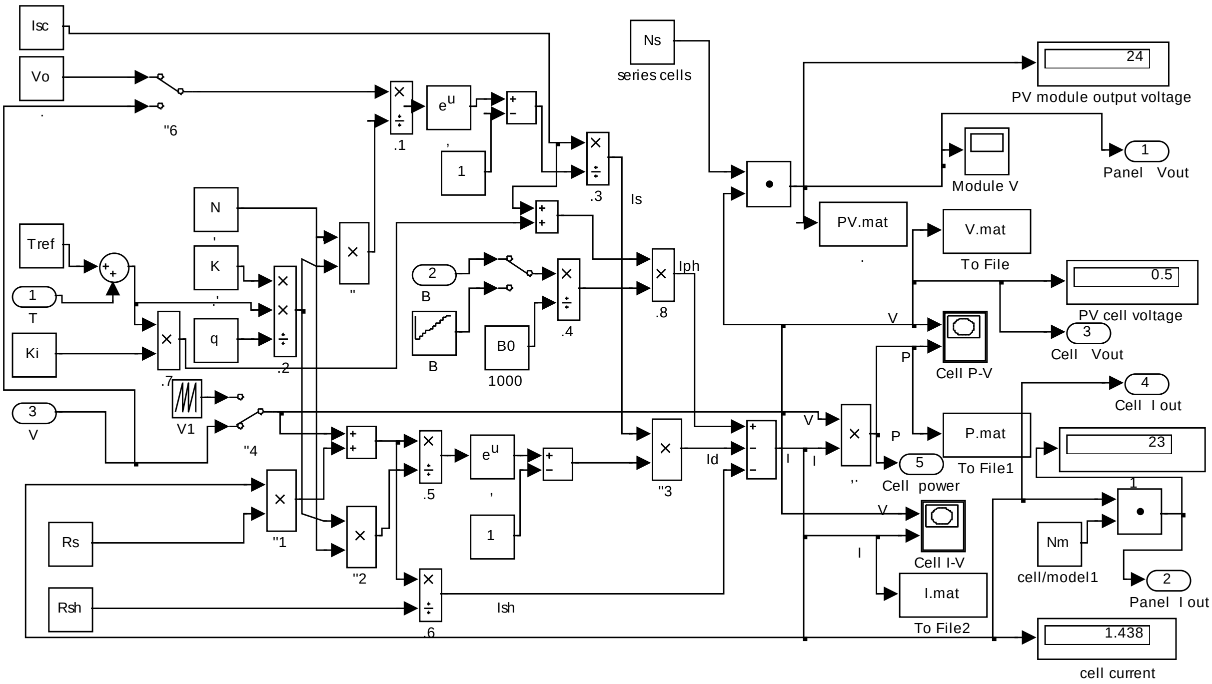


Figure 4(a) PV cell (panel) MATLAB/Simulink subsystem model.

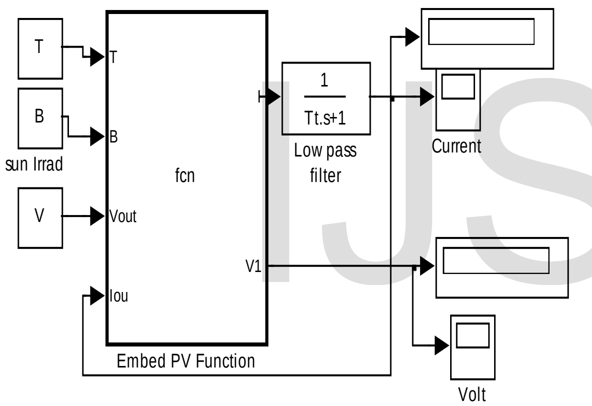


Figure 4(b) PV cell-panel- MATLAB/Simulink subsystem model using defined function with prefilter

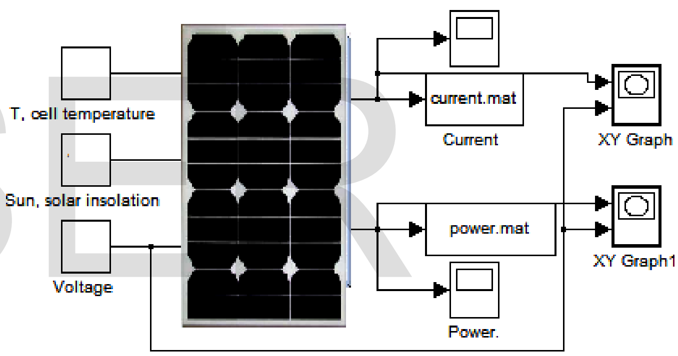


Figure 4(c) PV cell MATLAB/Simulink model

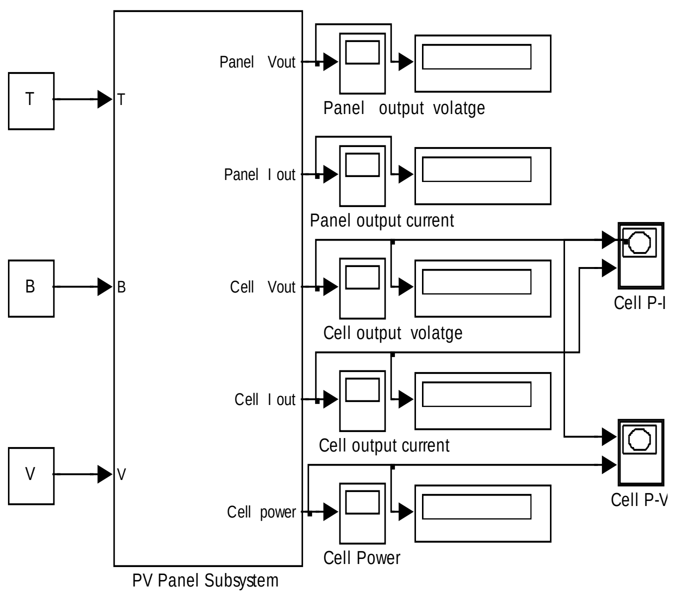


Figure 4(d) PV cell MATLAB/Simulink model

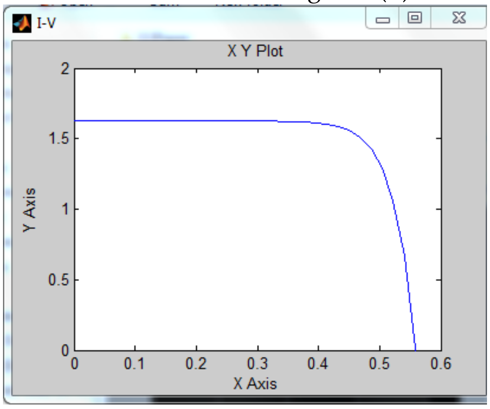


Figure 5(a) V-I Characteristics

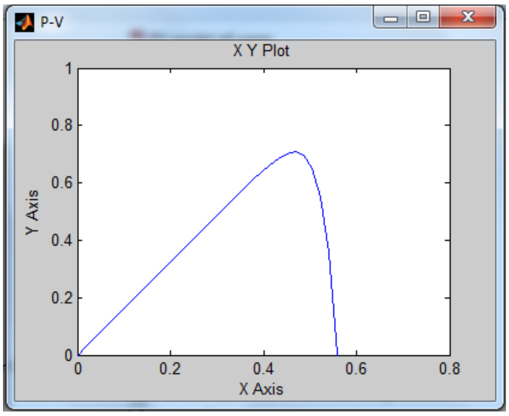


Figure 5(b) P-V Characteristics

2.3 Modeling the converter subsystem

Converters can be classified intro three main types; step-up, step-down and step up and down. Most used and simple to model and simulate DC/DC power converter include *Boost, Buck and buck-boost converters*. *Buck converter* is used for voltage step-down; it is power converter which DC input voltage is greater than DC output voltage. Boost converter is used for voltage step-up [4]. *buck-boost converter* is a step up and down converter, *other such converters include* Cúk, and SEPIC. In this paper *Buck* converter will be applied in proposed PVPC system, and tested to result in constant desired output voltage of *12V* or *6V*.

2.3.1 Modeling the buck converter

A simplified buck converter circuit diagram is shown in Figure 6. The exact control of output voltage is accomplished by using a Pulse-Width-Modulation (PWM) signal to drive the buck converter *MOSFET*-switch ON or OFF, by controlling the switch-duty cycle D, based on this, if the principle of conservation of energy is applied then the ratio of output voltage to input voltage is given by Eq.(9):

$$\frac{V_{out}}{V_{in}} = D = \frac{I_{in}}{I_{out}} \Rightarrow V_{out} = D * V_{in} \Leftrightarrow D = \frac{T_{on}}{T_{on} + T_{off}} \qquad (9)$$

Where: I_{out} and I_{in}, : the output and input currents. D : the duty ratio (cycle) and defined as the ratio of the ON time of the switch to the total switching period. The PWM generator is assumed as ideal gain system, In this paper, for transfer function block diagram representation, the duty cycle of the PWM output will be multiplied with gain $K_v = K_D$, This equation shows that the output voltage is lower than the input voltage; hence, the duty cycle is always less than 1.

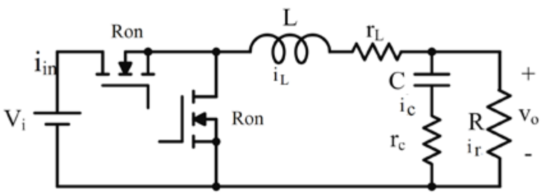


Figure 6(a) Buck converter circuit diagram

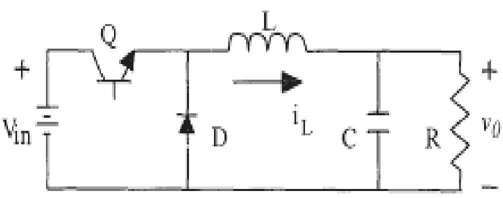


Figure 6(b) The buck converter with ideal switching devices

Refereeing to Figure 6(b), and Figure 7 the mathematical model of buck converter in its two switch positions (ON , OFF), can be derived applying Kirchoff's voltage and current laws, for buck converter, different models can be introduced including simplified and refined models. When the ideal switch is ON, the *refined* dynamics of the inductor current $i_L(t)$ and the capacitor voltage $v_C(t)$ are given by Eq.(10) , meanwhile the *simplified* dynamics are given by Eq.(11) . When the switch is OFF the *refined* dynamics are given by Eq.(12) meanwhile, the *simplified* dynamics are presented by Eq.(13) ,:[18-19].

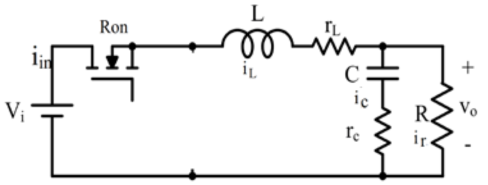


Figure 7(a) Buck converter ON state

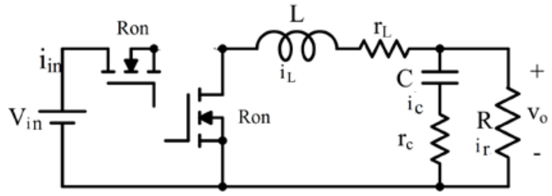


Figure 7(b) Buck converter OFF state

The *refined* dynamics when the switch is ON are derived by the next differential equations:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{in} - V_o - \mathrm{R}_{on}\, i_L + \mathrm{R}_L\, i_L) \\ \dfrac{dV_o}{dt} = (v_o + \mathrm{R}_{on}\, i_L + \mathrm{R}_L\, i_L + \mathrm{L}\dfrac{di_L}{dt}) \end{cases} , \quad 0 < t < dT \ , \quad Q:ON$$

Where:

$$C = \frac{dv_c}{dt} = \frac{R}{R+R_C} i_L - \frac{1}{R+R_C} V_C$$

$$V_o = i_R R$$

The state equations are obtained by applying Kirchoff's voltage and current laws

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}\left[V_{in} - \left(R_{on} + R_L + \dfrac{R}{R_C}\right)\right] i_L - \dfrac{R}{R+R_C} V_C \\ \dfrac{dV_C}{dt} = \dfrac{1}{C}\left[\dfrac{R}{R+R_C} i_L - \dfrac{1}{R+R_C} V_C\right] \end{cases} , \quad 0 < t < dT \ , \quad Q:ON$$

$$i_{in} = i_L$$

$$V_o = \frac{R}{R_C} i_L + \frac{R}{R+R_C} V_C$$

The state equation matrices are given as:

$$(10) \begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \dfrac{di_L}{dt} \\ \dfrac{dv_C}{dt} \end{bmatrix} = \begin{bmatrix} -\left(R_{on} + R_L + \dfrac{R}{R_C}\right) & -\dfrac{R}{R+R_C} \\ \dfrac{R}{R+R_C} & -\dfrac{1}{R+R_C} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_{in}$$

$$\begin{bmatrix} V_o \\ i_{in} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{R}{R_C}\right) & \dfrac{R}{R+R_C} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in}$$

The *simplified* dynamics when the ideal switch is ON are given by Eq.(11)(11)

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{in} - v_o) \\ \dfrac{dv_o}{dt} = \dfrac{1}{C*R}(i_L - v_o) \end{cases} , \quad 0 < t < dT \ , \quad Q:ON$$

$$\begin{bmatrix} \dfrac{di_L}{dt} \\ \dfrac{dv_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1}{L} \\ \dfrac{1}{C} & -\dfrac{1}{C*R} \end{bmatrix} \begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix} V_{in}$$

Referring to Figure 7(b), The State equation for *refined* dynamics when the switch is OFF are given by:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}\left[-\left(R_{on} + R_L + \dfrac{R}{R_C}\right)\right] i_L - \dfrac{R}{R+R_C} V_C \\ \dfrac{dV_C}{dt} = \dfrac{1}{C}\left[\dfrac{R}{R+R_C} i_L - \dfrac{1}{R+R_C} V_C\right] \end{cases} , \qquad Q:OFF$$

$$i_{in} = 0$$

$$V_o = \frac{R}{R_C} i_L + \frac{R}{R+R_C} V_C$$

The state equation matrices are given as:

$$\begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \dfrac{di_L}{dt} \\ \dfrac{dv_C}{dt} \end{bmatrix} = \begin{bmatrix} -\left(R_{on} + R_L + \dfrac{R}{R_C}\right) & -\dfrac{R}{R+R_C} \\ \dfrac{R}{R+R_C} & -\dfrac{1}{R+R_C} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \quad (12)$$

$$\begin{bmatrix} V_o \\ i_{in} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{R}{R_C}\right) & \dfrac{R}{R+R_C} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in}$$

The *simplified* dynamics when the ideal switch is OFF are given by Eq.(13)

(13)

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(-v_o) \\ \dfrac{dv_o}{dt} = \dfrac{1}{C*R}(i_L - v_o) \end{cases} , \quad dT < t < T \ , \quad Q:OFF$$

The steady state equations of buck converter can be defined by Eq.(14), solving this equation for steady state solution, will result in Eq.(15), and the efficiency is calculated by Eq.(16),

$$0 = \begin{bmatrix} -\left(R_{on} + R_L + \dfrac{R}{R_C}\right) & -\dfrac{R}{R+R_C} \\ \dfrac{R}{R+R_C} & -\dfrac{1}{R+R_C} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_{in}$$

$$\begin{bmatrix} V_o \\ I_{in} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{R}{R_C}\right) & \dfrac{R}{R+R_C} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in}$$

(14)

$$\frac{V_{out}}{V_{in}} = D\left[\frac{R}{R + R_L + R_{on}}\right]$$

$$I_{out} = D^2\left[\frac{V_{out}}{R + R_L + R_{on}}\right]$$

(15)

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{in} I_{in}} = \frac{R}{R + R_L + R_{on}} \qquad (16)$$

2.3.1.2 Buck converter simulation and testing

2.3.1.2.1 Simulation and testing of simplified dynamics model

Based on *simplified* mathematical model, where the non-idealities of transistor ON resistance *Ron (or rl),* and inductor series resistance *Rc (or rc)* are *not* included, , Simulink block model shown in Figure 8(a) is developed, the proposed model consists of two subsystems; buck converter subsystem shown in Figure 8(b) and PWM generator subsystem shown in Figure 8 (c). To facilitate subsequent simulation, and feedback controller design and verification, the inputs to buck converter sub-block are, input voltage V_{in} and duty ratio D. The outputs are inductor current and output voltage.

2.3.1.2.2 Modeling the PWM signal

the PWM signal can be generated using any of the proposed three different approaches including; to be assumed for transfer function block diagram representation as ideal gain system constant gain D=Kv as shown in Figure 8(b)), where, the duty cycle of the PWM output will be multiplied with gain *Kv*.

Defining converter parameters to be; V_{in}*= 24 V, R=5 Ohm; L=.64e-6 H;C=40e-6 F*, and running this model for duty cycle *D=0.5*, will result in; output voltage of 12.14 V, output current of *1.49 A* and other readings shown in Figure 8(a). An alternative *simplified* mathematical model, is shown in Figure 10 , where a closed loops for output voltages and currents comparison are used. Running this model for the same previously defined, parameters will result in output voltage of *11.99 V* and output current of *2.03 A*. Based on buck converter simplified circuit diagram shown in Figure 3(b), the transfer function of buck converter represented in block diagram is shown in Figure 11 , running this model for defined parameters including V_{in}= 24 V, D=0.5 will return output voltage of *12.05 V*.

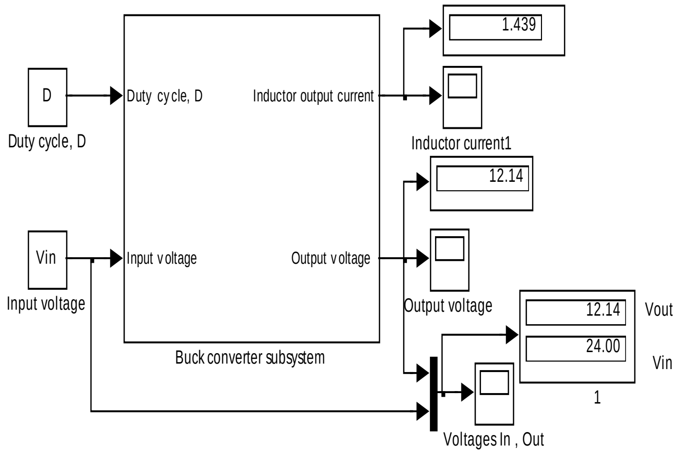


Figure 9(a) buck converter subsystem

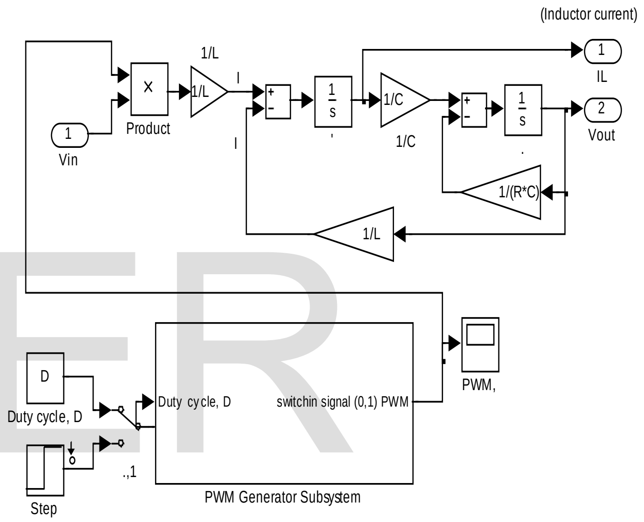
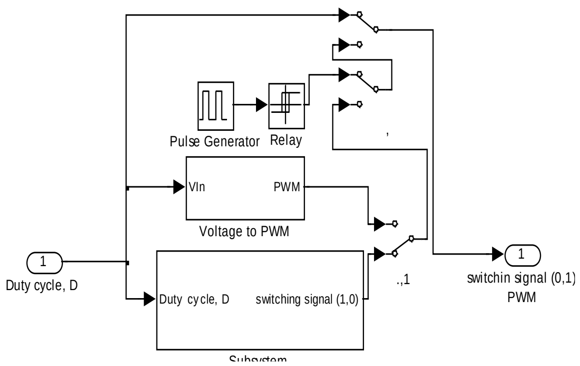
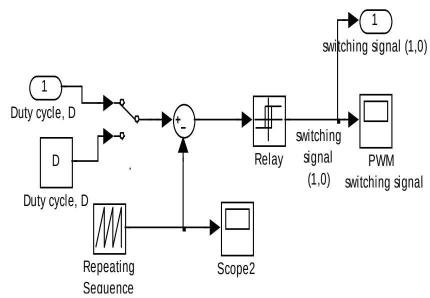


Figure 9(b) Buck converter subsystem connected to PWM generator subsystem





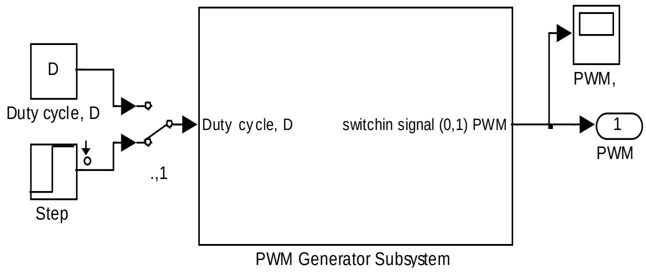


Figure 9(c) PWM generator subsystem

Figure 9(a)(b)(c) simplified buck converter Simulink model with sum systems models

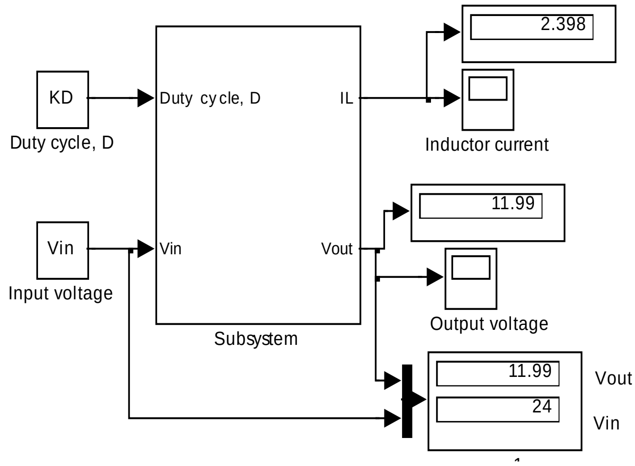


Figure 10(a) buck converter Simulink model

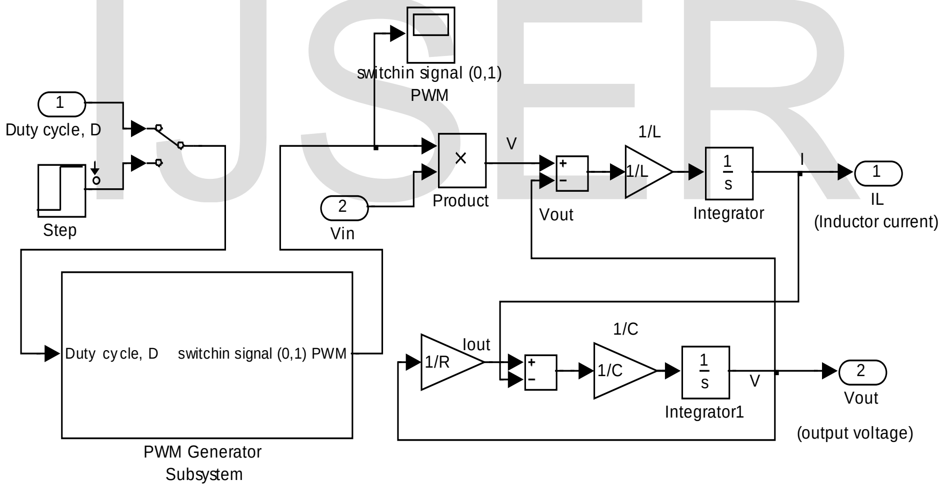


Figure 10(b) subsystem model

Figure 10(b) converter model with closed loops used for output voltages and currents comparison

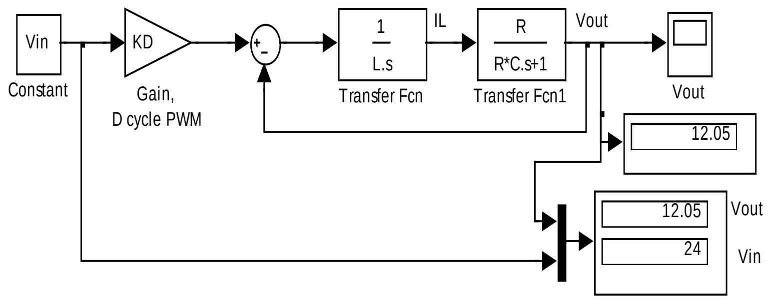


Figure 11(a)

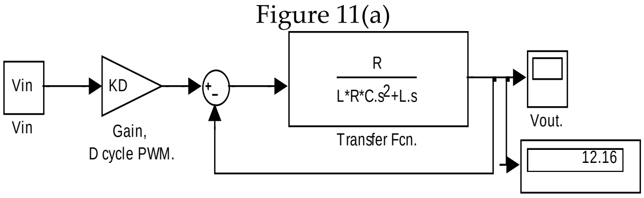


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Figure 11(b)

Figure NN(a)(b) the transfer function of buck converter represented in block diagram

2.3.1.2.3 Simulation of converter's moderate *accuracy* model

Introducing the converter's capacitor equivalent series resistance *RC, (or rc),* inductor series resistance *RL, (or rl)*, will result in Simulink sub-model shown in Figure 12(a), and corresponding Simulink mask shown in Figure 12(b). in proposed model the following quantities are calculated and displayed; *the input power, output power, converter efficiency, converter current*, load current and error in currents. Running this model for defined parameters in table-1 including V_{in}= *24 V, D=0.5, rc= 100e-3, rl=7e-3* , will return converter output voltage of *12.01 V*, and converter output current *0.0549* A

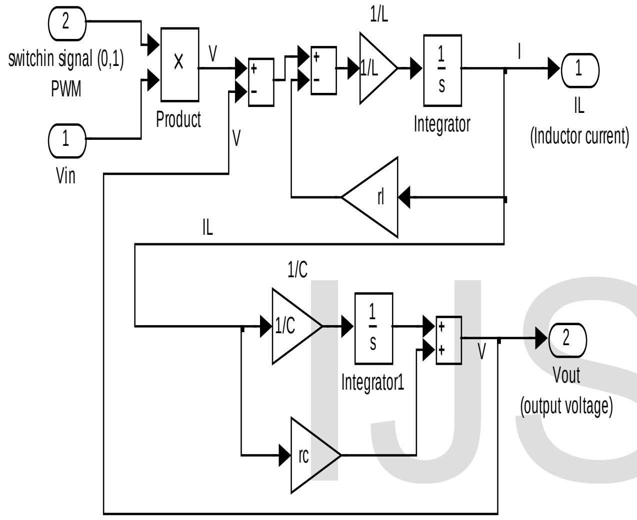

Figure 12(a) converter sub-system model

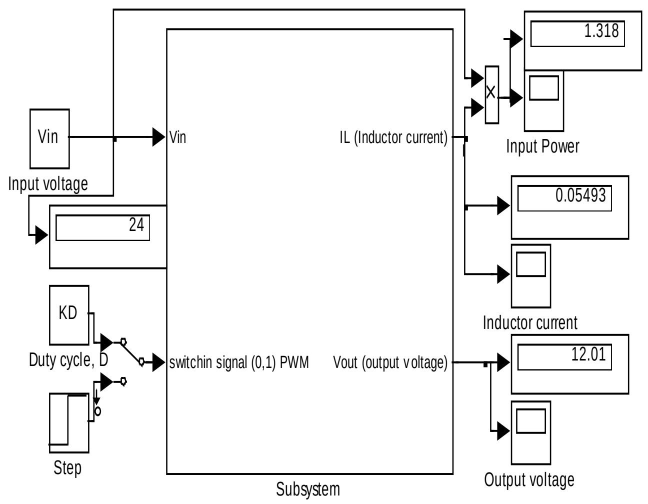

Figure 12(b)

2.3.1.2.3.1 Matching load current using moderate accuracy model

The developed Simulink model shown Figure 12, can be used (as well as other models) to match the load current, this approach is accomplished by in introducing output load as load resistance L_{load} and load current I_{load}, to be matched, this approach is shown in Figure 13(a), the corresponding Simulink function block shown in Figure 13 (b), where the output load resistance L_{load}, multiplied by converter output voltage resulting in load current I_{load} , which is fedback to converter and compared with the converter output current, the difference is used to match the load current. In this model the following quantities are calculated and displayed; *the input power, output power, efficiency, converter current, load current and error in current*. Running this model for defined parameters V_{in}= *24 V, D=0.5, rc= 100e-3,* Inductor series resistance *rl=7e-3* , will result in matching the output load current of *7.5 A*, and also will return, shown in Figure 13 (b), converter's output voltage of *12 V*, efficiency *0.4999*

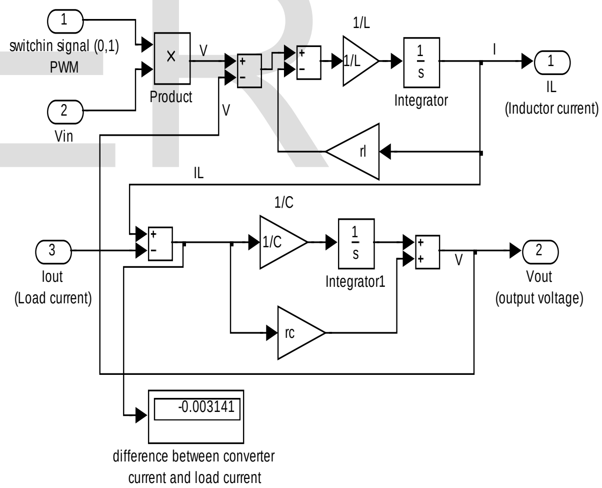

Figure 13 (a)

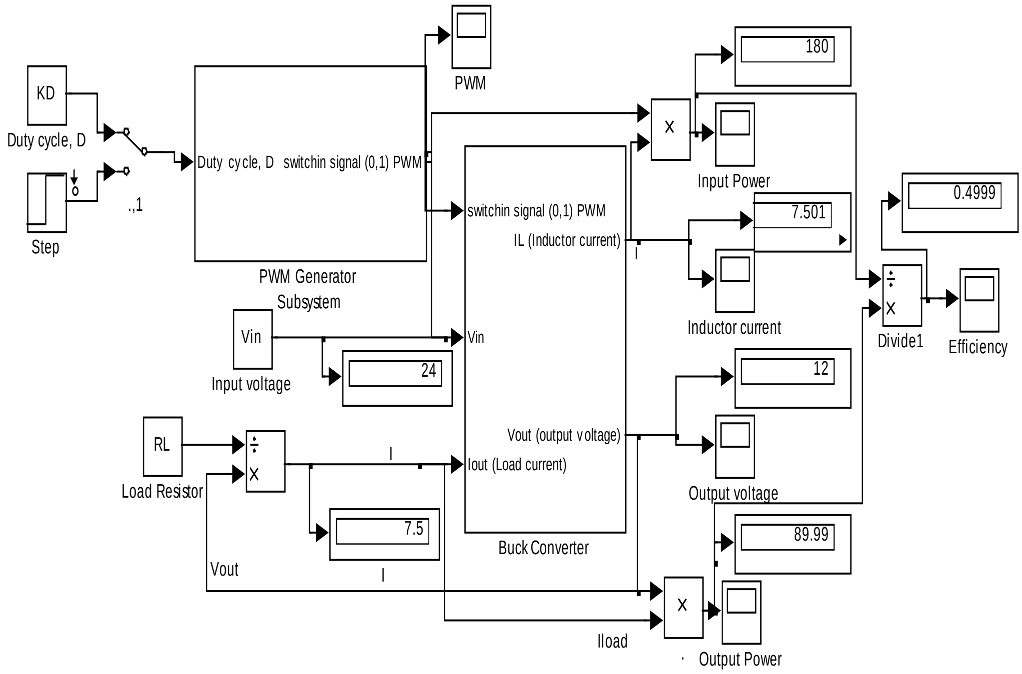

Figure 13 (b)

2.3.1.2.4 *Simulation of refined* dynamics model

To develop more refined buck converter model, the non-idealities of transistor ON resistance *Ron (or rl),*as well as, Capacitor equivalent series resistance *RC* and inductor series resistance *Rc (or rc)* are to be included, correspondingly, Based on buck converter *refined* mathematical model, in its two switch positions, Simulink model shown in Figure 14 (a) is implemented, the proposed model consists of two subsystems; buck converter subsystem and PWM generator subsystem both shown in Figure 14 (b). Running this model for next parameters; *Vin= 24; C=300e-6;L=225e-6;* Inductor series resistance *RL=7e-3;* Capacitor equivalent series resistance *Rc=100e-3;R=8.33;* Transistor ON resistance *Ron=1e-3; KD=.5*,will return output voltage of *11.99 V*, output current of *1.439* A .

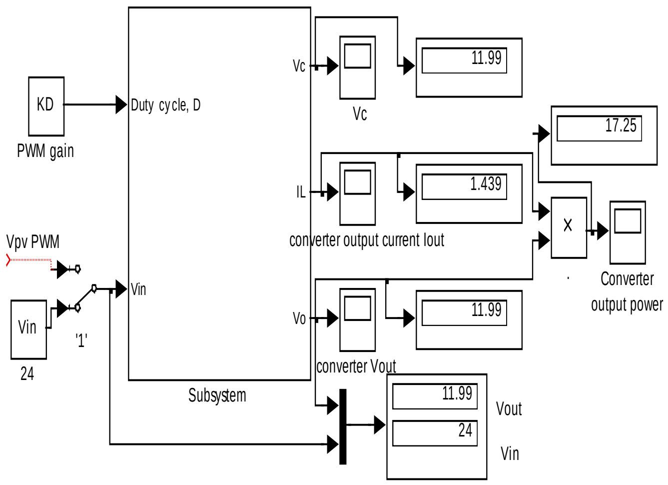

Figure 14(b) buck converter Simulink model, based on refined math model

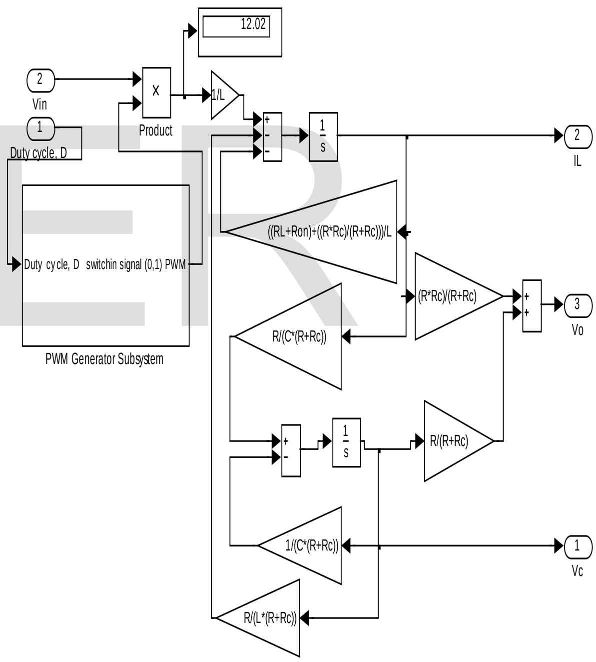

Figure 14(b) buck converter subsystems refined model

2.3.2 Boost converter modeling and simulation

Boost converter is used for voltage step-up. The boost converter circuit diagram is shown in Figure 15(a) the corresponding Simulink model is shown in Figure 15 (b). If the switch operates with a duty cycle D, the steady state output voltage (the DC voltage gain) of the boost converter is given by Eq.(17):

$$K_{DC} = \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \qquad (17)$$

The minimum value of inductance for boost converter to operate in continuous conduction is given by Eq.(18).

$$L_c = \frac{\left(1-D^2\right)DR}{2f} \tag{18}$$

If the chopping frequency is sufficiently higher than the system characteristic frequencies, we can replace the converter with an equivalent continuous model. Assuming continuous conduction mode of operation the mathematical model of boost converter, can be derived applying Kirchoff's voltage and current laws. The state space equations when the main switch is ON are shown by Eq.(17): [19] ,[20].

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{in}) \\ \dfrac{dv_o}{dt} = \dfrac{1}{C}(-\dfrac{v_o}{R}) \end{cases}, \quad 0 < t < dT, \quad Q:ON \tag{19}$$

And the state space equations when the switch is OFF are given by Eq.(18)

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{in} - v_o) \\ \dfrac{dv_o}{dt} = \dfrac{1}{C}(i_L - \dfrac{v_o}{R}) \end{cases}, \quad dT < t < T, \quad Q:OFF \tag{20}$$

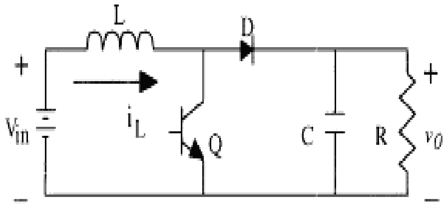

Figure 15(a) circuit diagram of boost converter

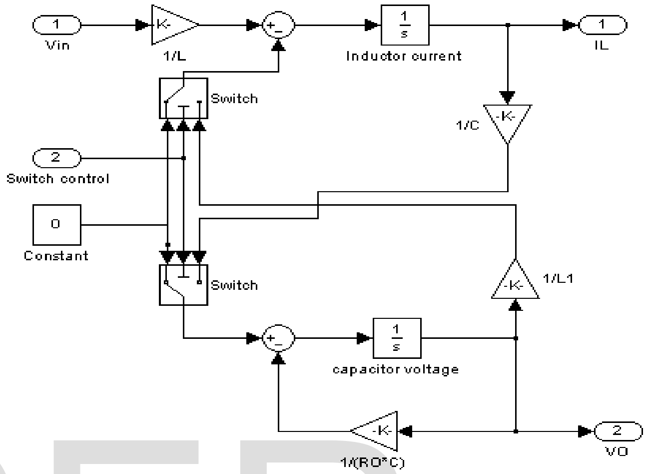

Figure 15(a) boost converter Simulink model[18]

2.3.3 buck-boost converter modeling and simulation

The buck-boost converter is capable of producing a DC output voltage which is either greater or smaller in magnitude than the DC input voltage. The boost converter circuit diagram is shown in Figure 16(a), the Simulink model is shown in Figure 16(b). The steady state output voltage (the DC voltage gain) of the buck-boost converter is given by Eq.(21)

$$K_{DC} = \frac{V_{out}}{V_{in}} = \frac{D}{1-D} \tag{21}$$

The duty cycle D, varies between 0 and 1, therefore the output voltage can be lower or higher than the input voltage in magnitude but opposite in polarity.

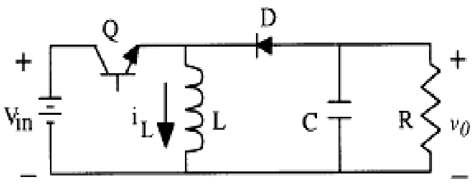

Figure 16(a) circuit diagram of buck-boost converter

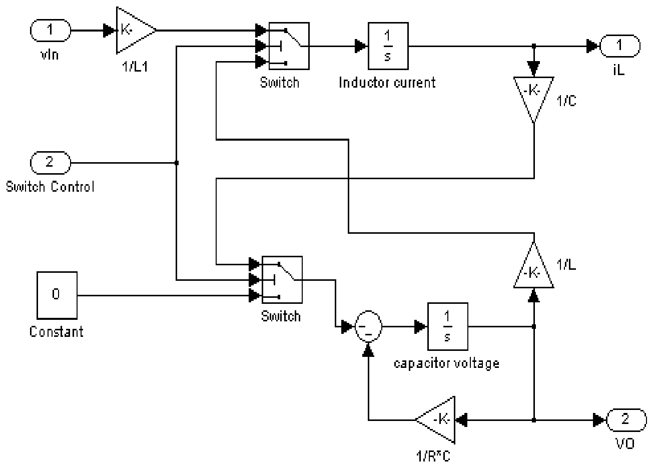

Figure 16(b) buck-boost converter Simulink model[18]

2.4 Photovoltaic panel-Converter (PVPC) system model

The developed both Photovoltaic panel-Converter (PVPC) subsystems; PV model and buck converter ,are integrated to result in Simulink model shown in Figure 17(a),

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depending on particular application and desired analysis accuracy, any of the proposed models for PV and buck converter systems can be used, in this proposed model, the refined model of buck converter is used. Running this model for PV panel and converter parameters defined in Table-1 and *D=0.5* will result in graphical (see Figure 17 (b)) and visual output readings including output voltage of *11.99 V* for PV panel output voltage of *24 V*, resulting at given irradiation *β*, temperature *T*, and *V* , as well as P-I, and I-V characteristics.

Model given in Figure 17 (a), can be modified in single block shown in Figure 17 (c) and to display more data including PV panel output voltage, currents and system duty cycle.

2.4.1 Generalized Photovoltaic panel-Converter (PVPC) system model

Based on refined mathematical models of both PV panel and buck converter subsystems, the model shown in Figure 17, can be modified to have the generalized form shown in Figure 18, to return the maximum desired characteristic visual numerical and graphical data for analysis, design and verification of both subsystems and overall PVPC system, for particular PV panel design considering series and parallel PV cells (*Ns* , *Np*), cell surface area *A*, at given working conditions including Irradiation *β*, temperature *T* and duty cycle *D*.

Running this model for defined in Table 1 PVPC system parameters including; *duty cycle D=0.5*, irradiation *β =200, T=50, Ns=48, Np =30*, cell surface area *A= 0.0025 m²*, will result in visual numerical readings, shown in Figure 18 (a)) and listed in Table -2 and graphical shown in Figure 18 (c,d,e).

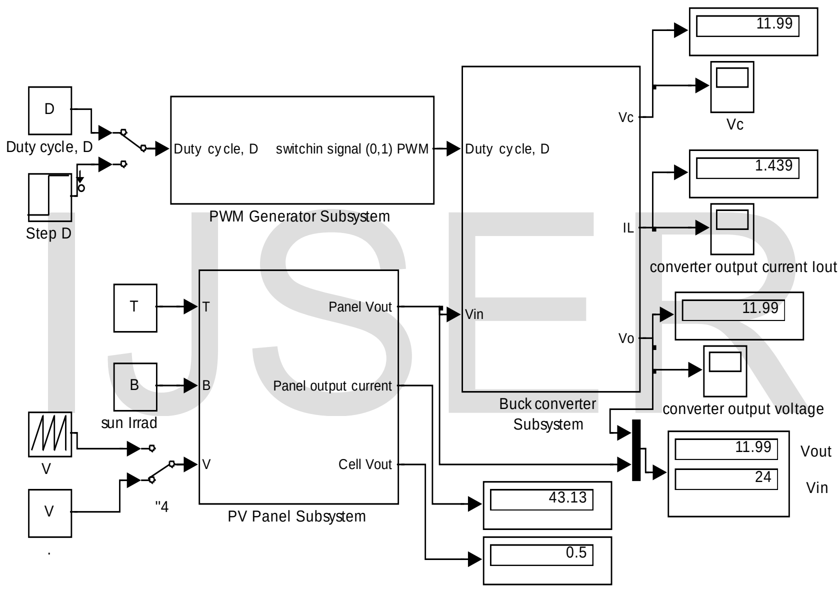

Figure 17Photovoltaic panel-Converter system Simulink mode

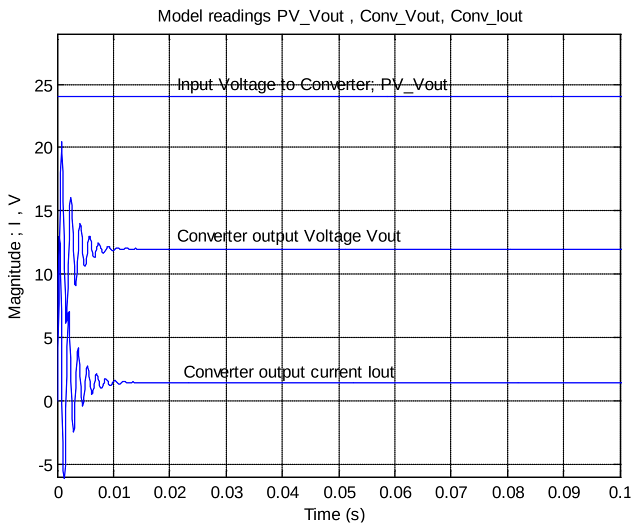

Figure 17 (b) Inputs-outputs data of proposed PVPC system

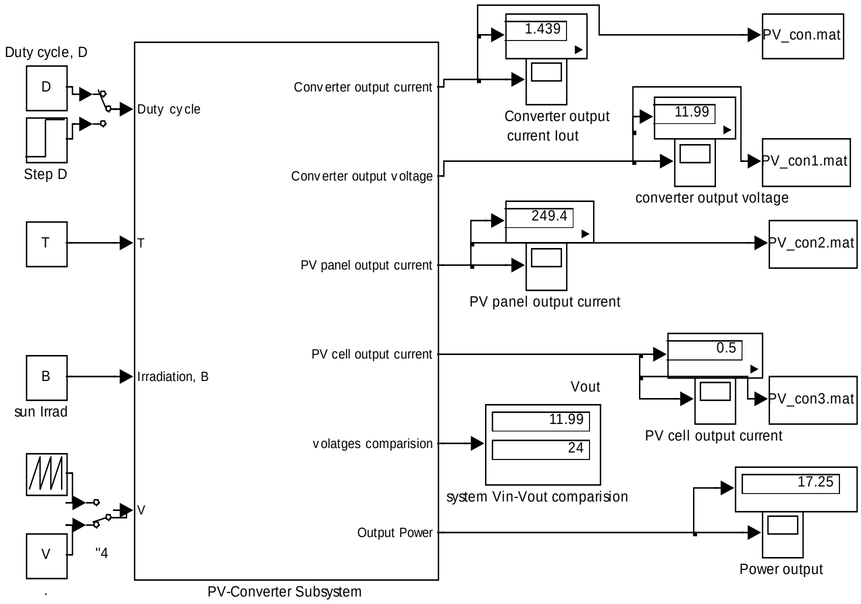

Figure 17 (c) Generalized PV-Converter Simulink model

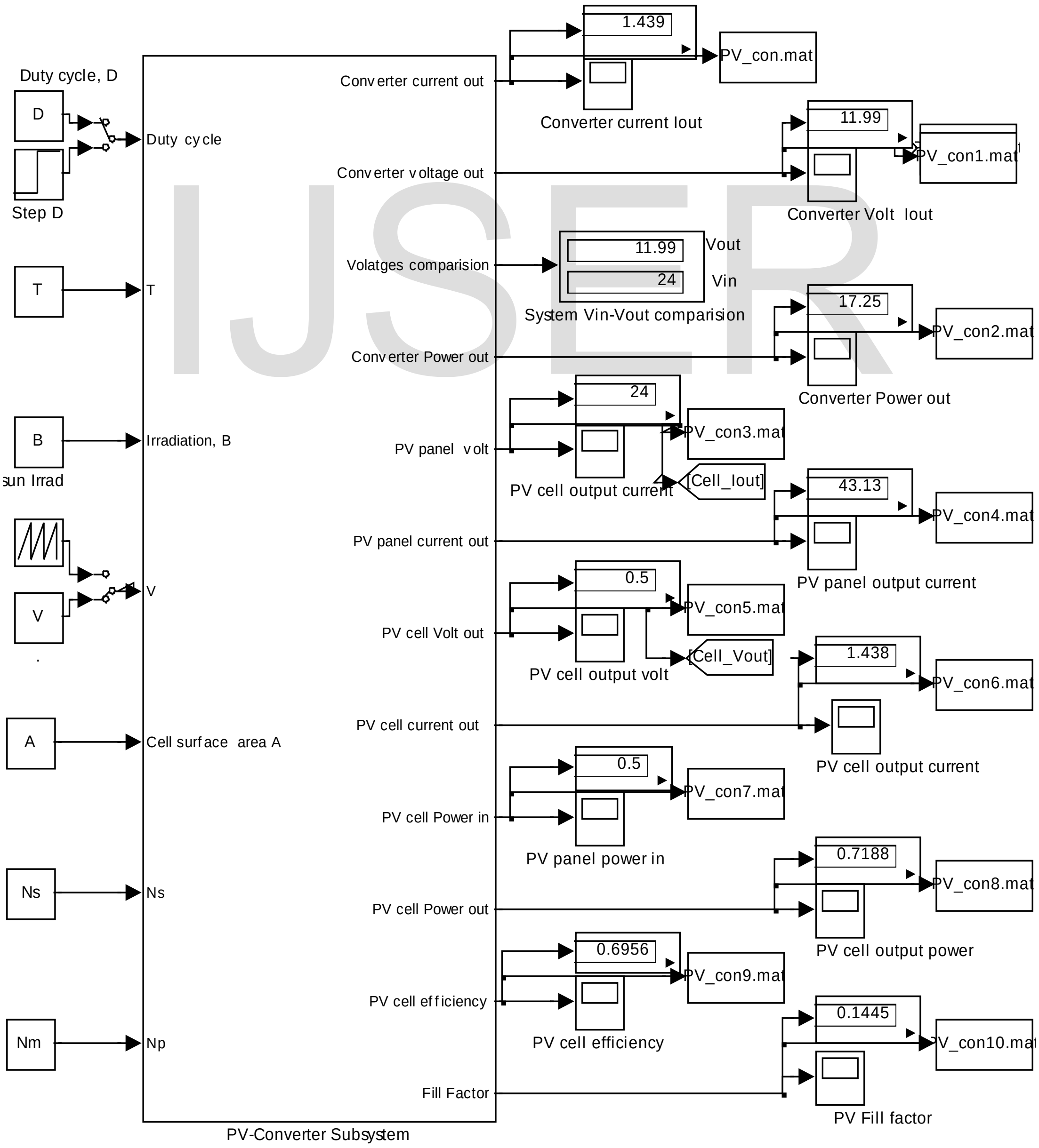

Figure 18(a) Generalized Photovoltaic panel-Converter (PVPC) system Simulink model

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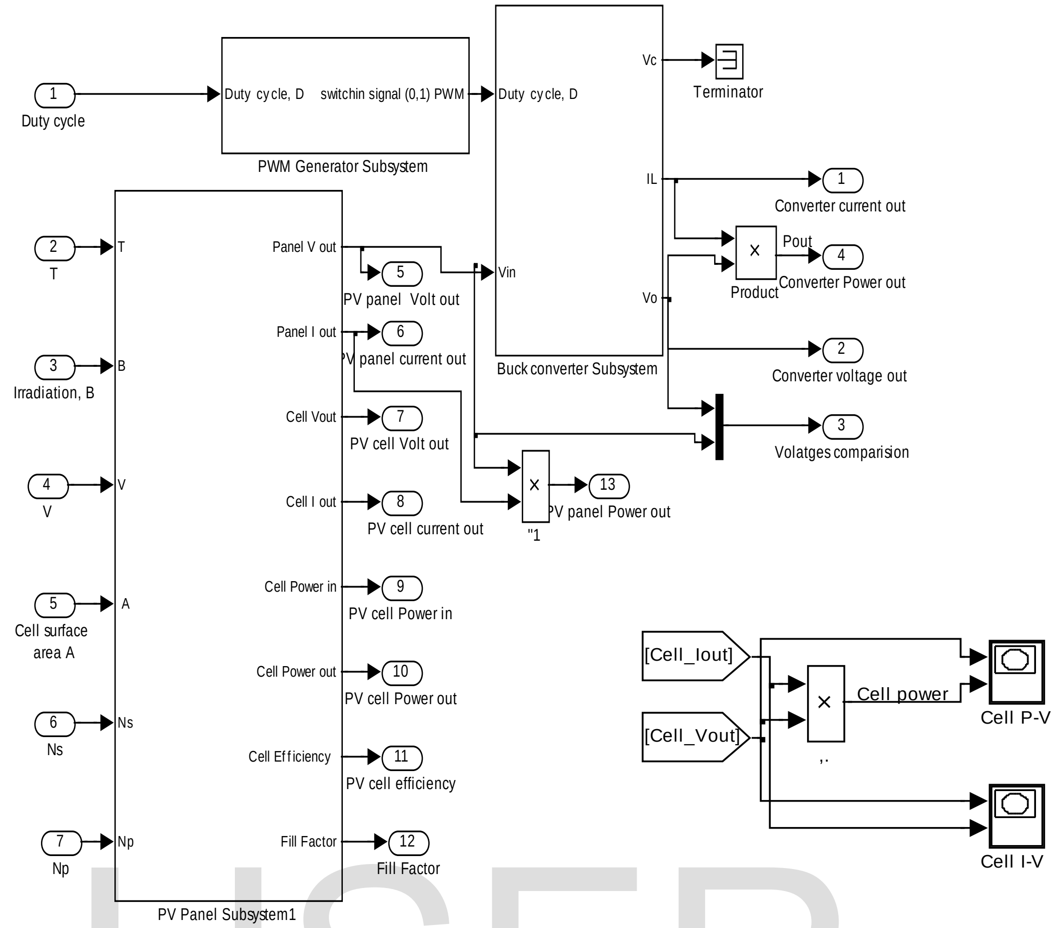

Figure 18(b) Generalized Photovoltaic panel-Converter (PVPC) subsystems

Table 2 Simulation results of each subsystem and whole system

PVPC system inputs		**PV cell outputs**		**PV Panel outputs**		**Converter outputs**	
β	200	**Voltage**	0.5 V	**Voltage**	24 V	**Voltage**	11.99 V
T	50	**Current**	1.438 A	**Current**	43.134A	**Current**	1.439 A
D	0.5	**Fill factor**	0.1445			**Power out**	17.25
A	0.0025	**Power out**	0.7188				
N_S	48	**Power in**	0.5				
N_P	30	**Efficiency**	0.6956				

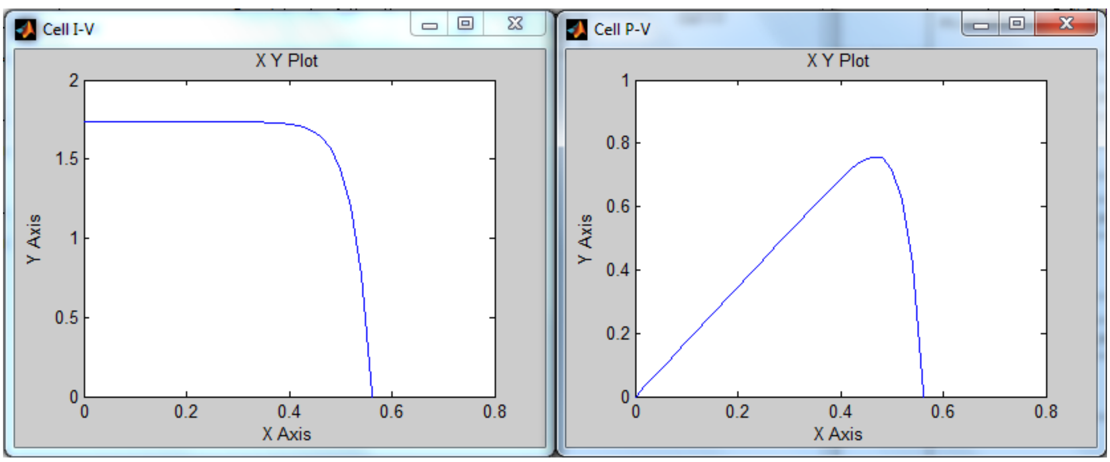

Figure 18(c) P-V and I-V characteristics resulting from generalized Photovoltaic panel-Converter (PVPC) subsystems

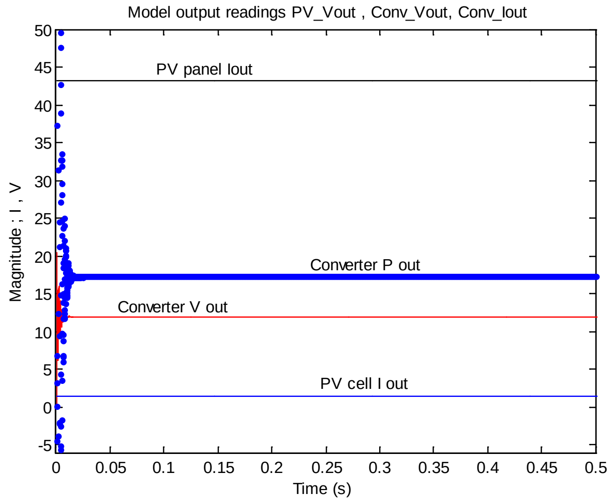

Figure 18(d) Graphical results of PVPC system; Converter's output voltage, and power, PV cell output current and PV panel output current

2.4.1.1 Matching load current using proposed PVPC system

The developed Generalized Photovoltaic panel-Converter (PVPC) shown Figure 18(a) can be used to match the load current I_{Load}, this accomplished by in introducing output load as load resistance R_{Load} and load current to be matched as shown in Simulink subsystem Figure 19(a), the output load is introduced as load resistance R_{Load}, multiplied by converter output voltage resulting in load current , which is fedback to converter and compared with the converter output current, the difference is used to match the load current, these parts are shown in Figure 19(b)

Running this model for defined previously parameters and load resistance of R_{load} =5 ohm, will result in matching the output load current of *2.396 A*, converter's output voltage of *11.99 V*, efficiency *0.4999*,

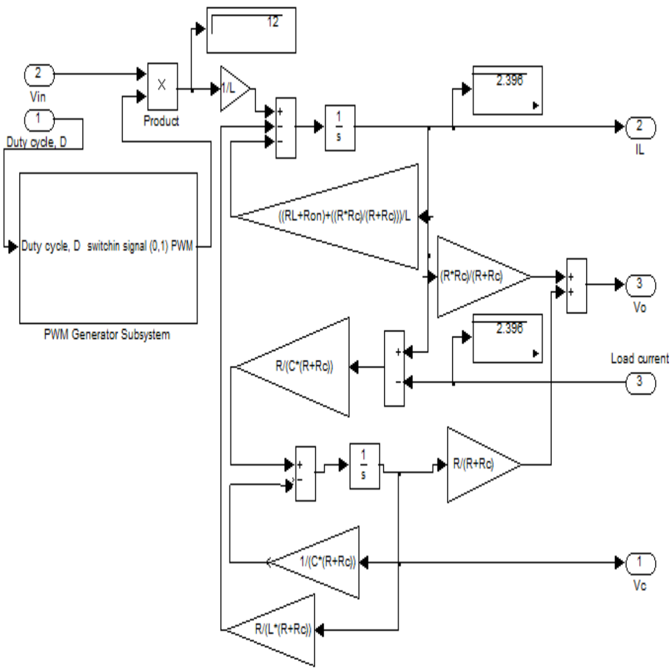

Figure 19(a)

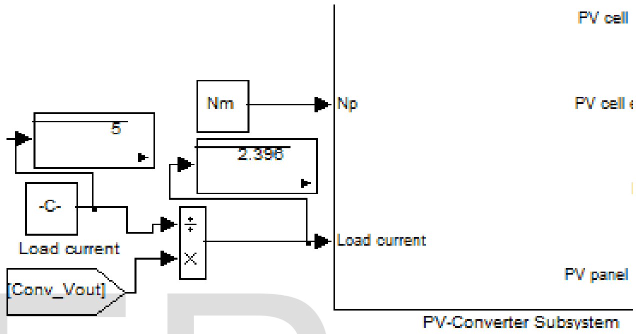

Figure 19(b) the load resistance $R_{Load,}$ multiplied by converter output voltage resulting in load current (2.396 A) , which is fedback to converter and compared with the converter output current

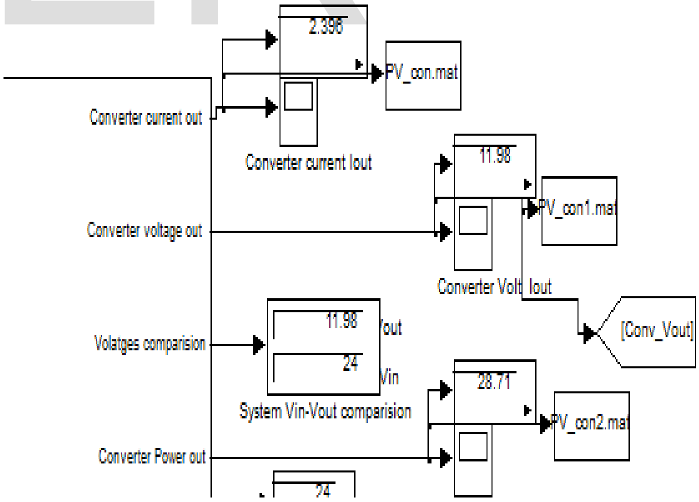

Figure 19(c) The converter output current of *2.396 A*

3 Conclusions

Modeling, simulation and dynamics analysis issues on PhotoVoltaic Panel-Converter (PVPC) system are proposed, developed and tested. using different approaches, both subsystems are mathematically modeled and corresponding Simulink models are developed, then is developed generalized PVPC system Simulink model that allows designer to have the maximum output data to design, tested and analyze the PVPC system for desired overall and either subsystem's outputs under various PV system operating conditions, to meet particular Mechatronics design of solar electric application requirements. Mathematical and Simulink models of both subsystems and overall system were derived, developed and tested in MATLAB/Simulink.

As future work, different control approaches (algorithms) are to be selected, designed and integrated with the proposed generalized PVPC system model , then tested, to meet the desired outputs requirements-characteritics based on working operating conditions. A proposed overall system circuit diagram is shown in Figure 1

Table 1 Nomenclature and electric characteristic

Solar cell parameters	
Isc=8.13 A , 2.55 A , 3.8	The short-circuit current, at reference temp 25°C
I A	The PV cell current (*the* PV *module current*)
I_{ph} A	The light-generated *photocurrent* at the nominal condition (25°C and 1000 W/m²),
E_g : =1.1	The band gap energy of the semiconductor
$V_t = KT / q$,	The thermo voltage of cell . For array :($V_t = N_s KT / q$)
I_s A	The reverse saturation current of the diode or leakage current of the diode
Rs=0.001 Ohm	The series resistors of the PV cell, it they may be neglected to simplify the analysis.
Rsh=1000 Ohm	The shunt resistors of the PV cell
V	The voltage across the diode, output
q=1.6e-19 C	The electron charge
Bo=1000 W/m²	The Sun irradiation
β =B=200 W/m²	The irradiation on the device surface
Ki=0.0017 A/°C	The cell's short circuit current temperature coefficient
Vo= 30.6/50 V	Open circuit voltage
Ns= 48 , 36	Series connections of cells in the given photovoltaic module
Nm= 1 , 30	Parallel connections of cells in the given photovoltaic module
K=1.38e-23 J/oK;	The Boltzmann's constant
N=1.2	The diode ideality factor, takes the value between 1 and 2
T= 50 Kelvin	Working temperature of the *p-n* junction
T_{ref}=273 Kelvin	The nominal reference temperature
Buck converter parameters	
C=300e-6; 40e-6 F	Capacitance
L=225e-6 ; .64e-6 H	Inductance
Rl=RL=7e-3	Inductor series DC resistance
rc= RC=100e-3	Capacitor equivalent series resistance, ESR of C ,
V_{in}= 24 V	Input voltage
R=8.33; 5 Ohm;	Resistance
Ron=1e-3;	Transistor ON resistance
KD=D= 0.5, 0.2,	Duty cycle
Tt=0.1 , 0.005	Low pass Prefilter time constant
V_L	Voltage across inductor
I_C	Current across Capacitor

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