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 presents 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
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 $\beta$, 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].

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the past 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, 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:

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

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

$$I_{ph} = (I_0 + K_r (T - T_{ref})) \frac{\beta}{1000} \quad (2)$$

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 $V=0)=I_{sc}$, at a $T=25^\circ C$ and the solar insolation $\beta=1kW/m^2$, given in datasheet specifications of PV panel.

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

$$I_d = I_i \left( e^{\frac{qV + R_h}{NKT}} - 1 \right) \quad (3)$$

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

$$I = I_{ph} - I_d - I_{RSSH} \quad (4)$$

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 losses, to get a more real behavior and to pick up these characteristics of a practical PV module and real operation circuit model, does not represent actual the I-V simplified exist, this basic Eq. (4) of equivalent circuit model of the PV shown in Figure 3(a), based on this, the derived equations of PVPC system and shown in Figure 4(b), with maximum output data for analysis.

The derived equations of $I_{ph}$, $I_d$, and $I_{RSSH}$, 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 ($\beta$,$T$,$V$,$I$) and two outputs ($V$, $I$), 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)

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

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, $I_{sc} = 1.7 A$, $V_{oc} = 0.587V$, $I_{max} = 1.51 A$, $V_{max} = 0.5 V$, $P_{max} = I_{max} * V_{max} = 0.755$. 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
2.3 Modeling the converter subsystem

Converters can be classified into 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 Cuk, 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):

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

Where: $I_{\text{out}}$ and $I_{\text{in}}$ : 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.

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].
The \textit{refined} dynamics when the switch is ON are derived by the next differential equations:

\[
\frac{di_L}{dt} = \frac{1}{L} (V_{in} - V_o - R_m i_L + R_L i_L), \quad 0 < t < dT, \quad Q : ON
\]

\[
\frac{dv_o}{dt} = (v_o + R_m i_L + R_L i_L + L \frac{di_L}{dt})
\]

Where:

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

\[V_o = \frac{R}{R_C} i_L + \frac{R}{R + R_C} V_C\]

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

\[
\frac{di_L}{dt} = \frac{1}{L} \left[ V_o - \left( R + R_C \right) i_L - R \frac{1}{R + R_C} V_C \right], \quad 0 < t < dT, \quad Q : ON
\]

\[
\frac{dv_o}{dt} = \frac{1}{C} \left[ R \left( i_L - \frac{1}{R + R_C} V_C \right) \right]
\]

\[i_o = i_L, \quad V_o = \frac{R}{R_C} i_L + \frac{R}{R + R_C} V_C\]

The state equation matrices are given as:

\[
\begin{bmatrix}
-L & 0 \\
0 & C
\end{bmatrix}
\begin{bmatrix}
\frac{di_L}{dt} \\
\frac{dv_o}{dt}
\end{bmatrix}
= \begin{bmatrix}
-R_m + R_L + \frac{R}{R_C} \\
R
\end{bmatrix}
\begin{bmatrix}
i_L \\
v_C
\end{bmatrix} + \begin{bmatrix}
0 \\
1
\end{bmatrix} V_o
\]

\[i_o = \begin{bmatrix}
R \\
R + R_C
\end{bmatrix} \begin{bmatrix}
i_L \\
v_C
\end{bmatrix} + \begin{bmatrix}
0 \\
0
\end{bmatrix} V_o
\]

The \textit{simplified} dynamics when the ideal switch is ON are given by Eq.(11)

\[
\frac{di_L}{dt} = \frac{1}{L} (V_{in} - V_o), \quad 0 < t < dT, \quad Q : ON
\]

\[
\frac{dv_o}{dt} = \frac{1}{C} \left( i_L - v_o \right)
\]

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),

\[
\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{in} I_{in}} = \frac{R}{R + R_L + R_{on}}
\]
### 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 $R_{on}$ (or $r_l$), and inductor series resistance $R_c$ (or $r_c$) are not included, a 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 $D = K_v$ as shown in Figure 8(b)), where, the duty cycle of the PWM output will be multiplied with gain $K_v$.

Defining converter parameters to be; $V_n = 24$ V, $R=5$ Ohm; $L=6.4e-6$ 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 $V_n= 24$ V, D=0.5 will return output voltage of 12.05 V.
**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 11(a)**
2.3.1.2.3 Simulation of converter’s moderate accuracy model

Introducing the converter’s capacitor equivalent series resistance $R_C$, (or $r_c$), inductor series resistance $R_L$, (or $r_l$), 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, $D=0.5$, $r_c=100e^{-3}$, $r_l=7e^{-3}$, will return converter output voltage of 12.01 V, and converter output current 0.0549 A.

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 $R_{load}$ 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 $R_{load}$, multiplied by converter output voltage resulting in load current $I_{load}$, which is feedback 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, $D=0.5$, $r_c=100e^{-3}$, Inductor series resistance $r_l=7e^{-3}$, 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.
2.3.1.2.4 Simulation of refined dynamics model

To develop more refined buck converter model, the non-idealities of transistor ON resistance $R_{on}$ (or $r_l$), as well as, Capacitor equivalent series resistance $R_C$ and inductor series resistance $R_L$ (or $r_c$) 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; $V_{in}=24$; $C=300e-6;L=225e-6$; Inductor series resistance $R_L=7e-3$; Capacitor equivalent series resistance $R_C=100e-3;R=8.33$; Transistor ON resistance $R_{on}=1e-3$; $K_{D}=5$, 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](image)

![Figure 14(b buck converter subsystems refined model](image)

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):

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

(17)

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

\[
\begin{align*}
\frac{dv_c}{dt} &= \frac{1}{C} (-\frac{v_c}{R}) \quad \text{for} \quad 0 < t < dT, \quad Q: ON \\
\frac{di_L}{dt} &= \frac{1}{L} (V_{in} - v_c) \quad \text{for} \quad dT < t < T, \quad Q: OFF
\end{align*}
\]

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

\[
\begin{align*}
\frac{dv_c}{dt} &= \frac{1}{C} (-\frac{v_c}{R}) \quad \text{for} \quad 0 < t < dT, \quad Q: ON \\
\frac{di_L}{dt} &= \frac{1}{L} (V_{in} - v_c) \quad \text{for} \quad dT < t < T, \quad Q: OFF
\end{align*}
\]

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)

\[
K_{DC} = \frac{V_{out}}{V_{in}} = \frac{D}{1 - D}
\]

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.

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),
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-I 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 \(\beta\), 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 \((N_s, N_p)\), cell surface area \(A\), at given working conditions including Irradiation \(\beta\), temperature \(T\) and duty cycle \(D\).

Running this model for defined in Table 1 PVPC system parameters including; duty cycle \(D=0.5\), irradiation \(\beta =200\), \(T=50\), \(N_s=48\), \(N_p =30\), cell surface area \(A= 0.0025 \, m^2\), 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 17 (c) Generalized PV-Converter Simulink model

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

Table 2 Simulation results of each subsystem and whole system

<table>
<thead>
<tr>
<th>PVPC system inputs</th>
<th>PV cell outputs</th>
<th>PV Panel outputs</th>
<th>Converter outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ 200</td>
<td>Voltage 0.5 V</td>
<td>Voltage 24 V</td>
<td>Voltage 11.99 V</td>
</tr>
<tr>
<td>$T$ 50</td>
<td>Current 1.438 A</td>
<td>Current 43.134 A</td>
<td>Current 1.439 A</td>
</tr>
<tr>
<td>$D$ 0.5</td>
<td>Fill factor 0.1445</td>
<td>Power out 0.7188</td>
<td>Power out 17.25</td>
</tr>
<tr>
<td>$A$ 0.0025</td>
<td>Power in 0.5</td>
<td>Efficiency 0.6956</td>
<td></td>
</tr>
</tbody>
</table>
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 feedback 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 $R_{load} = 5 \, \text{ohm}$, will result in matching the output load current of 2.396 A, converter's output voltage of 11.99 V, efficiency 0.4999.

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-characteristics based on working operating conditions. A proposed overall system circuit diagram is shown in Figure 1.

Table 1 Nomenclature and electric characteristic

<table>
<thead>
<tr>
<th>Solar cell parameters</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Isc=8.13 A , 2.55 A</td>
<td>The short-circuit current, at reference temp 25°C</td>
</tr>
<tr>
<td>Ipv A</td>
<td>The PV cell current (the PV module current)</td>
</tr>
<tr>
<td>Eg :=1.1</td>
<td>The band gap energy of the semiconductor</td>
</tr>
<tr>
<td>Vth = KT / q</td>
<td>The thermo voltage of cell ; For array : (Vth = NKT / q )</td>
</tr>
<tr>
<td>Ir A</td>
<td>The reverse saturation current of the diode or leakage current of the diode</td>
</tr>
<tr>
<td>Rs=0.001 Ohm</td>
<td>The series resistors of the PV cell, they may be neglected to simplify the analysis.</td>
</tr>
<tr>
<td>Rsh=1000 Ohm</td>
<td>The shunt resistors of the PV cell</td>
</tr>
<tr>
<td>V</td>
<td>The voltage across the diode, output</td>
</tr>
</tbody>
</table>

Buck converter parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=300e-6 ; 40e-6 F</td>
</tr>
<tr>
<td>L=225e-6 ; 64e-6 H</td>
</tr>
<tr>
<td>Rl=RL=7e-3</td>
</tr>
<tr>
<td>rc= RC=100e-3</td>
</tr>
<tr>
<td>Vin= 24 V</td>
</tr>
<tr>
<td>R=8.33; 5 Ohm;</td>
</tr>
<tr>
<td>Ron=1e-3;</td>
</tr>
<tr>
<td>KD=D= 0.5, 0.2,</td>
</tr>
<tr>
<td>Ti=0.1 , 0.005</td>
</tr>
<tr>
<td>Vl</td>
</tr>
<tr>
<td>Ic</td>
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</table>

References


