

# Employing Open Loop Control Model of DC-DC Buck Converter to Supply a Solenoid Coil

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**Abstract**— In this paper an open loop controller model of switch mode DC-DC buck converter category supplied an inductive load is presented. The voltage-mode control scheme of the step down converter worked in continuous conduction mode was illustrated to convert the input voltage level to the specified output voltage level required to energize a specified load consists of solenoid coil with plunger.

The mathematical model of the proposed system has been introduced and the simulation of the controller models have been done using MATLAB/SIMULINK software package to investigate the performance of the open loop control model feeding the solenoid coil. The simulation results show that the capability of applying such model to drive the load at the desired value regardless of unregulated input voltage source. The analysis of the simulation model is carried out and the stabilization of the controller structure is considered for gaining better results.

**Index Terms**— DC-DC buck converter, Controller model, Matlab/Simulink, Solenoid coil.

## I. INTRODUCTION

The DC-DC buck converter is some of the power electronic converter circuits that used to convert the electrical input energy from high level of DC voltage into lower level and regulate the output voltage. This converter has been widely employed in variety of electrical applications such as the power supplies due to maintain the voltage supplied to the load constant with high conversion efficiency [1].

The buck converter is one of the most efficient used step-down converters which provide non-isolated, controlled switch-mode DC-DC fast conversion with the advantages of simplicity and low cost. The electrical circuit of this converter is basically consists of the switching network comprised from (MOSFET) transistor and the diode to chops the input voltage and (LC) network to filter the output signal and produced the average output voltage. A voltage mode controller scheme of this converter in which a pulse width modulated (PWM) signal is used as a control signal and the duty cycle is altered based on error between set voltage and measured output voltage is widely employed in many researches to keep the output voltage at the specified level [2]-[4].

In this work an idle buck converter circuit containing MOSFET and diode as a controllable switches with high switching frequency to obtain the desired level of the output voltage will be employed for feeding the solenoid coil with required electrical energy. The open loop controller structure

of the buck converter with a pulse width modulation (PWM) used to driving the power transistor (MOSFET) have been illustrated in the suggested model.

The solenoid coil can be considered as an inductive load consists of resistance and inductance in series combination .It represents an electromechanical device that contains a movable iron core (plunger) and converts the electrical energy to mechanical output energy. Solenoid valves are widely used in different industrial applications such as hydraulic circuits or pneumatic circuits to control the flow of liquids or gases [5].

The MATLAB/SIMULINK model of the suggested system has been implemented and the results will be displayed to investigate the performance characteristics of the proposed model.

This paper is organized as follows; construction of the employed DC-DC buck converter is given in section 2. Section 3 contains the open loop model of the employed system in addition to the mathematical calculations of the solenoid. Matlab simulation results are obtained in section 4, and the concluding remarks are given in section 5.

## II. THE BUCK CONVERTER CIRCUIT

The ideal buck converter circuit under consideration comprises of power MOSFET, a freewheeling diode (D), an inductor (L) and a filter capacitor(C) as shown in Figure (1). A pulse width modulating signal is applying to the gate of the MOSFET with voltage mode controlled scheme and the ratio of the (ON) time to switching period time of the converter (the duty cycle) has been selected to ensure that the convertor operate in the continuous conduction mode [5].

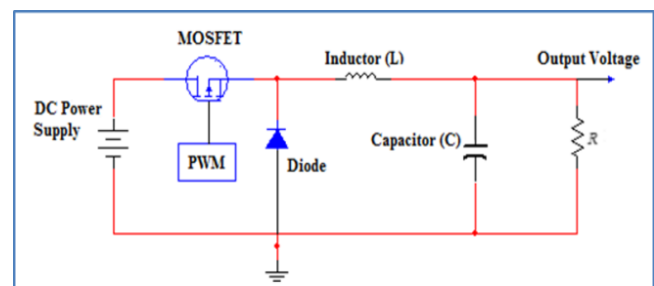


Figure (1) the Schematic Diagram of the Buck Converter.

The buck converter circuit has two states of operation depending on the controllable switch ,when the switch is closed then the buck operates in the (ON) state ,while its operate at (OFF) state when the switch is opened. Conceptually the buck converter circuit can be mathematical represented as two state variables equations as in [6].

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$$\dot{x}_1 = -\frac{1}{L}x_2 + \frac{V_{in}}{L} - \frac{uV_{in}}{L} \quad (1)$$

$$\dot{x}_2 = \frac{1}{C}x_1 - \frac{1}{RC}x_2 \quad (2)$$

$$[I_L \ V_C]^T = [x_1, x_2]^T \quad (3)$$

Where

$V_{in}$  is the input DC voltage.

$V_C$  is the voltage across the capacitor (output voltage).

$I_L$  is the inductor current

$x_1, x_2$  are the state vectors

$$u = \begin{cases} 1 & \text{Switch is OFF} \\ 0 & \text{Switch is ON} \end{cases}$$

To ensure the buck converter operates under continuous conduction mode the minimum value of the inductance of the inductor (L) connected in the buck circuit must be greater than ( $L_{critical}$ ) [7].

Where

$$L_{critical} \geq \frac{(1-D)}{2f_s} \quad (4)$$

At steady-state conditions the duty cycle (D) can be varied from (0 to 100 %), leading to the output voltage level ( $V_o$ ) ranged as ( $V_o = DV_{in}$ ).

### III. THE EMPLOYED CONTROLLER MODEL

The open loop control scheme DC to DC buck converter will be illustrated to regulate the DC voltage source required to energize the solenoid coil with the desired voltage level as shown in figure (2).

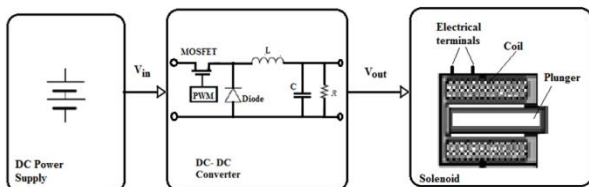


Figure (2) the Employed Controller Model of the Solenoid Coil.

The electrical solenoid consists of a wire wound coil in the form of a cylinder around an iron movable core named as plunger. If the coil energized then magnetic field builds and attracts the plunger. When the electrical current reaches to zero and the coil de-energized, the magnetic field collapses and the plunger returns to its original position. The mathematical model of the solenoid can be represented as series combination of resistance (R) and inductance (L) as shown in figure (3) [5].

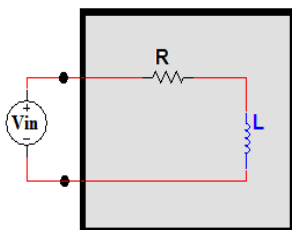


Figure (3) the Equivalent Circuit of the Solenoid Coil.

Hence, the impedance of the solenoid coil can be determined as in equation (5)

$$Z_{sol} = R + jx_L \quad (5)$$

Where

$Z_{sol}$  is the impedance of the solenoid, ( $\Omega$ ).

$R$  is the resistance of the solenoid, ( $\Omega$ ).

$x_L$  is the inductive reactance of the solenoid, ( $\Omega$ ).

The voltage across the solenoid can be determined by applying Kirchhoff's voltage law as following:-

$$V(t) = Ri(t) + L \frac{di(t)}{dt} \quad (6)$$

Taking the Laplace transform for the both side of equation (6), leads to

$$V(s) = R I(s) + L[sI(s) - i(0)] \quad (7)$$

With the initial conditions assumed to be zero, then the transfer function between voltage and current will be

$$\frac{I(s)}{V(s)} = \frac{1}{Ls + R} \quad (8)$$

The selective parameters of the buck converter for driving the suggested load will be listed as shown in table (1), the frequency is chosen as (200 kHz) and switching period equal to (10 $\mu$ sec), The (24V DC) voltage source is used to energize with duty cycle (D=0.5) and the regulated output voltage equal to 12V will be implemented to feed the selective load with resistance (R=4 $\Omega$ ) and inductance (L=0.6H).

Table (1) the Parameters of the Buck Converter.

$V_{in}$ (V)	$V_o$ (V)	$f$ (Hz)	$L$ (H)	$C$ (F)	$D$
24	12	$100 \times 10^3$	$800 \times 10^{-6}$	$400 \times 10^{-6}$	0.5

### IV. SIMULATION AND RESULTS

The Matlab/Simulink model of the proposed controller structure to feed the solenoid coil via the buck converter is depicted as shown in figure (4). The simulation process is done with using the equivalent circuit of the solenoid coil as mentioned previously connected to the buck converter electrical circuit with the specific parameters as listed in table (1).

Firstly 24V DC voltage source is used to supply the converter circuit and a pulse generator model which available in matlab software package is implemented to generate pulse width modulating (PWM) signal applied to the gate of the MOSFET transistor with switching (ON) time period equal to (5 $\mu$ sec) as shown in figure(5). The buck converter circuit will reduce the input voltage and the output voltage supplied to the solenoid coil will become (11.51V) as shown in figures (6).

In the solenoid equivalent circuit the voltage drops across the inductance and the resistance of the solenoid will be as displayed in figures (7) and (8) respectively. Finally the obtained results of the employed Simulink model can be summarized as shown in table (2).

**Table (2) the Results of the Simulink Model.**

Input Voltage (V)	Inductor Current (A)	Capacitor Voltage (V)	Output Current (A)	Solenoid Voltage (V)	Solenoid Current (A)
24	1.038	11.51	0.527	12	0.5257

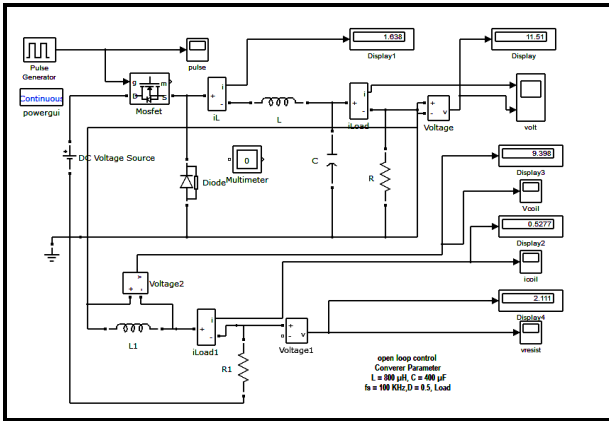


Figure (4) the Simulink Model of the Proposed Buck Converter.

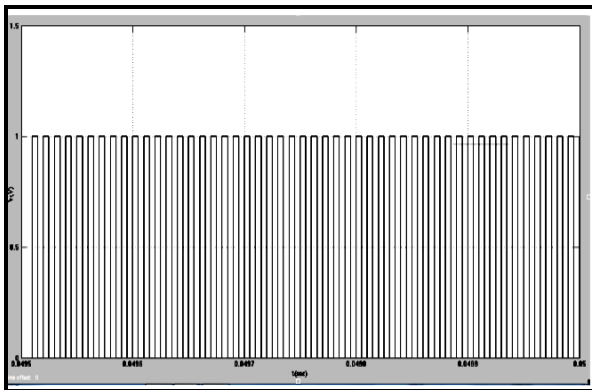


Figure (5) the Pulse Width Modulating Signal.

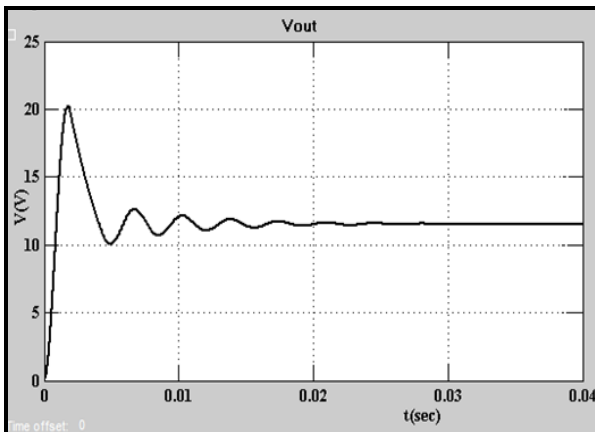


Figure (6) the Voltage across the Solenoid Coil.

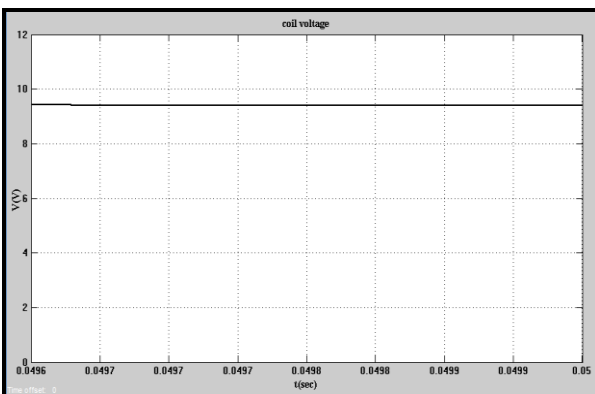


Figure (7) the Inductance Voltage of the Solenoid Coil.

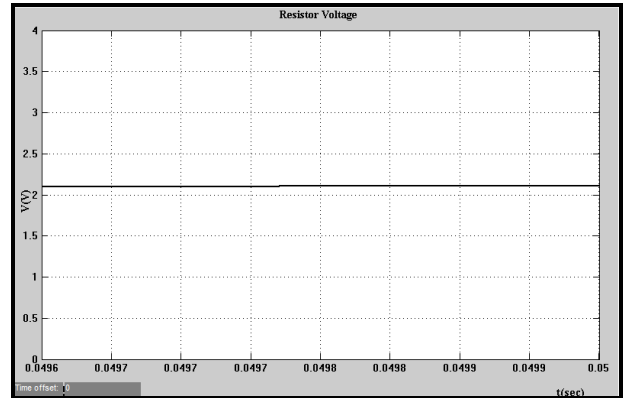


Figure (8) the Resistance Voltage of the Solenoid Coil.

## V. CONCLUSION

In this work an attempt to energized an inductive load such as a solenoid coil has been done through implementation an open loop model of the buck converter, it can be concluded that

- ❖ The required level of the solenoid voltage (12V) can be obtained using the ideal buck DC to DC converter supplied with input voltage (24V) and operates under voltage control mode.
- ❖ The matlab simulation has been done using Matlab/Simulink model and the simulation results show that solenoid voltage reaches the expected value at the end of the simulation process.
- ❖ To improve the dynamic behavior of the DC converter and to achieve a satisfactory output value of the voltage applied to the solenoid despite the changing of the input voltage, a suitable closed loop controller model is needed to realize the better performance of the proposed model.

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