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Modelling and Simulation of Closed Loop Controlled DC-DC Converter Fed Solenoid Coil

Munaf F. Badr

Lecturer, Mechanical Engineering Department, College of Engineering
Al-Mustansiriya University, Baghdad, Iraq

Abstract

In this paper a proposed driving system of the solenoid coil with a step-down DC-DC converter topology is presented. A closed loop model of the switch mode buck converter was illustrated to provide a regulated output voltage to the solenoid coil.

The switching frequency of the converter is set to 100 kHz for faster switching operation and the voltage-mode control scheme involving PID controller has been used to convert the input DC voltage to the specified output voltage.

The simulation has been done using MATLAB/SIMULINK environment to verify the behavior of the controlled model. The obtained results of the simulation show that the accuracy and the precision of the employed model to meet the desired voltage of the solenoid coil.

Keywords: Buck converter, Closed loop controller, Solenoid coil, MATLAB/Simulink.

1. Introduction

The switched mode DC-DC converters are some of the most widely used power electronic circuits which convert one level of electrical voltage into another level by switching action.

These converters have received an increasing deal of interest in many areas of applications due to maintain the voltage supplied to the load constant from no load to full load with high conversion efficiency [1].

Buck converter is one of the simplest but most useful power converters. It is a controlled step-down converter that converts an unregulated dc input voltage to a regulated dc output at a lower voltage [2].

The analysis; control and stabilization of the switching converters are the main factors that need to be considered and a suitable controller structure is always in demand for most industrial and high performance applications. The pulse width modulated (PWM) voltage mode control scheme in which the duty cycle is altered, based on the error between the set voltage and the measured output voltage such that the output voltage of the converter is very nearly equal to the desired value is well documented and widely used[3], [4] & [5].

The main objective in this work is to illustrate a closed loop model of the buck converter to obtain the desired voltage of the DC solenoid coil with high accuracy regardless of unregulated input voltage source. Solenoid is an electromechanical device containing a movable iron core that is activated by a current flow and convert electrical energy into mechanical energy .It is widely used in linear as well as rotary actuations for valves, switches, and relays with variety applications. Solenoid coil consists of copper wire (or aluminum) wound around a hollow form. It behaves like an electromagnet, when electric current flows through the coil; a magnetic field is created [6].

Simulation of the buck converter model associated with controller is carried out via MATLAB/SIMULINK program to investigate the performance characteristics and to display the results.

This paper is organized as follows; implementation of DC-DC buck converter is given in section 2. Section 3 describes the closed loop controller model of the employed converter. MATLAB/SIMULINK model and the simulation results are obtained in section 4, followed by concluding remarks that given in section 5.

2. Implementation of the Buck Converter

The idle buck converter configuration comprises of power MOSFET switch, diode, inductor and capacitor was implemented as shown in figure (1). It is presumed that is working in continuous-conduction mode (CCM), and the controllable MOSFET switch is turned (ON) and (OFF) repeatedly by a control signal applied to its gate. An inductor (L) acts as energy storage element that keeps the current flowing while the diode facilitates inductor current wheeling during the (OFF) time of the MOSFET. Filter made of capacitor (*C*) is normally added to the output of the converter to reduce output voltage ripple [5].

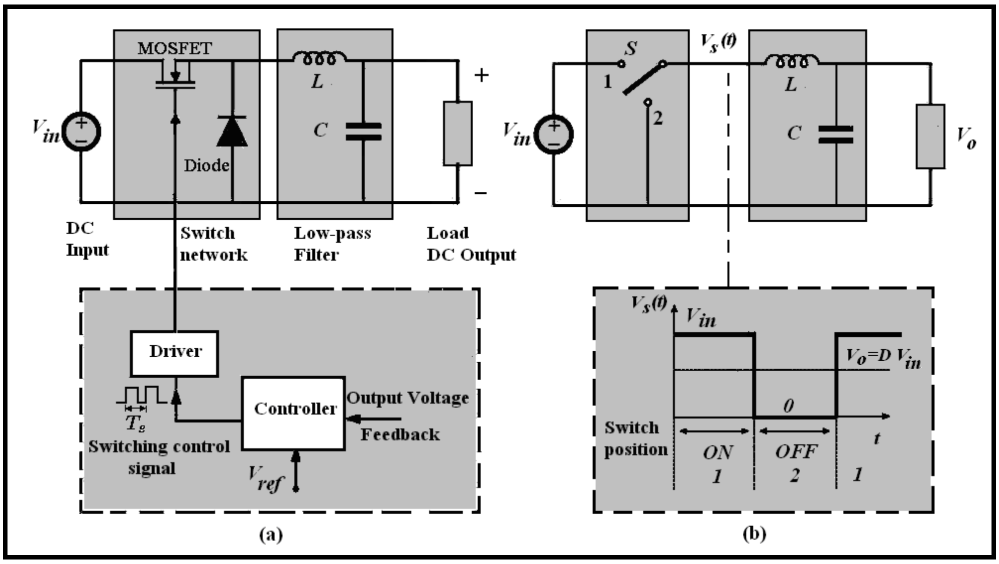


Figure (1) the Schematic Diagram of the Buck Converter.

The state space representation of the buck converter can be described using two state variables, the inductor current (I_L) and the capacitor voltage (V_C) expressed as following [2] & [3]: -

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

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

Where

$[x_1, x_2]^T = [I_L\ V_C]^T$ is the state vector and $d = \begin{cases} 1 & \text{Switch is } OFF \\ 0 & \text{Switch is } ON \end{cases}$

The duty cycle denoted by (D), is expressed as a ratio of the switch (ON) time to the time of one complete switching cycle (T_S).

$$D = \frac{t_{ON}}{T_S} \tag{3}$$

Under steady-state conditions, the duty cycle can be varied from (0 to 100 %), this means that the output voltage (V_o) ranges from (0 to V_{in}), hence

$$V_o = DV_{in} \tag{4}$$

3. Controller Model

The proposed closed-loop model of the converter for energizing the DC solenoid coil under consideration is shown in figure (2). It is essentially consisting of unregulated DC voltage source, DC-DC buck converter, voltage controller and pulse width modulator (PWM) model. The voltage mode controlled scheme of the converter in continuous conduction mode is implemented and a combined proportional-integral-derivative (PID) controller is incorporated in the system to obtain the required characteristics.

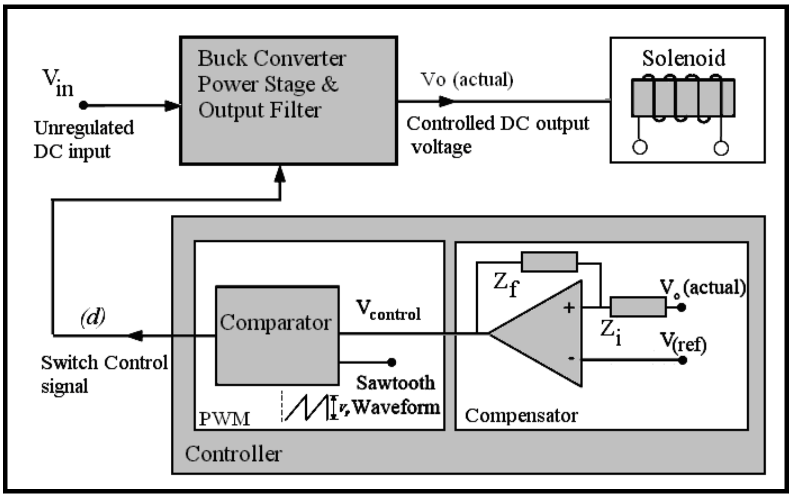


Figure (2).the Proposed Control Diagram of the Solenoid Coil.

As shown in figure (2) the converter's output voltage (V_O) is compared with a reference voltage (V_{ref}) via compensation circuit to generate the error voltage signal (V_{error}). The (PWM) unit converts the error voltage into the clocking signal (*d*) with duty cycle for control the switching converter. The duty cycle is adjusted based on the error signal to make the output voltage follow the reference value and varied the output voltage to a fixed voltage level.

The averaged small-signal model of the idle buck converter in the closed loop configuration consists of two transfer functions, *Gvd(s)* and *Gvi(s)* as shown in figure (3). *Gvd(s)* models the influence of the duty cycle on the output, and *Gvi(s)* models the influence of the input voltage on the output [5].

The control-to-output transfer function *Gvd(s)* of idle buck converter is utilized to design the employed controller and described as in equation (5).

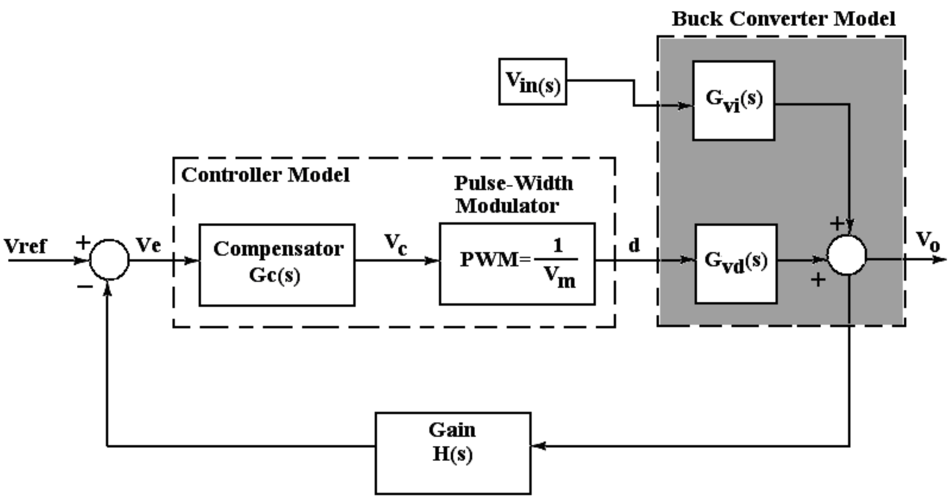


Figure (3) the Transfer Functions of the Buck Converter Model.

$$G_{vd}(s) = \left. \frac{\hat{v}_o(s)}{\hat{d}(s)} \right|_{\hat{v}_{in}(s)=0} = \frac{V_{in}}{1 + S\frac{L}{R} + S^2 LC} \quad (5)$$

Where

V_{in} and V_o are the input and output voltages respectively.

$\hat{v}_o(s), \hat{v}_{in}(s)$ and $\hat{d}\,(s)$ are the small variations of the output voltage, input voltage and duty cycle, respectively.

The regulation of the output voltage is achieved through a compensator constructed from an op-amp with appropriate values of resistors and capacitors as shown in figure (4) to realize the desired voltage [4].

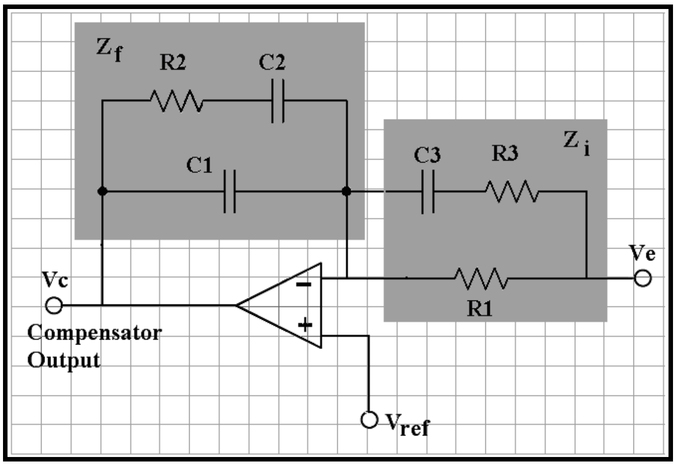


Figure (4) the Compensated Error Amplifier (Type III).

The transfer functions of the compensator *Gc(s)* and the pulse width modulating circuit used to drive the MOSFET switch of the converter are expressed as in equations (6) & (7) respectively.

$$G_C = \frac{V_C}{V_e} = \frac{(1 + sC_1R_2)[(1 + sC_3(R_1 + R_3)]}{[sR_1(C_1 + C_2)](1 + s\frac{C_1C_2R_2}{C_1 + C_2})(1 + sSC_3R_3)} \quad (6)$$

$$T_m = \frac{d(s)}{V_c(s)} = \frac{1}{V_m} \quad (7)$$

Where

V_m represents the maximum value of the sawtooth waveform of the pulse width modulator.

Combining the transfer function of the compensator and the transfer function of the pulse-width modulator, together with buck converter's small signal control-to-output transfer function, then the loop gain of the system is:

$$G_S(s) = G_C(s) * \frac{1}{V_m} * Gvd(s) * H(s) \quad (8)$$

The DC solenoid is the simplest electromagnetic actuator, consists of a stationary iron frame, a coil, and a ferromagnetic plunger in the center of the coil as shown in figure (5).When the coil is energized, a magnetic field is established that provides the force to push or pull the iron core. The solenoid coil can be modeled as an (*RL*) circuit including a resistance in series with an inductance [6] & [7].

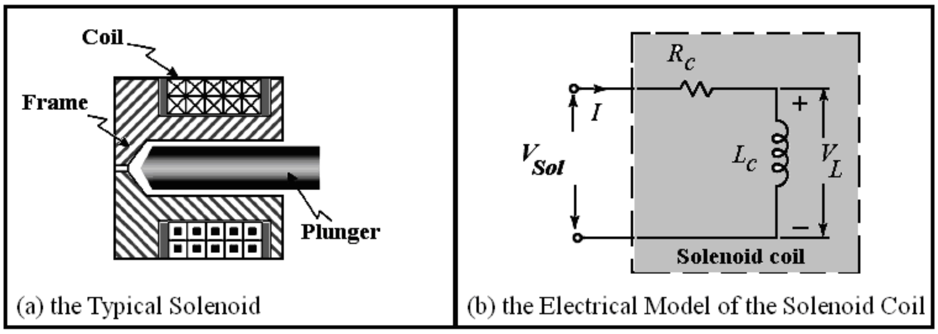


Figure (5) the Solenoid Actuator.

The voltage equation across the solenoid coil (V_{Sol}) can be expressed using Kirchhoff's voltage law; as in equation (10).

$$V_{Sol} = R_C I + V_L \tag{9}$$

Where

L_C is the inductance of solenoid coil.

R_C is the solenoid coil resistance.

4.Simulation

To verify the performance of the proposed closed-loop controller model of the buck converter driving solenoid coil, a computer simulation has been carried out via Matlab/Simulink environment. The simulink model depicted in figure (6) was implemented to emulate the idle (PWM) buck converter; the employed compensators as well as the solenoid coil [8].

To simulate the buck converter in continuous conduction mode, the values of inductance L = 800µH, capacitance C = 1200µF, resistance R = 20Ω with V_{in} = 220V and switching frequency f_s=100 kHz are used. The (ON-OFF) solenoid coil model with specified voltage equal to 12V and electrical parameters as resistance (R_C = 20.9Ω) and inductance (L_C = 10mH) is illustrated in the simulation [9].

A MATLAB m-file script has been written and run to determine the parameters of compensator in order to be used in the Matlab/Simulink model and the results are listed as shown in table (1).The control to output transfer function of the buck converter at the nominal operating points and the corresponding transfer function of the employed compensator can be expressed as in equations (10) & (11) respectively [4].

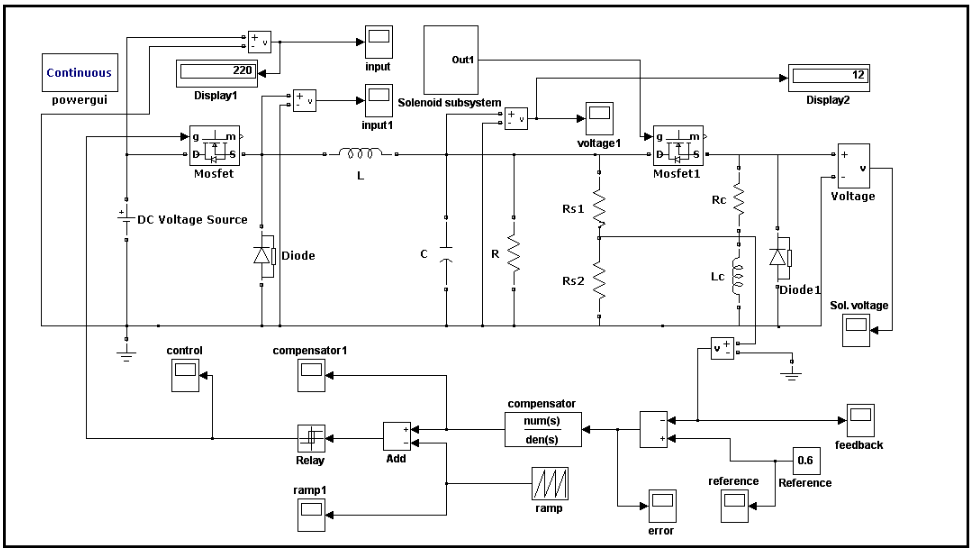


Figure (6) the Proposed Simulink Model of the Controlled Solenoid Coil.

$$G_{vd}(s) = \frac{220}{9.6\times10^{-07}s^2 + 4\times10^{-05}s + 1} \tag{10}$$

$$G_c(s) = \frac{3.843\times10^{-6}s^2 + 0.003921s + 1}{5.377\times10^{-16}s^3 + 6.759\times10^{-10}s^2 + 0.0002124s} \tag{11}$$

The maximum value of the sawtooth wave is taken equal to 3.3V and the feedback attenuator *H(s)* is:-

$$H(s) = \frac{R_{S2}}{R_{S1} + R_{S2}} = \frac{5\times10^3}{95\times10^3 + 5\times10^3} = 0.05 \tag{12}$$

Based on the obtained transfer functions of the proposed controller model, the bode diagrams of the uncompensated and compensated buck converter system are plotted as shown in figure (7) & (8) respectively.

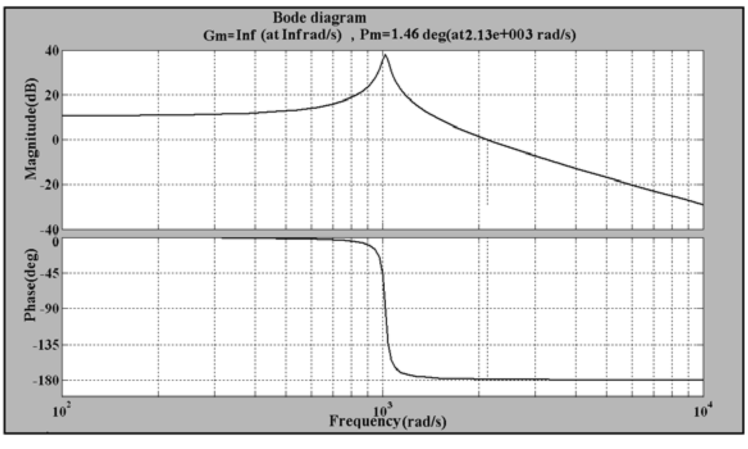


Figure (7) the Bode Plot of the Uncompensated Buck Converter.

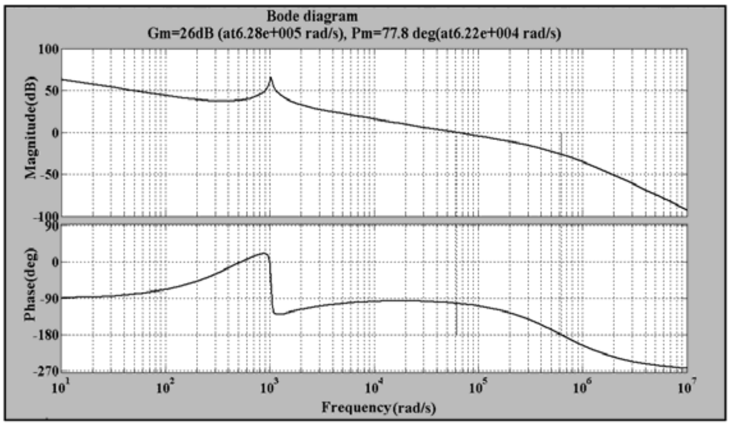


Figure (8) the Bode Plot of the Compensated Buck Converter.

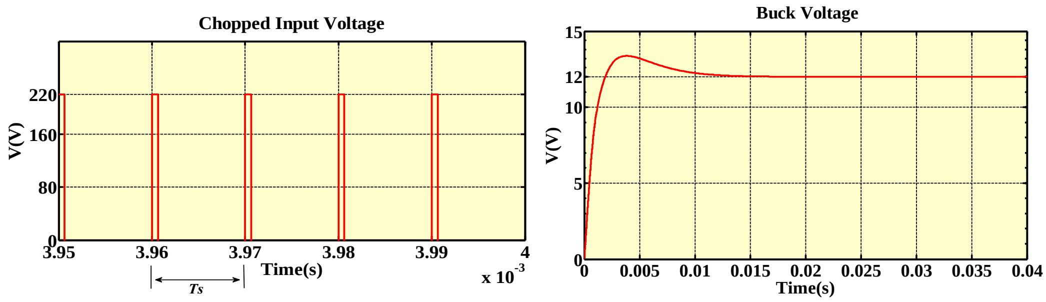
It can been seen from the closed loop bode plot shown in Figure (8) that the phase margin after adding the compensation is improved to 77.8° which is good enough to ensure stability.

Table (1)
the Calculated Parameters of the Compensator.

Item	Parameter	Description	Value	Unit
1	W_O	Angular frequency $W_O = \frac{1}{\sqrt{LC}}$	1.0206×10^3	rad/s
2	W_C	Crossover frequency $W_C = (\frac{2\pi f_s}{10})$	6.283×10^4	rad/s
3	G_C	Magnitude $\lvert G_C(jw_c)\rvert$	1.1367×10^3	
4	A_2	Gain $A_2 = (2\pi f_s)(\frac{1}{W_C})(G_C)$	1.1367×10^4	
5	R_2	Resistance	10	kΩ
6	R_3	Resistance $R_3 = (\frac{R_2}{A_2})$	0.8798	Ω
7	C_1	Capacitance $C_1 = (\frac{2}{W_O R_2})$	0.19596	μF
8	C_2	Capacitance $C_2 = (\frac{1}{2\pi f_s R_2})$	0.15915	pF
9	C_3	Capacitance $C_3 = (\frac{1}{2\pi f_s R_3})$	1.809	µF
10	R_1	Resistance $R_1 = (\frac{2}{W_O C_3})$	1.0832	kΩ

In the employed simulink model the control voltage is applied as a short pulse trains to the MOSFET switch of the buck converter with a switching period (T_S =10µs) and duty cycle (D = 0.0545).

The conducting state of the MOSFET switch has time interval ($T_{ON} = DT_S$), and the filter of the converter sees a square wave between (0V) and (220V) as shown in figure (9a). The output voltage of the buck converter is shown in figure (9b).



(a) **(b)**

Figure (9)

(a-the Chopped Input Voltage. b- the Output Voltage of the Buck Converter)

The value of the output voltage of the buck converter has been reduced via the attenuator *H(s)* and compared with the reference value (V_{ref} = 0.6V) to produce the error voltage (V_{error}) as shown in Figure (10).

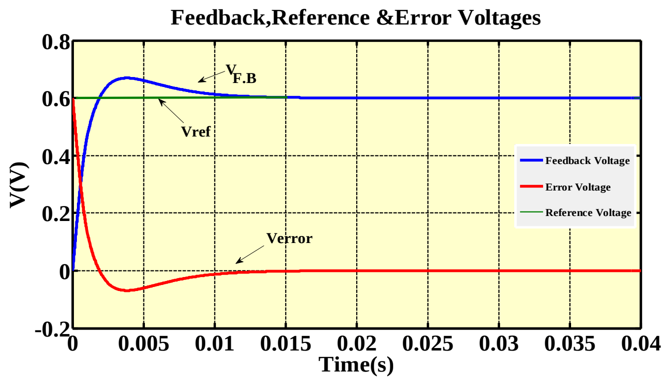


Figure (10) the Response of the Controlled Buck Converter Voltages.

The input voltage (V_{in} = 220V) is reduced to the desired value of the solenoid coil voltage (V_{Sol} =12V) with settling time near to (12 ms) as shown in figure (11).

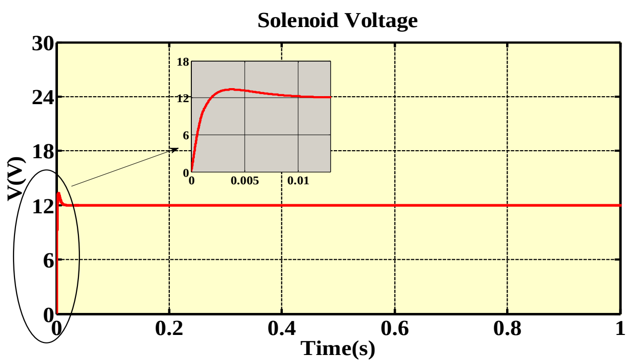


Figure (11) the Response of the Solenoid Coil Voltage.

5. Conclusion

- ❖As concluding remark, an attempt to regulate the DC voltage applied to the solenoid coil via buck converter has been achieved. The heart of this model is the fundamental topology of the switched mode DC-DC buck converter.
- ❖A closed loop (PWM) voltage mode controlled of the buck converter was illustrated. The Compensator was implied to achieve an accurate output voltage and to improve the performance of the system. The parameters of the controller are determined according to the requirements of the (ON/OFF) solenoid coil.
- ❖The simulations were done via MATLAB / SIMULINK and the obtained results are much closed to the particular values. The results show that possibility for future hardware implementation to derive the solenoid coil via buck converter.

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