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Modeling and Control of DC-DC Buck Converter using PEM Fuel Cell

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ABSTRACT- This paper is focused on the comparison with PI and One-Cycle Control methods that are carried out in terms of design and performance for buck converter using PEM Fuel Cell. The conventional PI control method has slow dynamic response to power source confusion. Another modulation technique known as One-Cycle Control overcomes this drawback of PI control and achieves good power source confusion rejection and fast dynamic response. In this study, the system is designed for 40V to 5V DC-DC Buck Converter that is supplied by PEM Fuel Cell. Designed circuits are tested and simulated on MATLAB/Simulink program. The simulation results are ensured to verify conclusion.

Keywords – *Buck Converter, PI Control, OCC, PEM fuel cell*

PEM Yakıt Pili Kullanılarak DC-DC Buck Dönüştürücüsünün Modellenmesi ve Kontrolü

ÖZET- Bu çalışma, PEM Yakıt Pili kullanılarak düşüren-tip dönüştürücüsü için tasarım ve performans açısından PI ve Tek Çevrim Denetleme yöntemlerinin karşılaştırmasına odaklanmıştır. Geleneksel PI kontrol yöntemi, güç kaynağı bozulmalarına karşı yavaş dinamik tepkiye sahiptir. Tek Çevrim denetleme olarak bilinen bir başka modülasyon tekniği, PI kontrolünün bu dezavantajını aşmakta ve iyi bir güç kaynağı bozulumuna karşı etkili ve hızlı dinamik tepkisi elde etmektedir. Bu çalışmada, sistem PEM Yakıt Pili tarafından sağlanan 40V - 5V DC-DC Çevirici için tasarlanmıştır. Tasarlanan devreler MATLAB / Simulink programında test edilip benzetim çalışması yapılmıştır. Simülasyon sonuçları elde edilen sonucun doğrulanmasını sağlanmaktadır.

Anahtar Kelimeler: *Düşüren tip dönüştürücü, PI kontrol, OCC, PEM yakıt pili*

1. Introduction

Nowadays, power electronic converters are playing a crucial role in electrical engineering from the generation to the utilization of electrical power. DC-DC buck converters are widely used in industrial applications. Therefore, a lot of control methods are performed on buck converter (step-down converter). In this paper, PI controlled Buck Converter and One-Cycle Control (OCC) of Buck Converter are examined on different ways (Umar Baki, 2008).

PI controlled converters are named with the Proportional (P) and Integral (I) control types they have. They are used in most process control of applications in industry. PI controlled converters can be used to regulate flow, voltage, current, temperature, pressure level and many other variables of industrial process.

OCC method is a nonlinear control technique that has advantage of the pulsed and nonlinear nature of the switching converters and provides instantaneous dynamic control of the mean value of the switched variable. In more circumstance, this method takes only one switching cycle for the mean value of the switched variable to reach a new steady-state value after a transient state. There is no steady-state and dynamic error between the reference value and the average value of the switched variable. This method supplies robust performance, fast dynamic response and automatic switching error correction. Recently, it has been used in dc-dc converters, power amplifiers, power factor correction circuits, active power filters and multi-input converters (Binitha and Kumar, 2013).

2. Material and Methods

2.1. The Circuit Description and Operation of Buck Converter

In Figure 1, the basic circuit configuration of buck converter is shown and used as an model to study the attributes of control methods will be mentioned before.

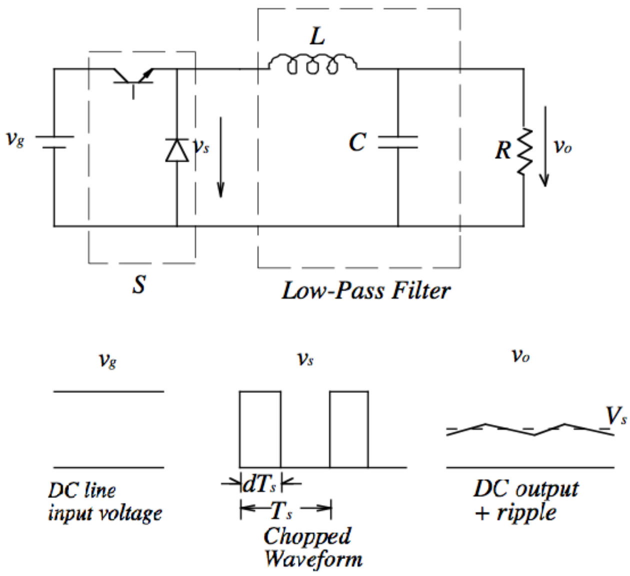

Figure 1. *The Topology of Buck Converter*

The DC input voltage is *Vg* that supplies the converter which switch, S is worked with a frequency (fs =1/Ts). When the transistor is in ON state, the diode is in OFF state, and the voltage of diode *Vs* is equal to the input voltage *Vg*. When the transistor is in OFF state, the diode is in ON state, and the voltage of diode *Vs* is equal to zero. The DC input voltage is chopped by the switching result in a chopped waveform *Vs*. The mean value of this signal is *Vs*.

$$Vs = Vo = \frac{1}{Ts}\int_0^{Ts} Vs\, dt = dV_g$$

The low-pass filter that is shown in Figure 1 transmits the proper value to the output while eliminates the most of unwanted frequencies. Therefore, the output voltage, *Vo* contains the

DC value of *dVg* and a small residual switch ripple. The buck converter has a transformation rate equal to its duty cycle, *d*. The output DC voltage is controlled by duty cycle *d* (Smedley and Cuk, 1995).

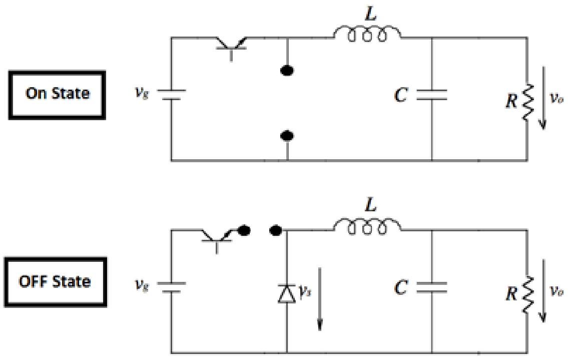

Figure 2. The Circuit of ON and OFF State for Buck Converter

In Table 1, formulas and parameters are given for designed dc-dc buck converter. These parameters are used both uncontrolled and controlled which are PI and One-Cycle Controls, for dc-dc buck converter. Also, controlled buck converter of circuits which are designed with parameters in Table 1, is tested different values of Vg, Vref and R_{load} on the MATLAB/Simulink program.

Table 1. *Design Parameters of Buck Converter*

Vg	12 V
Vout	5 V
Vref	5 V
D = $\frac{Vout}{Vin}$	41.66
C ≥ $\frac{\Delta I}{8 \times F \times \Delta Vo}$	125×10^{-6} F
L = $\frac{Vout \times (Vin - Vout)}{\Delta I \times F \times Vin}$	97.22×10^{-6} H
R(load) = $\frac{Vout}{I}$	1.66 Ω
fs	50 kHz
P	15 W
I	3 A

2.2. The Circuit Description and Operation of PI Control Method for Buck Converter

A PI control method is a control loop operation widely used in industrial process applications. A PI control method attempts to correct the error between a measured sample and a reference set point by calculating and then outputs a corrective action that can adjust the process according to controller. The calculation of PI control method involves two separate parameters, *P* and *I* values. The Proportional value calculates the reaction of the error; the Integral calculates the reaction based on the sum of recent errors.

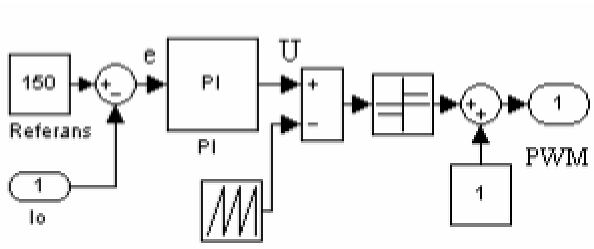

Figure 3. *Block diagram of PI Control Method of Buck Converter (Karaarslan and Iskender, 2005).*

2.2.1. Proportional Term of Control

The P parameter makes a change to the output that is proportional to the current error value. The P response can be adjusted by multiplying the error by a constant Kp, called the proportional gain.

The proportional parameter is given by:

$$Pout = Kp \times e(t)$$

- Pout: Proportional output
- Kp: Proportional gain
- e: Error = Reference-Sampling
- t: Instantaneous time

2.2.2. Integral Term of Control

The addition from the integral term is proportional to both the magnitude of the error and the duration of the error. The summation of instantaneous error over time gives the cumulative offset that should have been corrected previously. The cumulative error is multiplied by the integral gain and implemented to the control block of output. The amplitude of the addictive of the integral term to the overall control process is determined by the integral gain, Ki. The integral parameter is given by:

$$X_{out} = Ki\int_0^t e(\tau)\, d\tau$$

- X_{out}: Integral output
- K_i: Integral Gain, a tuning parameter
- e: Error = Reference-Sampling
- τ: Time in the past subscribe to the integral response

Results of PI control method parameters on the output current are shown in Table 2. (Karaarslan, 2013).

Table 2. *Results of PI controller parameters on the output current*

CL Response	Rise Time	Overshoot	Settling Time	S-S Error
Increase in Kp	Decrease	Increase	Small Change	Decrease
Increase in Ki	Decrease	Increase	Increase	Eliminate

2.3. The Circuit Description and Operation of One-Cycle Control Method for Buck Converter

The idea of OCC is to use an integrator to measure the average value of the diode signal in each cycle and force it to be equal to the reference value. By this simple operation, the input signal to the low pass filter, is controlled so that its average value, i.e. the output of the filter, is equal to the reference value (Rajitha at all, 2013). The output voltage of the buck converter is the mean value of the diode voltage, which is equal to the area of each diode voltage divided by the switching period.

$$Vo = \frac{1}{Ts}\int_0^{Ts} Vs\,dt = \frac{1}{Ts}\int_0^{dTs} Vg\,dt$$

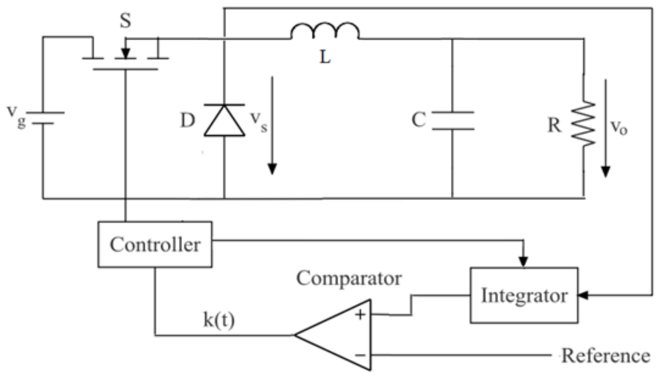

Figure 4. *One Cycle Control Method for Buck Converter Circuit Topology*

In more detail, clock which is worked of constant frequency, simultaneously turns on the MOSFET and activates the integrator at the beginning of each switching period. The voltage of diode is integrated and compared with control reference. The comparator changes its state, when the integrated diode voltage reaches the control reference. As a result the MOSFET is turned off and the integrator is reset to zero.

With this control process, the duty cycle, *d* is determined *by;*

$$\frac{1}{Ts}\int_0^{dTs} Vg\,dt = V_{ref}$$

The duty cycle of the current switching cycle is independent of the state of previous switching cycles. For this reason, the transient of the average value of the switched variable is completed within one switching cycle.

3. Results and Discussion

3.1 . Matlab Simulations and Results of Buck Converter

The designed buck converter circuit with Table 1 parameters under uncontrolled condition is simulated on the MATLAB/Simulink program. Figure 5 gives the schematic of the MATLAB/Simulink program.

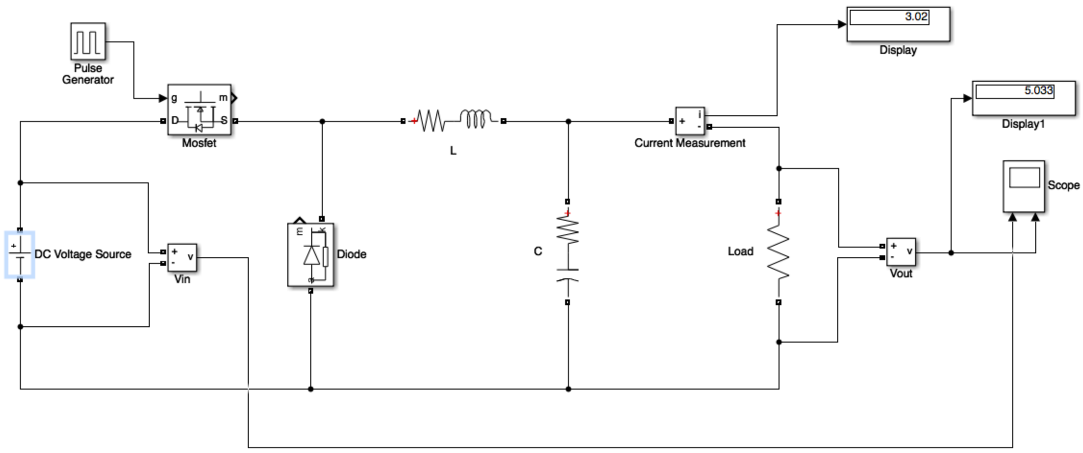

Figure 5. *The Simulation Model of Buck converter*

Figure 6 gives V_{in} and V_{out} scope view by designed buck converter on MATLAB/Simulink program. (V_{in}=12V, V_{out}=5V)

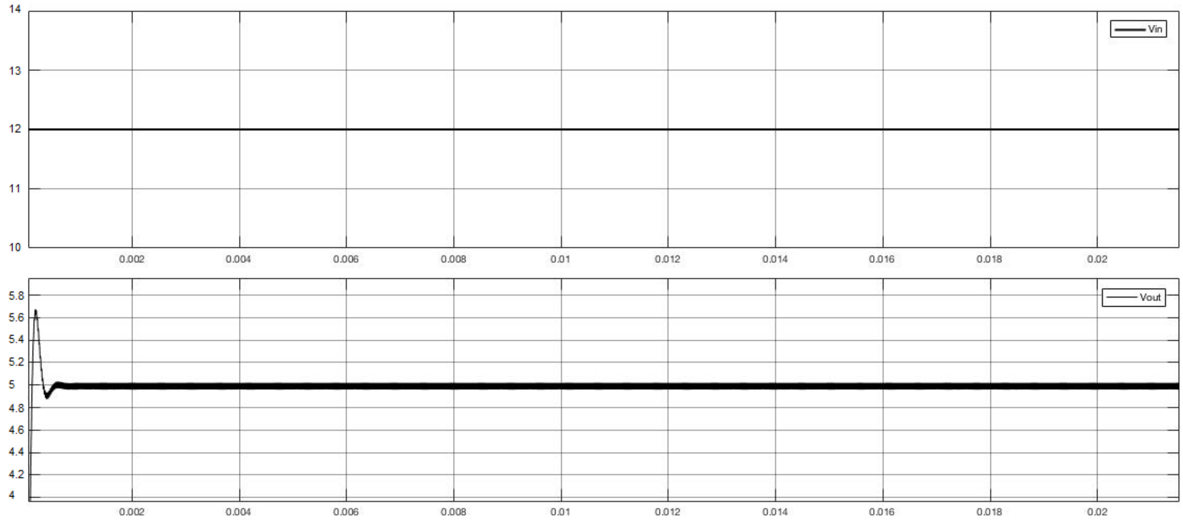

Figure 6. *Waveform of input and output (V_{in}-V_{out}) for Buck Converter*

Table 3. *Measurement of V_{out} for Buck Converter*

Overshoot	16.964 %
Rise Time	59.404 µs
Slew Rate	41.631 (/ms)
Settling Time	1.109

3.2. Matlab Simulations and Results of PI Control Method for Buck Converter

Figure 8 shows the V_{out} and V_{in} scope view by designed PI control method for buck converter on MATLAB/Simulink program. (V_{in}=12V, V_{out}=5V)

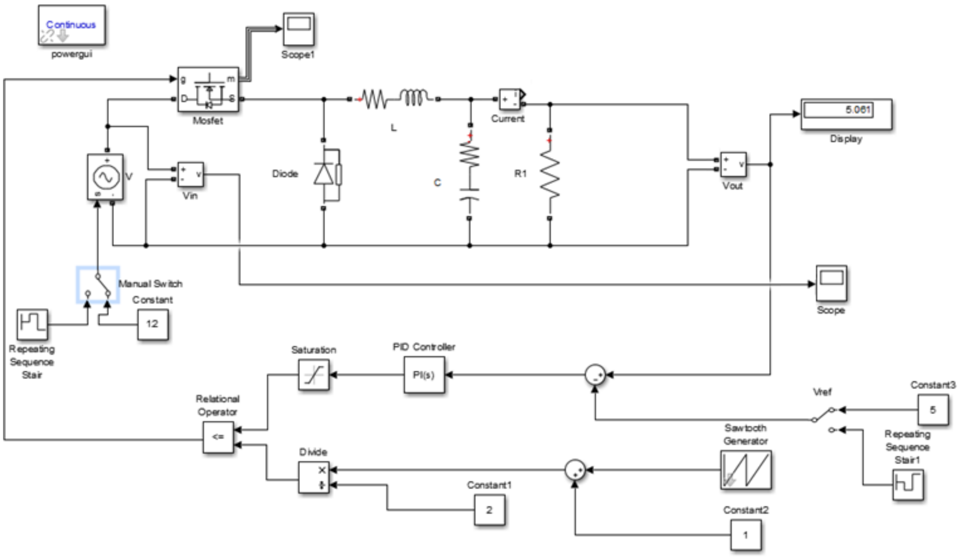

Figure 7. PI Control Method for Buck Converter in MATLAB/Simulink

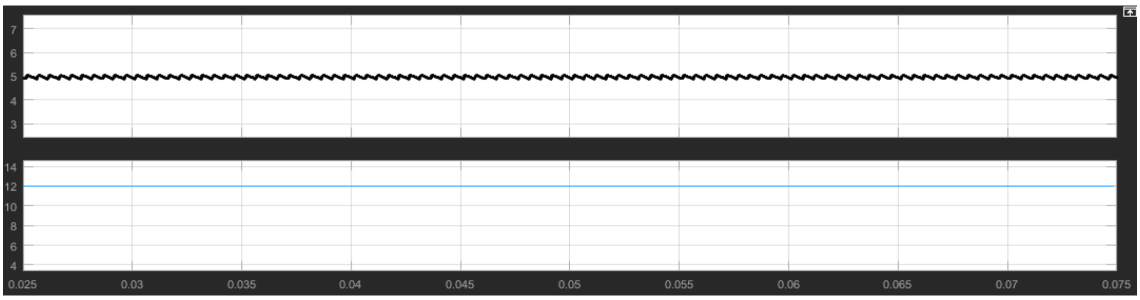

Figure 8. *Waveform of input&output (V_{in}-V_{out}) for PI Control Method for Buck Converter*

Table 4. *Measurement of V_{out} for PI Control Method of The Buck Converter*

Overshoot	3.646 %
Rise Time	223.175 µs
Slew Time	15.156 (/ms)
Settling Time	8.685 ms

The reaction of PI controlled circuit for %50 higher and lower input Voltages are given in Figure 9. It shows the V_{out} and V_{in} scope view by designed PI control method for buck converter on MATLAB/Simulink program with V_{in} voltage for 18V.

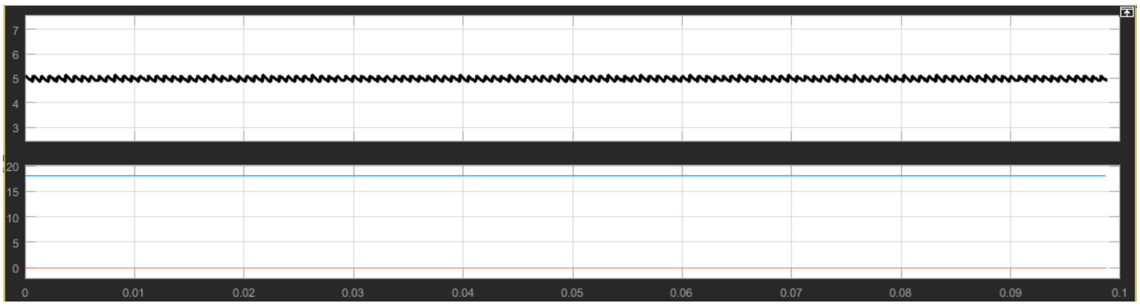

Figure 9. *Waveform of input&output (V_{in}-V_{out}) for Vin = 18V*

Figure 10 shows the V_{out} and V_{in} scope view by designed PI control method for buck converter on MATLAB/Simulink program with V_{in} voltages (6V).

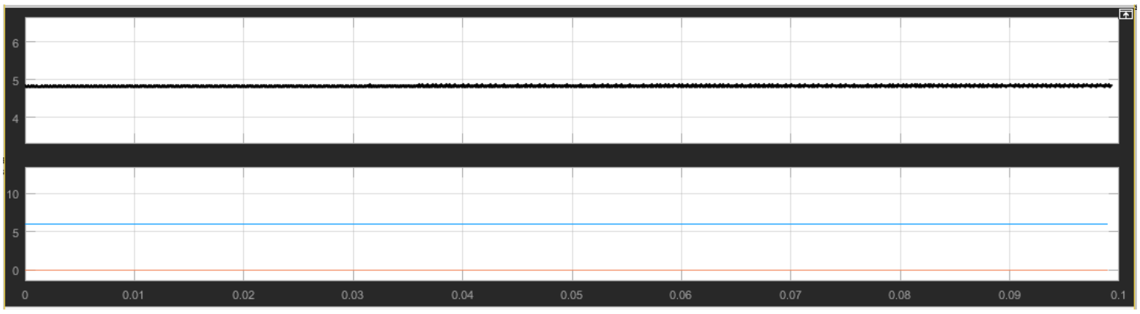

Figure 10. *Waveform of input&output (V_{in}-V_{out}) for Vin Voltages (6V)*

The reaction of PI controlled circuit for %25 higher and lower reference Voltages are given in Figure 11. It shows the V_{out} and V_{ref} scope view by designed one-cycle control method for buck converter on MATLAB/Simulink program with different V_{ref} voltages (5V, 3.75V, 6.25V).

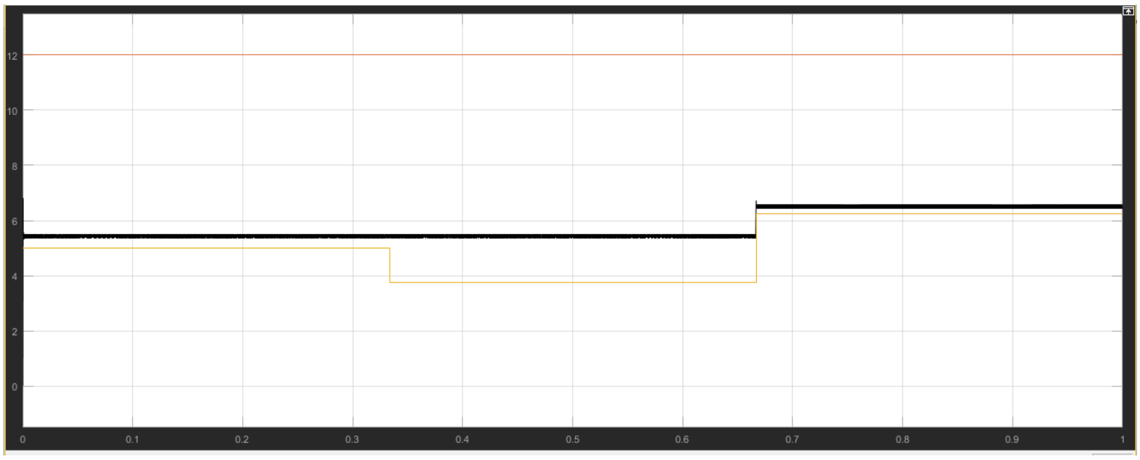

Figure 11. *V_{ref}-V_{out} Scope View for Different V_{ref} (5V, 3.75V, 6.12V)*

3.3. Matlab Simulations and Results of One-Cycle Control Method for Buck Converter

The buck converter circuit is designed by the parameters that are given in Table 1 under one-cycle controlled condition is simulated on the MATLAB/Simulink program. Figure 12 gives the schematic of One-Cycle Control Method for Buck Converter on the MATLAB/Simulink program.

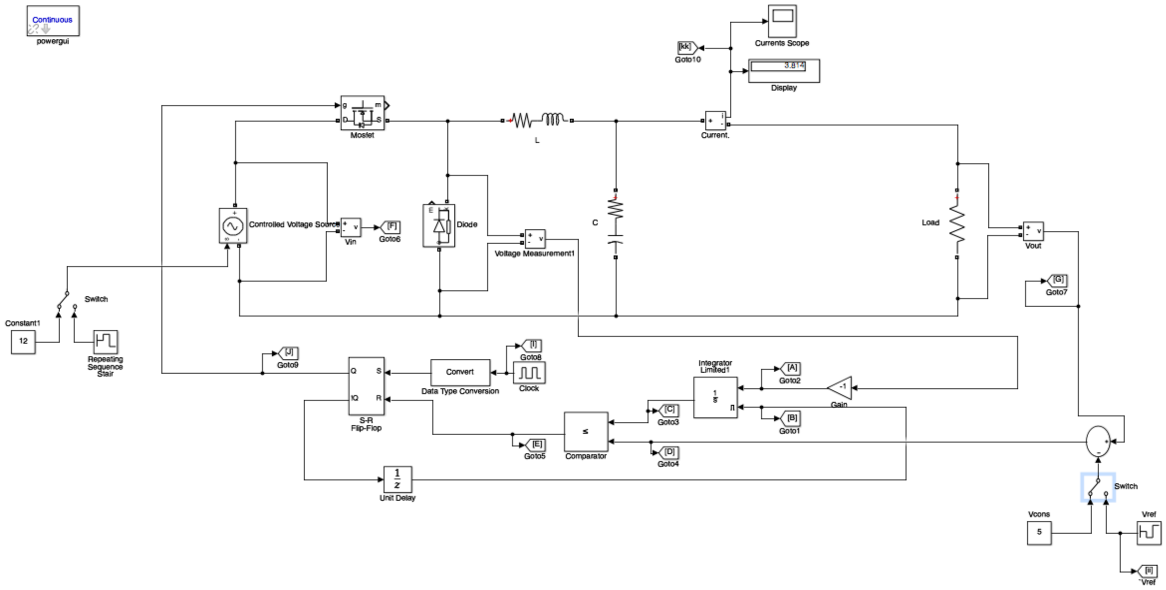

Figure 12. *One Cycle Control Method for Buck Converter in MATLAB/Simulink*

Figure 13 shows the V_{out} and V_{in} scope view by designed one-cycle control method for buck converter on MATLAB/Simulink program. (V_{in}=12V, V_{out}=5V)

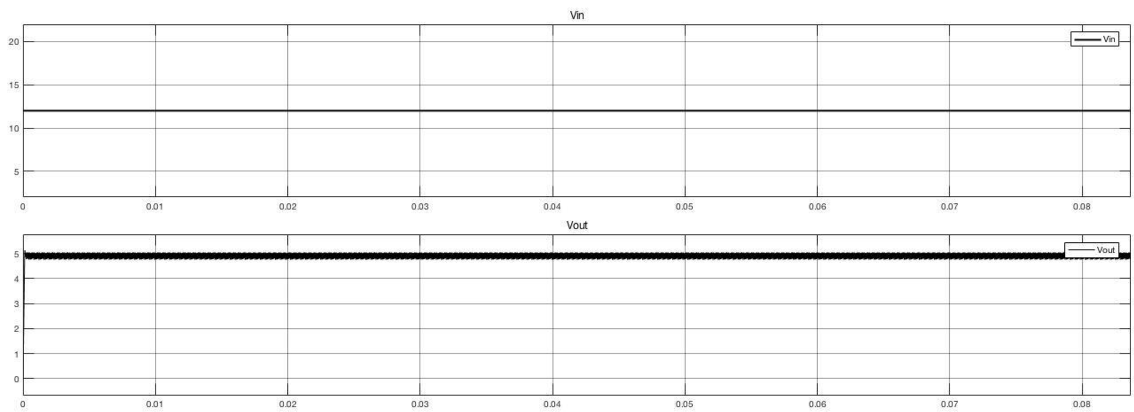

Figure 13. *Waveform of input&output (V_{in}-V_{out}) for One Cycle Control Method for Buck Converter*

Table 5. *Measurement of V_{out} for One-Cycle Control Method of Buck Converter*

Overshoot	3.646 %
Rise Time	97.333 µs
Slew Time	40.441 (/ms)
Settling Time	20.001 ms

Reaction of one cycle controlled buck converter circuit for %50 higher and lower input voltages are given in Figure 14. It shows the V_{out} and V_{in} scope view by designed one-cycle control method for buck converter on MATLAB/Simulink program with different V_{in} voltages (12V 18V 6V).

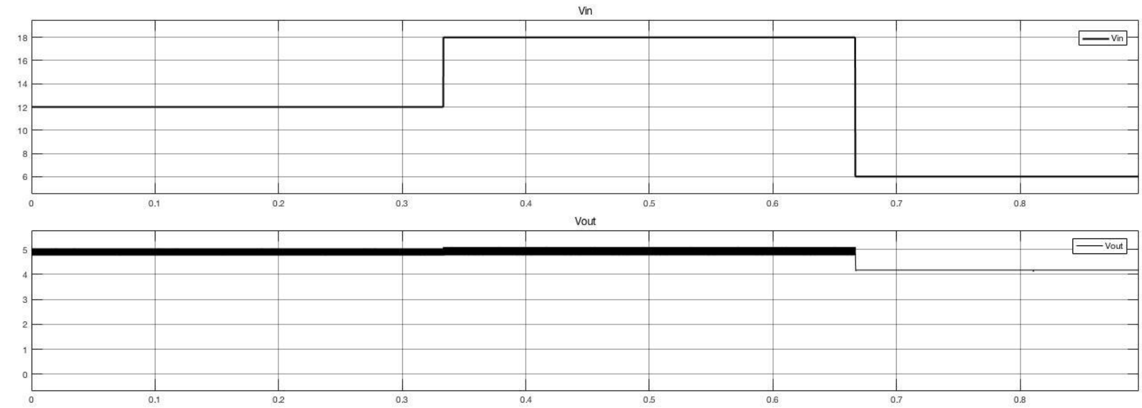

Figure 14. *Waveform of input&output (V_{in}-V_{out}) for Different V_{in} Voltage (12V, 18V, 6V)*

As shown in the Figure 14, circuit gives the different reaction (different waveform of output voltage) for each different input voltages. Easy to see that, when the input voltages %50 higher (18 V), waveform of output voltage has more oscillation. Also, when the input voltage %50 lower (6 V), waveform of output voltage cannot reach the exact reference voltage (6V). In this time, V_{out} voltage is nearly about 4.3 V.

The reaction of one cycle controlled buck converter circuit for %25 higher and lower reference voltages is given in Figure 15 that shows the V_{out} and V_{ref} scope view by designed one-cycle control method for buck converter on MATLAB/Simulink program with different V_{ref} voltages (5V, 3.75V, 6.25V).

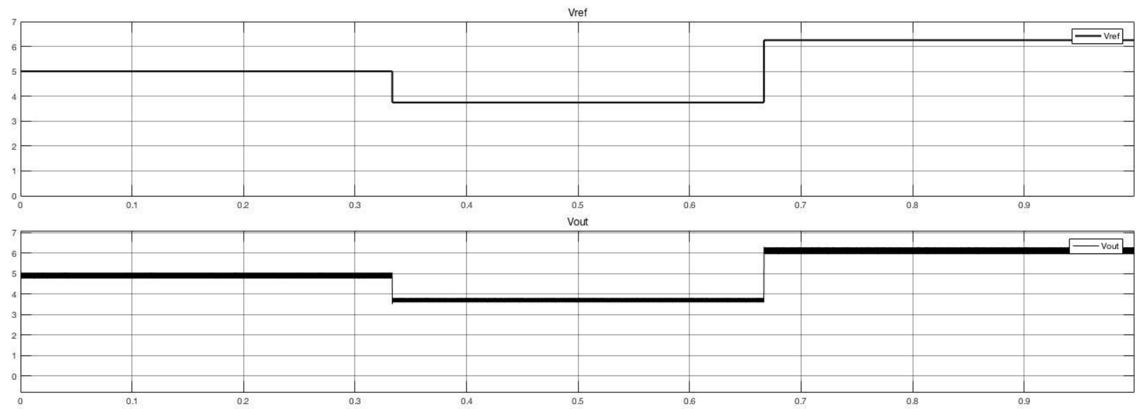

Figure 15. *V_{ref}-V_{out} Scope View for variation of V_{ref} (5V 3.75V 6.25V)*

As shown in the Figure 15, waveform of output voltages is changed by the different reference voltages. The simulation result of controlled circuit shows that circuit can give equal output voltages with the changing reference voltages.

The reaction of one cycle controlled buck converter circuit for %50 higher and lower load is given in Figure 16 that shows the current on the load and V_{out} scope view by designed one-cycle control method for buck converter on Matlab/Simulink program with different load values (R1=1.66 **Ω**, R2=2.49 **Ω**, R3=0.83 **Ω**)

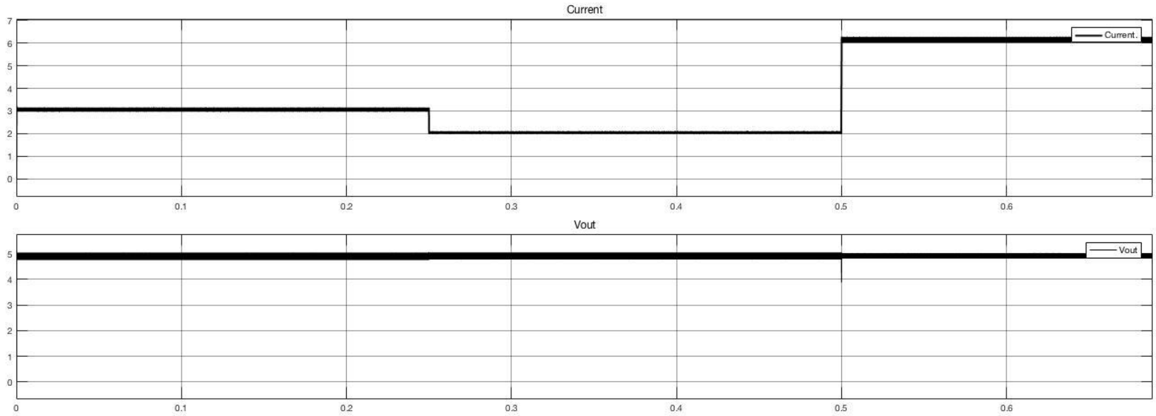

Figure 16. *Output Current-V_{out} scope View for Different Load (R_1=1.66Ω, R_2=2.49Ω, R_3=0.83Ω)*

As shown in Figure 16, current value of load is changed by the different R_{load} values. If the R_{load} is changed, current value of load must be changed when V_{out} is always equal to 12 V. The simulation result of one-cycle control method for buck converter circuit gives the same results with theoretical results.

4. Conclusion

In this study, PI control and One-Cycle control of DC - DC Buck converter was studied. First of all, we calculated buck converter circuit parameters and then created PI control of buck converter and One-cycle control of buck converter circuit in MATLAB/Simulink. The output voltages were tested according to the input voltage; reference voltage and R_{load} changes. The output voltage response in PI control is faster than One-Cycle control. The results show that both of control system suitable for buck converter.

Table 6. *The measurement of V_{out} waveform for Uncontrolled, PI Controlled and OCC Controlled of Buck Converter*

	Uncontrolled	PI Controlled	OCC Controlled
Overshoot Percentage	16.964 %	57.937 %	3.646 %
Rise Time	59.404 μs	76.403 μs	97.333 μs
Slew Rate	41.631 (/ms)	53.017 (/ms)	40.441 (/ms)
Settling Time	1.109 ms	679.152 ms	20.001 ms

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