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The Analysis of OCC and PI Control Method for Isolated Fly-Back Converter using PEM Fuel Cells

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ABSTRACT: In this study, PI control and One Cycle Control techniques of Fly-Back Converter has been analyzed using PEM Fuel Cell. Fly-back converter is the most commonly used SMPS circuit for power applications where the output voltage needs to be isolated from the input main supply. Fly-back converters can both step-up and step-down the input voltage. These converters have been used various fields due to their properties of simply design and low cost especially low input-high output facilities. As Fly-back converters are running, they have to be preserve output voltage values according to not only changes of input and reference voltage also changes of loads values. Generally, there have been more solutions in order to provide constant output voltage. This paper aims at designing of a Fly-Back converter by using PI Control and One Cycle Control (OCC) techniques for constant voltage that is supplied by PEM Fuel Cell. Therefore, system behaviors and simulation results have been explained in this paper.

Keywords – *Fly-back Converter, PI Control, One Cycle Control*

PEM Yakıt Hücreleri Kullanan İzole Fly-Back Dönüştürücünün Tek Döngü ve PI Denetim Metodu Analizi

ÖZET: Bu çalışmada, PEM yakıt pilleri kullanılarak Fly-Back Dönüştürücünün PI denetimi ve tek döngü denetimi teknikleri analiz edilmiştir. Fly-back dönüştürücü, yaygın bir şekilde çıkış geriliminin giriş geriliminden izole edilmesi gereken güç uygulamaları için anahtarlamalı güç kaynağı olarak kullanılmaktadır. Fly-back dönüştürücü, giriş gerilimini yükseltir veya düşürür. Fly-back dönüştürücüler düşük maliyet ve kolay tasarlanma özellikleri sayesinde özellikle düşük giriş yüksek çıkış elde etmek amacıyla birçok alanda kullanılmaktadır. Fly-back dönüştürücüler sadece giriş ve referans gerilim değerinin değişmesi değil aynı zamanda yük değerindeki değişikliklere rağmen çıkış gerilimini değerini sabitler ve korur. Genel itibariyle sabit çıkış gerilimi elde etmek amacıyla birçok çözüm bulunmaktadır. Bu makale, PEM yakıt hücreleri tarafından sağlanan sabit gerilim değerinin PI ve tek döngü denetim teknikleri kullanılarak tasarlanmasını amaçlamaktadır. Sonuç olarak, sistem davranışları ve benzetim sonuçları bu makalede açıklanmaktadır.

Anahtar Kelimeler – *Fly-back dönüştürücü, PI Denetimi, Tek Döngü Denetimi*

1. Introduction

Switched Mode Power Supplies are more popular than power supplies because of their efficiency and costs. SMPSs with high power density, high efficiency and constant operating frequency are preferred in most advanced systems.

A fly-back converter is a switching power supply topology widely used in low power applications such as chargers and PC power supplies. It is basically an implementation of buck-boost converter and has transformer isolation. One of the advantages is it is able to be possible to get multiple outputs by using another secondary winding and extra circuit elements such as filter, diode easily, if necessary. Also, fly-back converter fulfills requirements of many standards for designing of power supplies, since it has natural isolation between input and output. Fly-back converter is the power supply which is generally used when power requirement is low and the isolation between input and output is required. This power supply has simpler design circuitry due to presence of less number of components and no inductor is there in output side. Only one switch is there so its operation is easy to understand and control. It has generally one primary and secondary winding so its transformer design is also simple to design as compared to other SMPS. The circuit can also be build up to have multiple outputs just by increasing the number of secondary windings of transformer.

This converter is mainly of the same kind as that of buck-boost only differing by adding transformer in parallel to the inductor in the buck-boost topology offering the advantage of same polarity output as that of input with either step up, step down or both characteristics simultaneously (Kasundra and Kumar, 2016).

Minimum number of semiconductor and magnetic components, a fly-back converter is a very attractive candidate for off-line low-cost power supplies which require input/output isolation (Panov and Jovanovic, 2002).

Lately, there have been a lot of discussion about electromagnetic compatibility and low voltage applications of electric and electronic devices during their operation so this situation becomes the most important area to overcome harmonics and power losses. For fly-back converter, transformer leakage inductance changing approximately between %2 and %10 and the resonance occurring between inductance and parasitic capacitance of switches which cause large voltage stress with power losses are main disadvantages of decreasing efficiency.

Furthermore, in the case of multiple outputs from a single fly-back converter only, the cross regulation between the multiple transformer secondary windings is seriously affected by these high voltage spikes complicating the construction of dc power supplies with multiple outputs (Papanikolaou and Tatakis, 2004).

In the past several years, non-linear loads (rectifiers, electric drills, UPS, computers, arc furnaces industrial electronic equipment contains of power semiconductors such as thyristor converters, and Inverters) are becoming an important part of the electrical load in industrial and commercial power system (Karaarslan and Ires, 2013).

Advantages and disadvantages of fly-back converters are explained above but in detail, although these converters are used in generally systems which are worked 100W below, their topologies supply to control of motor voltage in electric cars and high speed trains, elevators, monitors for high power solutions commonly.

This paper discusses the design and simulation results of DC-DC Fly-Back converter between using of PI control method and One Cycle Control method for providing constant output voltage. The design has been implemented as changes of input voltage, reference voltage and load values. For voltage sources, the values have been changed both increasing and decreasing 50% of values, on the other hand load has been changed 25% as voltage values. Design and simulation have been applied on SIMULINK to same body and compared to behavior of systems. According to system behavior both related methods have been compared in scope of rise time, settling time and percent overshoot, respectively.

2. Materials and Method

Basic Topology of Fly-Back Converter

It is basically an implementation of buck-boost converter and has transformer isolation (Subramanian et al., 2015). In order to sustain the intended output voltage and control over switch for duty ratio very fast, mosfet is generally used as a switching device in fly-back converter.

Since between input and output voltage and current have requirements, the transformer is used for voltage isolation. The primary and secondary windings of the fly-back do not have synchronization during operation so the current cannot be carried simultaneously and this situation provides that fly-back transformer works differently from a normal transformer. In other words, primary and secondary windings of the fly-back are not able to conduct and they seem to be two coupled inductors magnetically.

In case the secondary winding voltage is rectified and filtered by using a diode and a capacitor solely, the output side of fly-back is simpler than in most other SMPS circuits significantly. The output voltage of fly back converter can be taken from filter capacitor with exception of load.

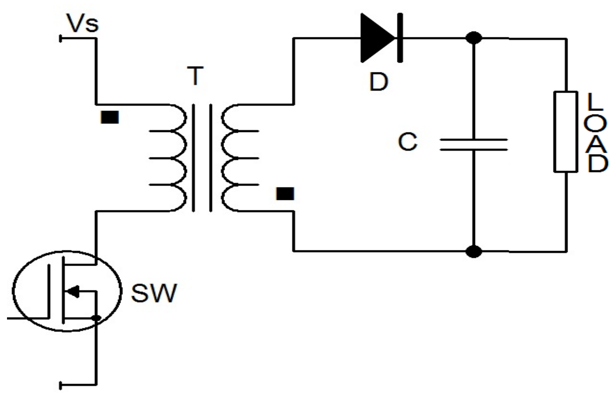

Figure 1: *Fly-back Converter*

Circuit Model and Equations of Fly-Back Converter

The Fly-back converters have to be assessed both in primary sides and secondary sides. The switch modes are given respectively.

Mode 1 (Switch is closed): When switch is on, the primary winding of the transformer is connected to the input voltage source at the same time dotted and positive side. Because of the induced voltage in the secondary which which is dotted and has potential being higher, the diode is connected in series with the secondary winding in reverse biased position Thus, with the turning on of switch, primary winding is able to carry current but current in the secondary winding is blocked due to the reverse biased diode. The flux established in the transformer core and linking the windings is entirely due to the primary winding current (Dogra and Pal, 2014).

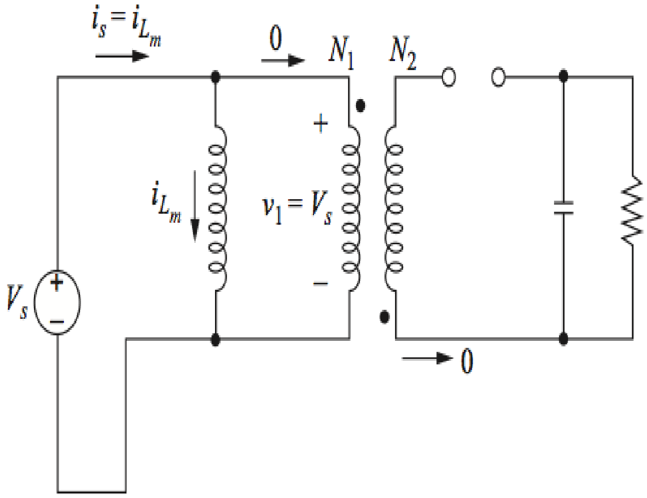

Figure 2: *Mode 1- switch is closed*

$$(\Delta i_{Lm})_{closed} = \frac{V_s DT}{L_m} \tag{1}$$

$$v_{Lm} = V_s \tag{2}$$

$$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0 \tag{3}$$

$$\frac{V_s DT}{L_m} + \frac{-V_o(1-D)T}{L_m}\left(\frac{N_1}{N_2}\right) = 0 \tag{4}$$

$$V_o = V_s\left(\frac{D}{1-D}\right)\left(\frac{N_2}{N_1}\right) \tag{5}$$

Mode 2 (Switch is open): When the switch is opened the primary winding current and magnetic flux are begin to decreasing. The secondary winding voltage becomes positive, the diode gets to forward-biasing position, in that case the current flows from the transformer. Therefore, transformer energy passed on the capacitor and the load.

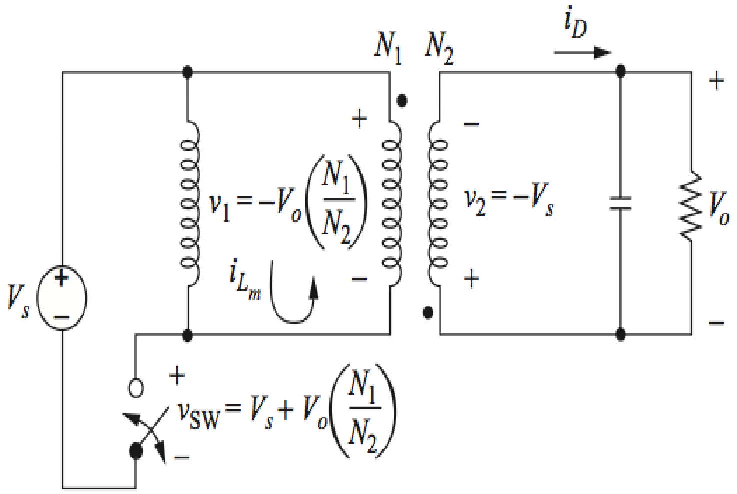

Figure 3: *Mode 2- switch is opened*

$$\left(\Delta i_{Lm}\right)_{open} = \frac{-V_o(1-D)T}{L_m}\left(\frac{N_1}{N_2}\right) \tag{6}$$

$$v_{Lm} = -V_o\left(\frac{N_1}{N_2}\right) \tag{7}$$

Inductor volt-second balanced *(Avarage.inductor voltage = 0)*

$$(DT)V_s - V_o\left(\frac{N_1}{N_2}\right)(1-D)T = 0 \tag{8}$$

$$V_o = V_s\left(\frac{D}{1-D}\right)\left(\frac{N_2}{N_1}\right) \tag{9}$$

Conduction Modes

The energy stored in primary winding is transferred in two modes which are continuous conduction mode (CCM) and discontinuous conduction mode (DCM).

Continuous Conduction Mode (CCM): In this mode, energy cannot be transferred entirely because the energy carries out in the transformer until on cycle position begins. Consequently, the load takes energy which is stated at transformer and the rest of the energy remains in the transformer at the beginning of the next ON cycle.

Discontinuous Conduction Mode (DCM): In this mode, switch is closed and the current passing on the primary winding increase and finally it arrives at peak value having twice or more to CCM peak current. Until switch is opened, energy starts to store in primary winding, at the same time energy storage process is completed. During the switch's OFF period, complete transfer of energy is made, which was stored during the ON-state. The secondary current goes to zero until next the ON-cycle appears (Sucu, 2011).

Fly-back Converter Design

DC-DC isolated converter has been designed according to parameter below. In this framework related converter design has been prepared and controlled two approaches including PI control and OCC. All calculations for related converter has been done based on formula of fly-back converter switching modes. Then, L_m, C_o and R_{Load} has been stated.

Table 1: *Parameters list for Fly-back*

Parameter	Values
Input Voltage (V_{in})	40Vdc
Output voltage(V_o)	400 V
Reference Voltage (V_{ref})	400 V
Duty Cycle	63 %
fs	20 kHz
ΔI_{Li}	Assuming 10% of I_{Li}
ΔV_{Co}	Assuming 5% of V_O
N2/N1=Transformer Ratio	6:1
L_m	20 μH
C_o	25 μF
R_{Load}	320 Ω

3. Results and Discussion

PI Control Method of Fly-Back Converter

According to design parameter, circuit of Fly-back converter has been verified on Simulink. While system is being run, values of V_{in} and R_{Load}, is increased and decreased ratio of 50 %, reference voltage (V_{ref}) ratio of 25 % as well. The output voltage V_{out} and compared with the input voltage V_{ref} . An error signal is produced which is processed through PI controller to generate a control voltage. The control voltage is used to feed to the PWM generator for control of switch. The PI controller has two parameters namely K_P and K_I (Karaarslan and Ires, 2006).

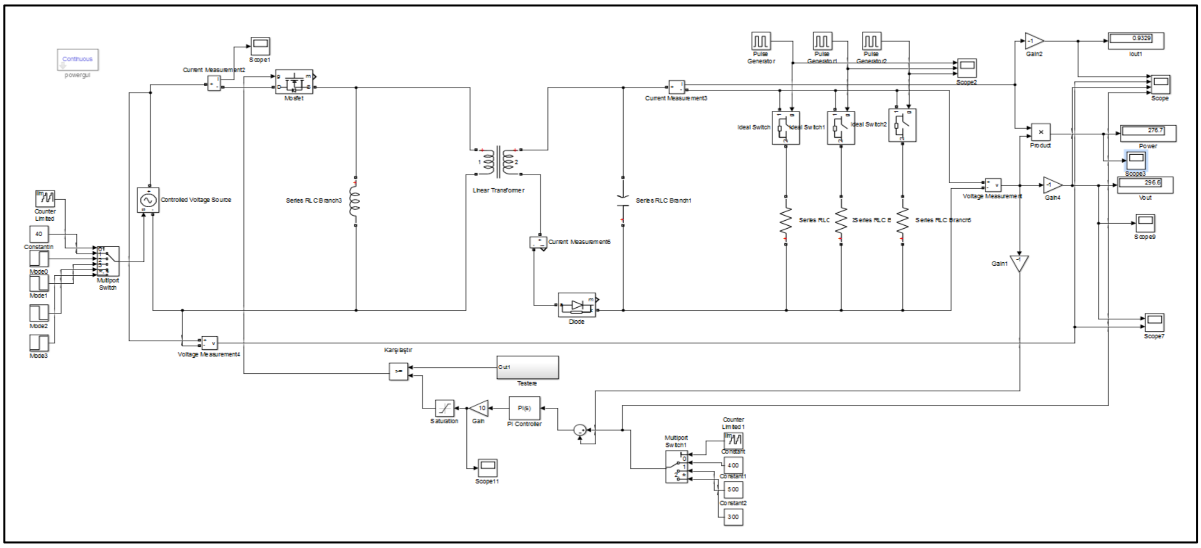

Figure 4: *Simulation model of Fly-back converter for PI Control Method*

Two parameters of PI Controller K_P and K_I has been tunning by using Ziegler-Nichols Theorem and implemented on circuit. Finally the best result has been found for related parameters as K_P= 0.00009 and K_I= 0.009 (Dogra and Pal, 2014). Depends on designing, the circuit has been given negative voltage values since Fly-back has transformer which does not have same side dot. As a result, the current has been changed its way. System has been worked according to design criteria and investigated the system behaviors in scope of changes of V_{in}, V_{ref}, R_{Load}. Therefore, simulation results have been taken from SIMULINK below. V_{in}, V_{ref} has been changed according to stated sampling time- 0.2 sec. Also R_{Load} has been changed in every 0.25 sec.

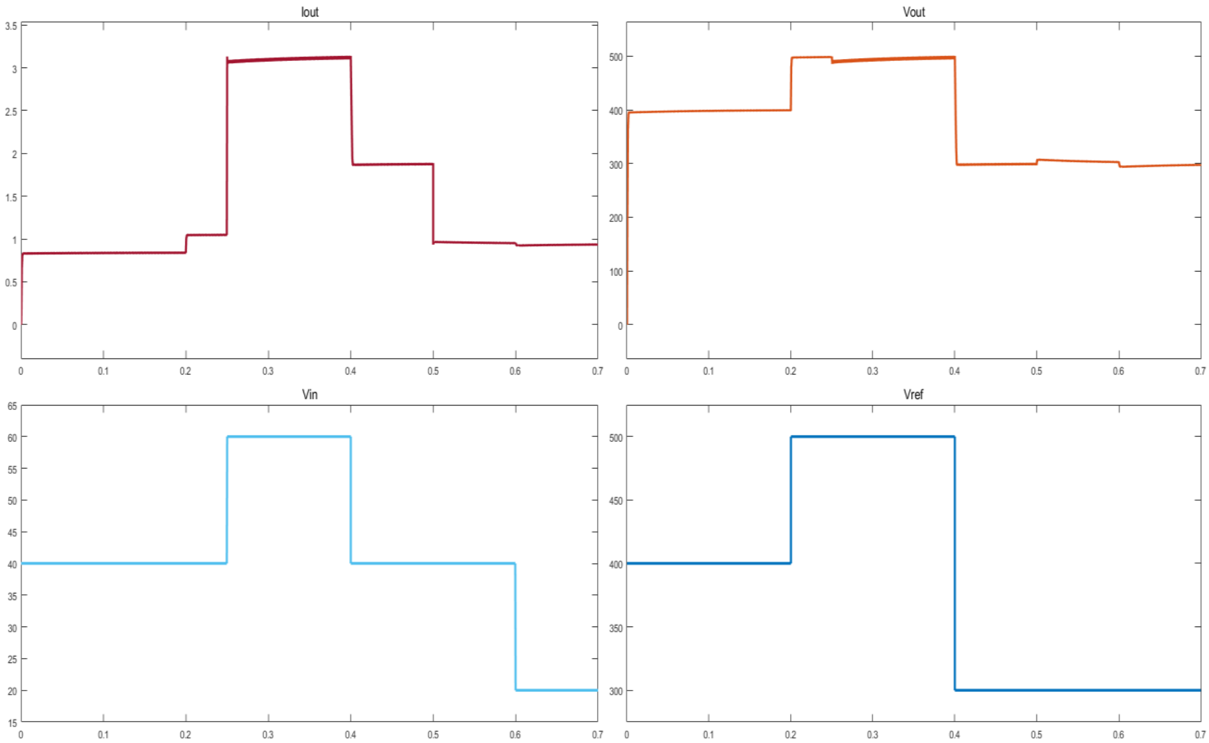

Figure 5: *The waveforms of V_{in} , V_{Ref} I_{out} and V_{out} for PI Control Method*

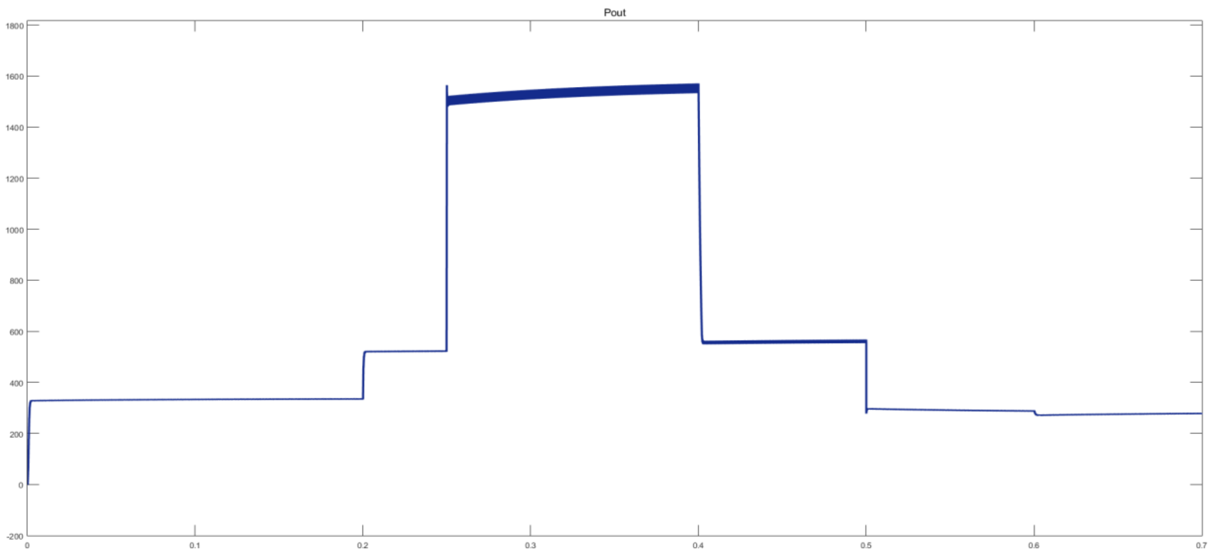

Figure 6: *Output power (P_{out}) waveform of PI Control Method*

OCC Method of Fly-Back Converter

A nonlinear control technique is used to control the duty ratio (T) of a switch in switching converters (Subramanian et al., 2015). OCC control of Fly-back converter circuit has been verified on Simulink. While system is being run, values of V_{in} and R_{Load}, is increased and decreased ratio of 50 %, reference voltage (V_{ref}) is increased and decreased ratio of 25 % as well. V_{out} is compared to input voltage V_{ref} ,by the time, an error signal is produced which is processed through OCC controller to produce a control voltage. On the other hand, the voltage is integrated and then compared with the error signal. The product of this operator and the converted clock signal is sent to flip-flop circuit. After they are compared and processed, the output signal is sent to the Mosfet.

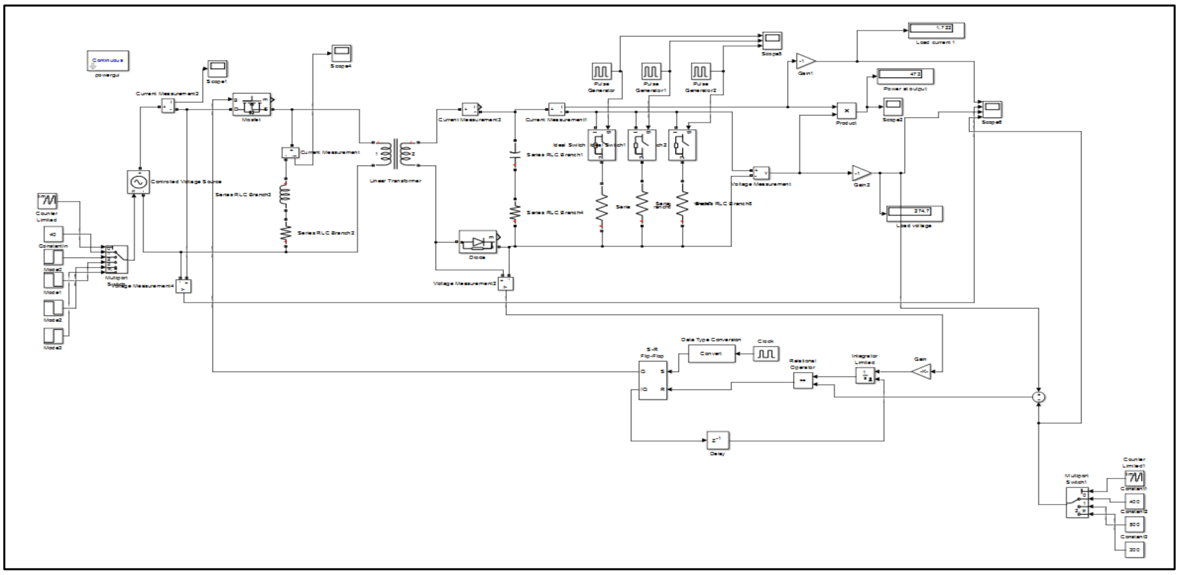

Figure 7: *Simulation model of Fly-back converter for OCC Method*

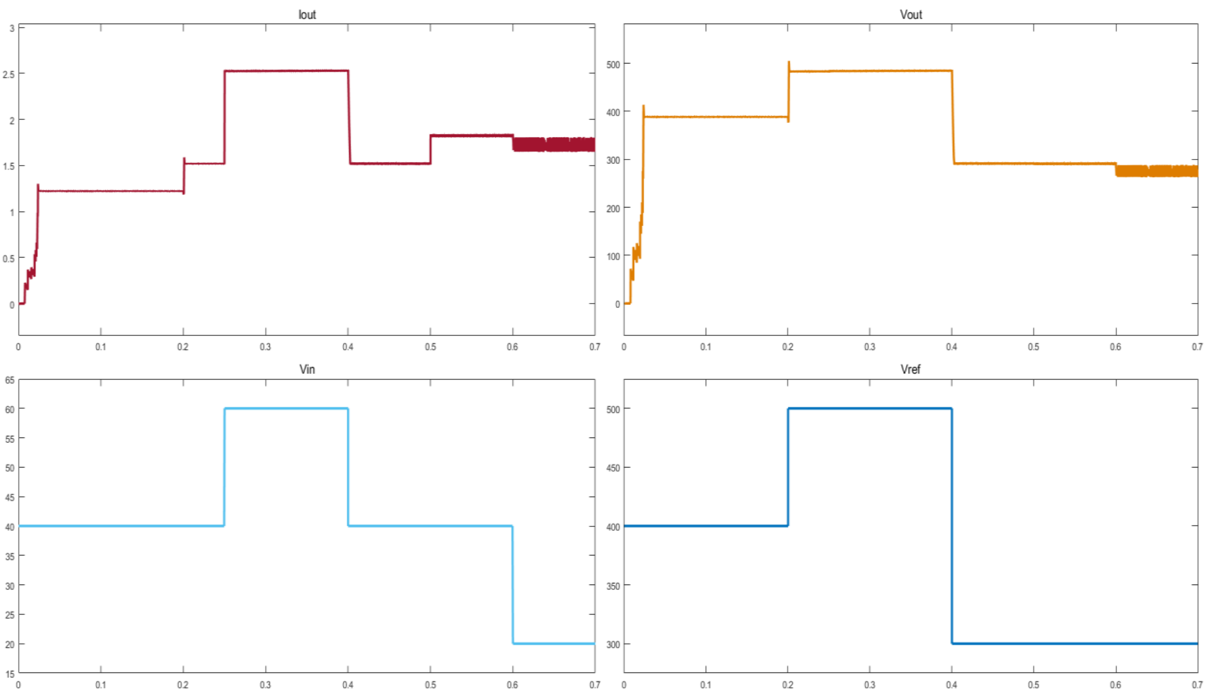

Figure 8: *The waveforms of V_{in}, V_{Ref} I_{out} and V_{out} of OCC Method*

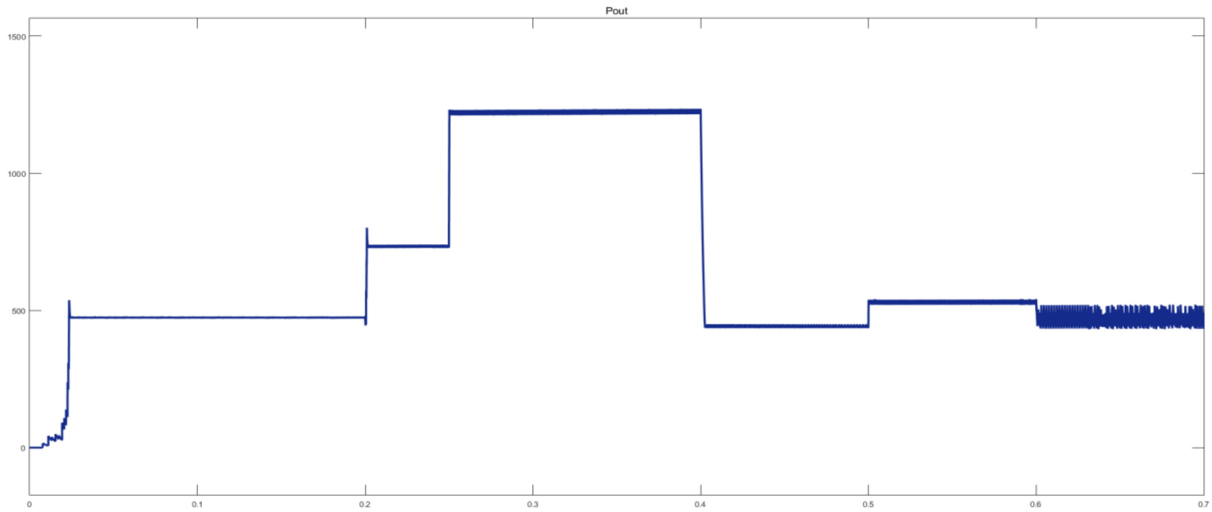

Figure 9: *Output power (Pout) waveform of OCC Method*

PI controller is very sensitive against to changes of the related values so sudden changes have not caused high percent overshoots that is seen above. But when system arrives at steady state position, it runs stable. While maintaining the working of system, the power cannot be constant for 500W in case of changes of loads and system cannot get balanced output power. As the system is being designed, both primary and secondary values of transformer have to be planned within the working field, otherwise, when the V_{in} is given unintended values, transformer is not be saturated.

On the other hand, OCC is very as sensitive as and gives response faster against to changes of the related values so sudden changes cause an ideal percent overshoots that is seen above. But when system arrives at steady state position, it runs stable with some oscillation. Meanwhile even if in this system the V_{out} is provided to constant value, the I_{out} cannot be taken for a while equals to work in DCM. While maintaining the working of system, the power cannot be constant for 500W in case of changes of loads and system cannot get balanced output power. Also OCC system, output power changes, according to the R_{load} values. The current changes depending on the load. As a result, power will be different for different resistor values. In addition, the system supply power in CCM while running.

Table 2: *SIMULINK Results*

Avarage Values for Voltage[1]	**PI**	**OCC**
Rising Time (T_r)	1.09 ms	10.94 ms
Settling Time (T_s)	1.33 ms	2.44 ms
Percent Overshoot (P.O)	2.72 %	12.79 %
Avarage Values for Current[2]	**PI**	**OCC**
Rising Time (T_r)	49.87 ms	0.004 ms
Settling Time (T_s)	-	-
Percent Overshoot (P.O)	2.06 %	16.63 %

[1] Avarage values of output voltage has been read from Simulink.
[2] Avarage values of output current has been read from Simulink.

5. Conclusion

PI control and OCC system has been worked on same parameter. System of OCC has responded very fast compared to PI control. On the other hand, OCC has had little percent overshoot during changes of V_{in}, V_{ref}, R_{Load}. PI control has provided to ideal high rising time and little percent overshoot according to OCC. In order to prevent high percent overshoot, the output capacitor values can be increased but this rise causes to delay response of the system for PI Control method especially. In case, the capacitor has to be optimized to run the system intended time and output values. In general, both system has been conducted the constant output voltage value. In detail, OCC systems have little local oscillation than PI control systems also. In case OCC systems has needed small resistance for arranging the current and voltage ripples the power usage has been started then, but these resistances can be ignored since the system has been accepted to work in ideal conditions and very short time. Therefore, PI control of fly -back converter is suitable way to get intended response and design within low cost as long as the design criteria has been calculated very well.

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