# FOT CONTROLLED BUCK CONVERTER BASED GRID INTEGRATED SCHEME USING PV SYSTEM

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**Abstract**— Variable frequency voltage based control technique which includes constant- on time (COT) and fixed-off time (FOT) are well suited for wide applications which require fast transient response. In this paper the operation of fixed off -time controlled dc-dc buck converter can be studied in three switching states which includes five operating modes. Here the equivalent or effective series resistance is also taken into consideration because the value of ESR should in permissible limits. Generally the value of ESR should lie in the range of 0-1Ω. Due to improper selection of ESR value of the controlled dc-dc buck converter mode shifting criteria takes place which can be further removed by selecting the suitable ratings of load resistance, inductance values. The behavior of this controlled buck converter with a sudden change in load is also exhibited in this paper. The simulation results for different values of inductance (L), load resistance (R) and effective series resistance ESR (r) and a step change in load are depicted which are obtained using MATLAB SOFTWARE. Here we are using this FOT controlled buck converter for photovoltaic energy generation concept which includes the grid connected system. The simulation results of grid connected PV system using FOT controlled dc-dc buck converter are also shown in this paper.

**Keywords**— Equivalent series resistance (r), FOT controlled buck converter, PV energy generation concept

## INTRODUCTION

**A**mong the chopper control techniques variable frequency control technique [1] has fast transient response and the controlling design is also simple and easy. The operation can also be easily understood. So due to the above advantages the variable frequency operation of choppers have gained large popularity which includes constant-on time control technique [2]-[3] and fixed-off time control technique [4]-[5]. When there is a variation in on-time [$T_{on}$] then the off-time [$T_{off}$] is kept constant or fixed and vice-versa. Here in this project we are keeping or maintain the off-time of the dc-dc buck converter to be constant.

Before the operation of fixed-off time dc-dc buck converter the design of filters should be taken into consideration as it plays a vital role in selection of its parameters. Hysteretic control [6]-[7] is also one of the technique among the variable frequency operation technique which have gained more popularity. For the above discussion we can say that the variable frequency control of dc-dc buck converter is quite suitable for its controlling [8]. In this paper we are discussing about the FOT control technique in order to overcome the disadvantages of constant on-time and hysteretic control techniques. The drawbacks of COT and Hysteretic techniques of variable frequency technique were, in COT control the on-time of the switch will be more in which it reduces the life span of the switch and hence the output voltage also decreases than required i.e. the efficiency of the converter will go down. Whereas in case of Hysteretic control it requires two comparators in order to compare the higher level i.e. the output voltage with the lower voltage which is nothing but the reference voltage which increases the cost of the circuit. Therefore, the above limitations are the advantages of the fixed off time buck converter.

From the above discussion it is very clear that we have concentrated more on the variable frequency control technique so we need to know the difference between conventional PWM dc-dc converters and the above mentioned technique. The main difference between them is that the variable frequency control technique depends on the effective series resistance of capacitor output [9] but whereas conventional dc-dc converter does not. During the hardware experiments the value of the ESR of output capacitance should be measured using the ESR meter as it plays a vital role in the circuit. For example if the capacitor with small ESR is chosen such as ceramic capacitor [10] as the output capacitance of buck converter then the inductor current phase may lead behind the phase voltage of output [11]-[12] resulting in the converter to operate in discontinuous mode of operation. All the above discussion is to say that the large ESR of output capacitance is essential to maintain variable frequency controlled buck converter to operate in stable state [5]-[13]. Otherwise the converter operates in unstable state. The above suggestions are very much needed for the design of variable frequency control dc-dc buck converter.

We are also going to discuss about the photovoltaic energy system because our main motive is the grid connected PV system using dc-dc converter. Renewable energy sources play a salient role due to increase of demand for energy. This increase in demand is due to the cause of increase in population. Solar, wind, hydro are the three different types of energy sources which are familiar to the people.

These energy sources do not exhaust. They are pollution free energy sources. Among the above three energy sources we are using the PV energy i.e. Solar energy which depends on the temperature and irradiation of heat. In order to create the interconnection among the PV system and the grid any of the switched mode power circuits need to be developed which is nothing but the fixed off-time controlled buck converter.

## I. VARIABLE FREQUENCY FOT CONTROL FOR BUCK CONVERTER

### A.Circuit Description

The FOT controlled buck converter essentially consists of source voltage $V_s$, power electronic switch S, diode D, inductor L, output capacitance C, output capacitance ESR and load resistance R. All the above elements are similar to that of a normal buck converter except the ESR. In addition to this variable frequency control technique also consists of a comparator which is used to compare the output voltage with the reference voltage in order to provide a gating signal. By fulfilling the above components a circuit is depicted in Fig. 1 [10] and the circuit configurations are as shown in table-1.

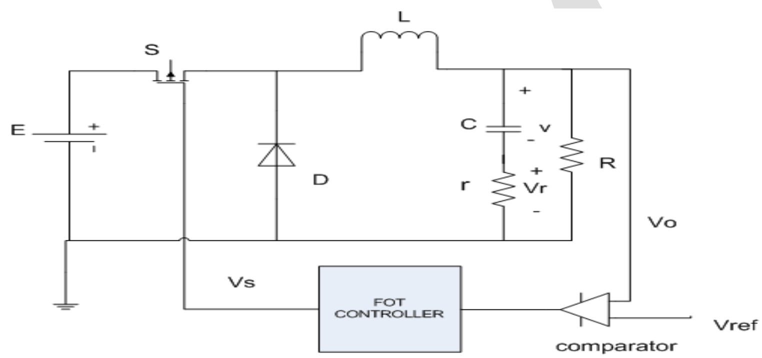


Fig.1 Variable frequency FOT controlled dc-dc buck converter

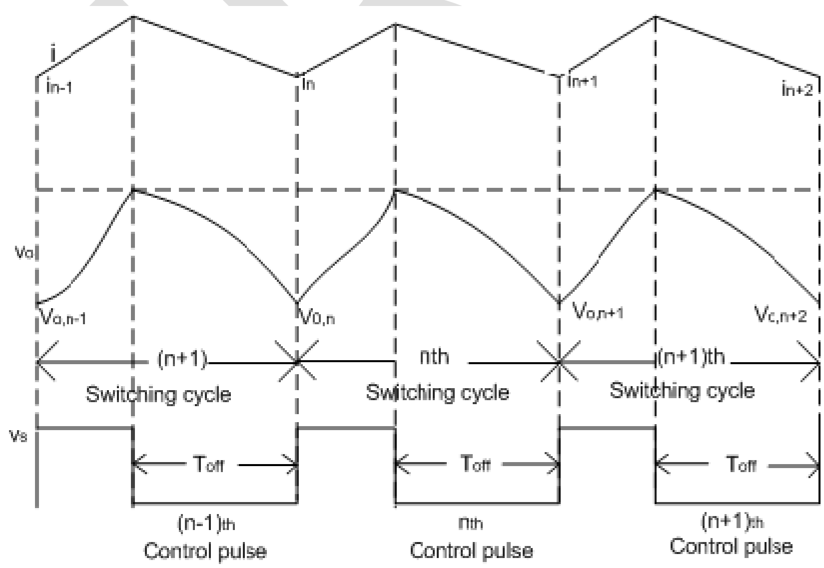


Fig.2 Waveforms of FOT controlled buck converter in continuous conduction mode

The waveforms depicted in Fig. 2 are related to the proposed converter operating in normal state. The operation of FOT controlled buck converter is similar and easily understood as that of the normal buck converter operating in continuous conduction mode. When the ESR of output capacitance is taken into account then the output $V_o$ for the proposed buck converter shown in Fig1 can be derived and written as follows.

$$V_o(t) = r\, i_1 \qquad (1)$$

$$\text{Where } i_1 = i(t) - V_o(t)/R \qquad (2)$$

Now substitute the equation (2 )in equation (1) to obtain the output voltage and is given as

$$V_o(t) = r\,[i(t) - V_o(t)/R] + V(t) \qquad (3)$$

By rearranging equation (3) the output voltage is written as

$$V_o(t) = [r\,i(t)R + V(t)]\,/(R+r)$$

Let $R/(R+r) = k$

Therefore finally $V_o(t) = Hx = k[ri(t) + V(t)]$ (4)

$$H = [kr \;\; k]\;;\; x = [i(t) \;\; V(t)]$$

For the operation of FOT controlled buck converter two conditions should be taken. Such as the value of ESR is small which can be neglected i.e. r =0 then $V_o(t) = V(t)$. This indicates that the output voltage variation is completely dominated by the capacitor voltage resulting in instability. The other case is if the load resistance R = ∞ Ω then the converter operates in discontinuous mode of operation.

**B. Operation Of The Proposed Converter**

The operation of the proposed converter depends upon the state of switch S and the diode D. The operation can be described with three switching states which includes five operating modes. As we are having a comparator in Fig.1 it compares the output voltage with the reference voltage. When the reference voltage $V_{ref}$ is less than $V_o(t)$ the output voltage, then the switch S will be in OFF state $S_{off}$ and diode is in ON state $D_{on}$. During this interval the inductor current $i_L(t)$ discharges through the diode D. When $i_L(t)$ reaches zero then the diode is in OFF state ($D_{off}$) which leads the converter to operate in discontinuous mode of operation. If not, the converter will undergo the CCM operation. Similarly when the output voltage $V_o(t)$ is beneath the reference voltage $V_{ref}$ then the switch will be in ON state and the diode will be in OFF state. Therefore, the switching states of proposed controlled buck converter can be judged as

$$V_o(t) = V_{ref} \text{ or } i(t) = 0$$

Three switching states or conditions are observed in one switching cycle depending upon the state of switch S and diode D. They are

Condition 1: Switch S ON; Diode D OFF

Condition 2: Switch S OFF; Diode D ON

Condition 3: Switch S OFF; Diode D OFF

The main theme of buck converter is to obtain the constant output voltage with the converter operating in CCM. Here in this proposed converter during the mode of CCM the switch conditions 1 and 2 exists which means the condition 3 does not takes place.

Depending upon the conditions of the switch the state space equations of the proposed fixed off-time dc-dc buck converter can be gleaned as follows.

The five operating modes of fixed off-time of variable frequency operation for buck converter were as follows.

Mode 1: During mode 1 the switching state conditions 1 and 2 takes place and the state space equations can be developed from the main equation i.e. equation (5). The waveforms are shown in Fig. 3(a).The output voltage during this mode of operation can be obtained from equation (4) as

$$v_o(t_1) = Hx(t_1) = k\,[v(t_1) + ri(t_1)] = V_{ref} \qquad (6)$$

Mode 2: In this mode of operation all the three switch conditions takes place. Here the current during the time interval $t_2$ is zero as shown in Fig. 3(b) i.e. $i(t_2) = 0$ and the output voltage during this mode of operation can be obtained similar to that of mode1.

Mode 3: Here in this mode of operation only one switch condition takes place which is nothing but the condition 2 which means the switch S is in OFF state and the diode D is in ON state. In this mode of operation the converter under goes the continuous conduction mode as the inductor current (i) is greater than zero as shown in Fig. 3(c). The output voltage during this mode of is

$$v_o(t_3) = i(t_2)T_{off}x_m \qquad (7)$$

Mode 4: During mode 4 the switch conditions 2 and 3 takes place in one cycle of switching. Here in this mode the output voltage is surpassing than the reference voltage and the current and the current i drops to zero as depicted in Fig. 3(d). The output voltage is uttered as

$$v_o(t_4) = i(t_3)\,v_o(t_3)x_m \qquad (8)$$

Mode 5: The switch condition 3 only exits in this mode which means both the diode and the switch are in OFF state. Therefore, the current through the inductor is zero during this mode. The output voltage is as follows and the waveforms were as in Fig. 3(e).

$$v_o(t_5) = i(t_3)T_{off}x_m \qquad (9)$$

The waveforms of variable frequency FOT controlled dc-dc buck converter for different values as tabulated in table-2 which include load resistance (R), inductance (L), effective series resistance (r) are shown in Fig. 6 and also the waveforms for table-3 which include a change in source (E) were depicted in Fig. 7 of section- 3.

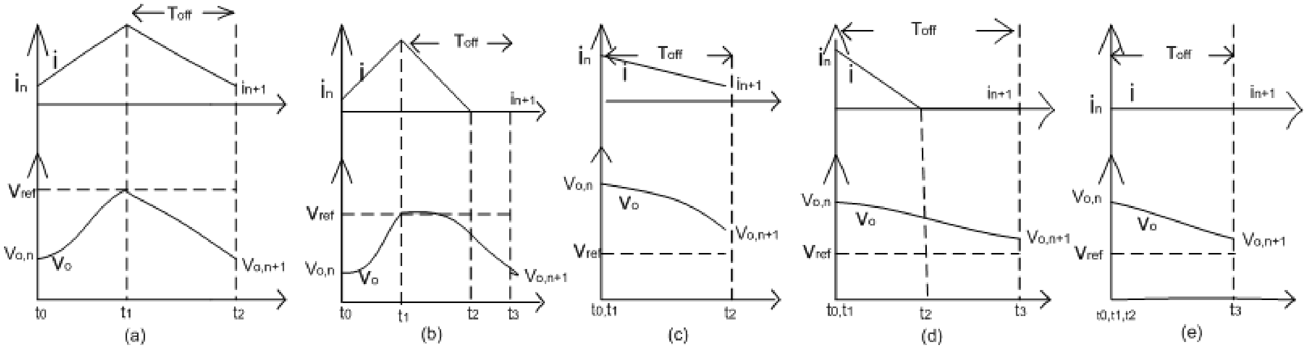


Fig. 3 Modes of operation (a) mode 1: $V_{0,n} \leq V_{ref}$ , i > 0 (b) mode 2: $V_{0,n} \leq V_{ref}$ , i becomes zero (c) mode 3: $V_{0,n} > V_{ref}$ , i > 0 (d) mode 4: $V_{0,n} > V_{ref}$ , i falls to zero (e) mode 5: $V_{0,n} > V_{ref}$ , i equals to zero .

### C. Introduction And Design For ESR Of Output Capacitance

ESR is nothing but the effective or equivalent series resistance of the capacitors. Before going through the operation of converter one need to pay attention towards the ESR of capacitance as it effects the efficiency and usage of power. Among the non-ideal characteristics of a capacitor ESR is one which plays a vital role in the performance of or in the operation of switched mode power electronic converters. A high value of ESR leads to noise, a large voltage drop and $I^2R$ losses. The heat generated due to ESR of capacitance is low in some cases which is not necessary to be taken into consideration. Without knowing the value of ESR if it is used in portable applications then the heat dissipated will be more which leads to high $I^2R$ losses and hence the efficiency of the device will degrade. In general an ESR meter is used to obtain the value of capacitor in case of hardware experiments. But here we are depending upon the ripple content of output capacitor [3].

$$\frac{d}{dt}V_{ESR} \;/\; t = nT_S = \frac{d}{dt}RI_{ESR} \qquad (10)$$

From Fig. 1, $\quad I_{ESR} = i_L - i_o \qquad (11)$

By substituting equation (10) in (11) and by derivating it we get

$$V_{ESR} = R_{ESR}\left(\frac{Vin}{L} - \frac{Vo}{L}\right)$$

$$= - R_{ESR}\frac{Vo}{L} \qquad (12)$$

Similarly, $\frac{d}{dt}V_{C\_ripple} \;/\; t = nT_S = i_L - i_o/C$

$$V_{C\_ripple} = \frac{-Vo}{2LC}T_{off} \qquad (13)$$

By equating (12) and (13) we get

$$R_{ESR} = \frac{Toff}{2C} \qquad (14)$$

From the above equation we can obtain the value for effective series resistance.

## II. GRID CONNECTED PHOTOVOLATIC SYSTEM FOR FOT CONTROLLED BUCK CONVERTER

### A. Introduction

The single line diagram for grid connected photovoltaic energy system for variable frequency FOT controlled buck converter is as shown in Fig.4. In order to have a interconnection between PV and grid system we are using a FOT controlled technique for buck converter instead of using MPPT technique.

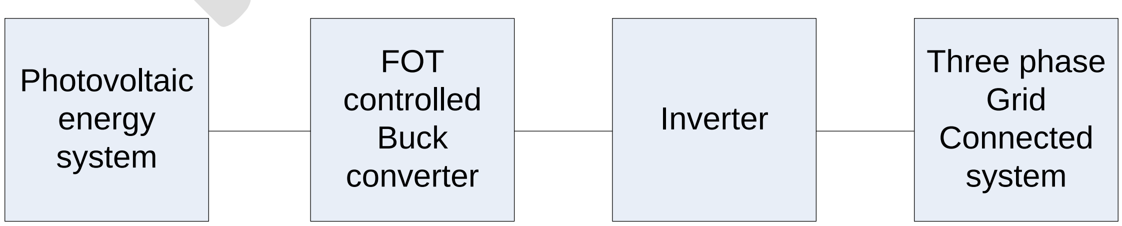


Fig. 4 Single line diagram

Fig. 4 essentially consists of PV energy system, FOT controlled buck converter, inverter and a grid system[2]. In section 2 we have discussed briefly about the FOT controlled buck converter. So in this section let us overcome across photovoltaic module, inverter and the three phase grid.

**B. Photovoltaic energy system**

RES are non-exhaustible sources and are pollution free. PV energy source is one among the renewable energy sources (RES). Solar panel is the heart of photovoltaic system. It provides the necessary information of PV cells whether they are connected in series or shunt. As we know that PV cells depends on the temperature and irradiation of sun, it converts the solar power into electrical power when there is an interaction between sunlight and the semiconductor materials in the PV cells. Single diode or one diode technique equivalent circuit of PV system is shown in Fig. 5. An array is formed by connecting the cells in series and parallel with desired voltage and power. All the cells together constitute a module to get the required voltage and current in turn power.

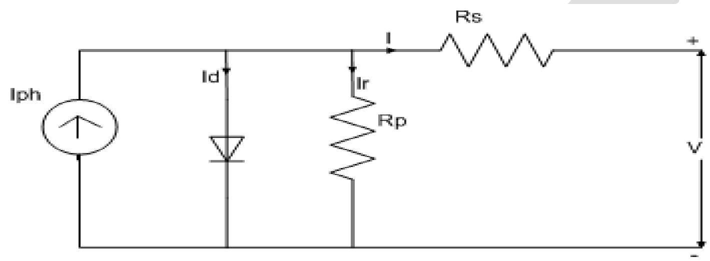


Fig. 5 Equivalent circuit of PV system

Here in this project an inverter is used to convert the DC power coming from the FOT controlled buck converter to required ac power which is the main theme of an inverter. An inverter fundamentally consists of six power electronic switches which are termed as S1-S6. The upper arm of the circuit consists of odd number of switches but whereas the lower arm consists of even number of switches. Each switch conducts for a period of $60^0$. The pure sinusoidal alternating current can be obtained from the inverter by proper conduction angle or firing angle of switch or the proper control of ON and OFF of switch. An sinusoidal signal is taken as the reference signal and triangular waveform is chosen as carrier signal. The sequence of switch depends upon the comparison of magnitude of the sinusoidal and triangular waveforms. When the reference signal amplitude is more than the carrier signal then the corresponding upper arm switch will be in conduction.

The three phase ac output power is given or provided to the grid finally.

## III. SIMULATION RESULTS

**A. Specifications**

The project is carried out using MATLAB software. The specifications of parasitic elements used in the converter is given below in Table 1.

| | |
|---|---|
| Input voltage, E | 15V |
| Reference voltage, $V_{ref}$ | 5V |
| Inductance, L | 25Uh |
| Capacitance, C | 100Uf |
| Output capacitance esr, r | 12mΩ |

| | |
|---|---|
| Load resistance, R | 10Ω |
| Fixed off-time, $T_{off}$ | 4us |

Table-1: Specifications of FOT controlled buck converter

FOT controlled buck converter operation can be studied and understand by the change in parameters of load resistance R, inductance L, output capacitance resistor r, supply voltage E as tabulated in Tables-2 and 3 and the waveforms corresponding to Table-2 are as in Fig. 6 and that of Table-3 are shown in Fig. 7.

| | |
|---|---|
| a | R = 10Ω, L = 25Uf, r = 12mΩ |
| b | R = 10Ω, L = 25Uf, r = 24mΩ |
| c | R = 10Ω, L = 12.48Uf, r =18.6mΩ |
| d | R = 6Ω, L = 12.48Uf, r = 21.4mΩ |
| e | R = 6Ω, L = 28.8Uf, r = 14mΩ |
| f | R = 15Ω, L = 28.8Uf, r = 18mΩ |
| g | R = 20Ω, L = 20Uf, r = 6mΩ |
| h | R = 500Ω, L = 20Uf, r = 6mΩ |

Table-2: Change in circuit parameters of FOT controlled buck converter

| | |
|---|---|
| a | E = 3.3V, r = 3mΩ |
| b | E = 3.3V, r = 6mΩ |
| c | E = 6V, r = 6mΩ |
| d | E = 6V, r = 12mΩ |

Table-3: Change in source voltage and ESR

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**B. Simulation Results of FOT controlled buck converter**

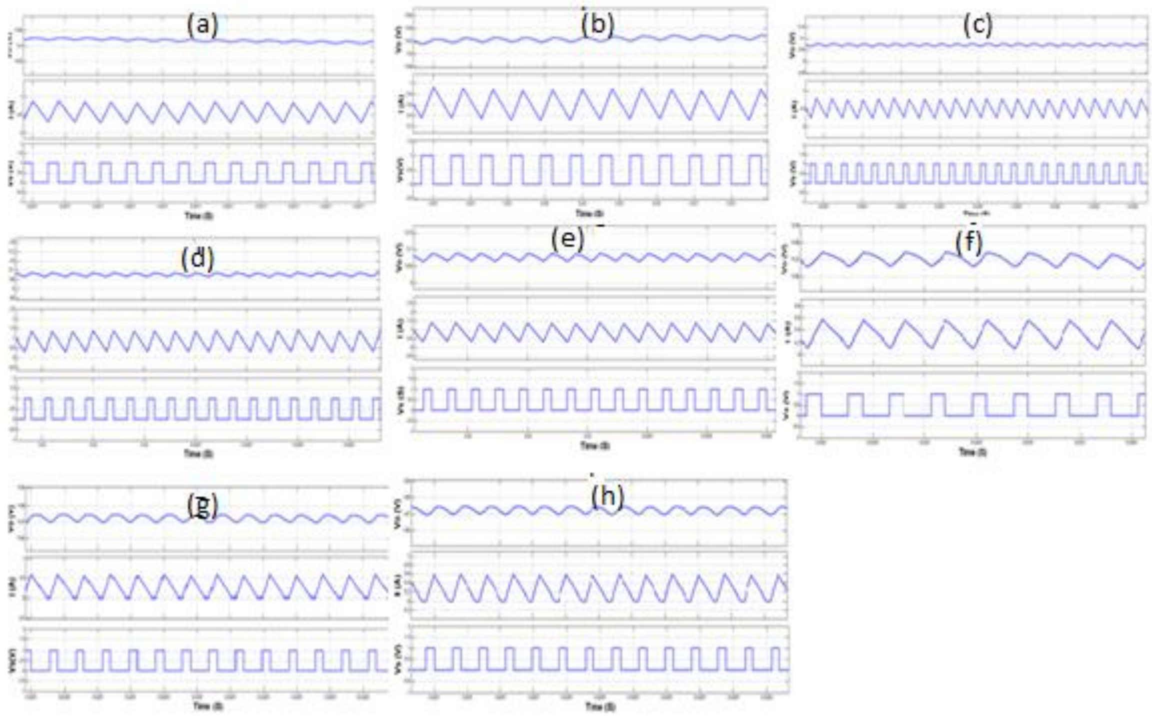


Fig. 6 Simulation results for parameters listed in Table-1 and Table-2

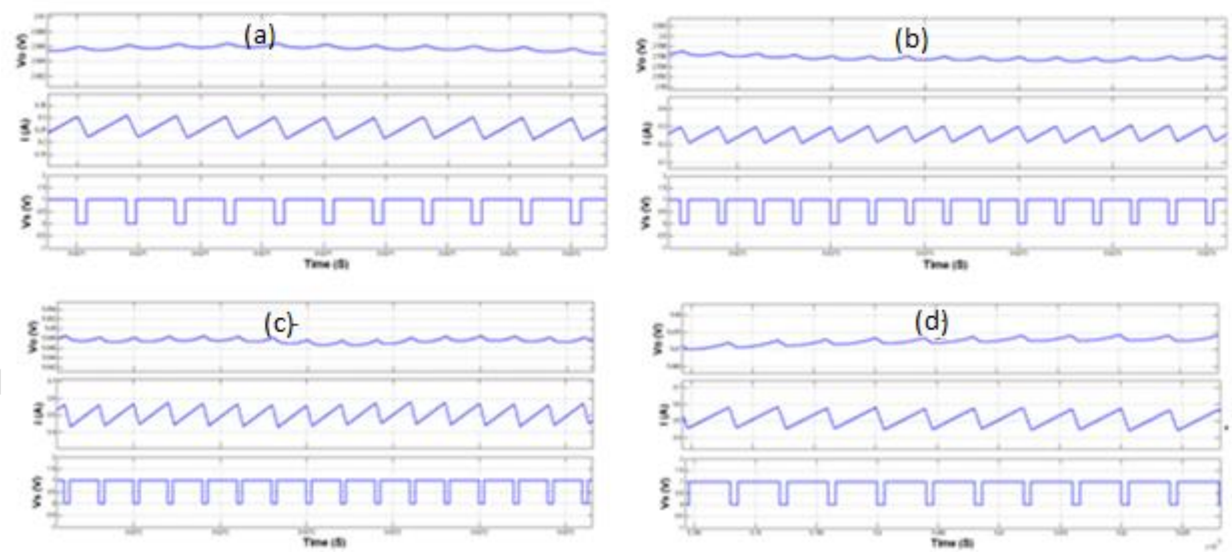


Fig. 7 Circuit simulation results for parameters listed in Table-1 and Table-3

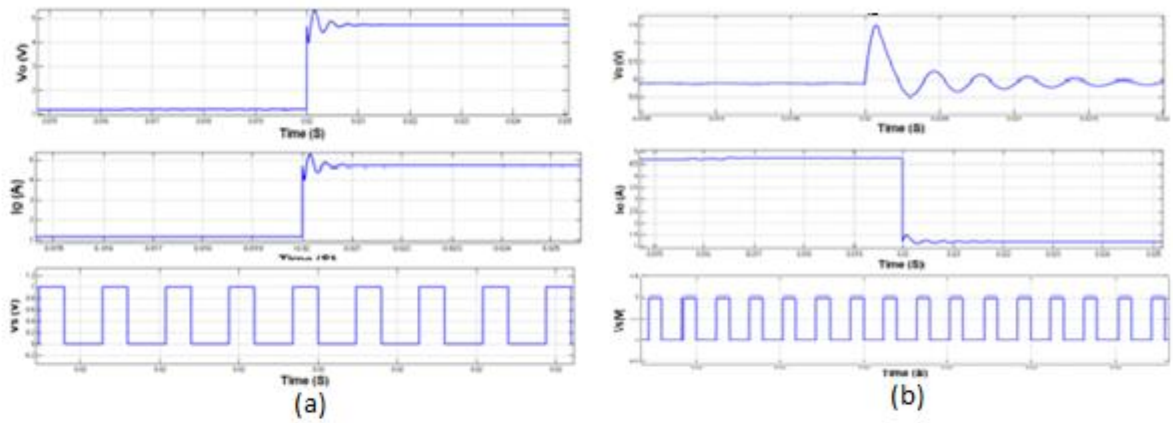


Fig. 8 Results for change in load when L = 10uH, r = 24mΩ and the other specifications as in Table-1

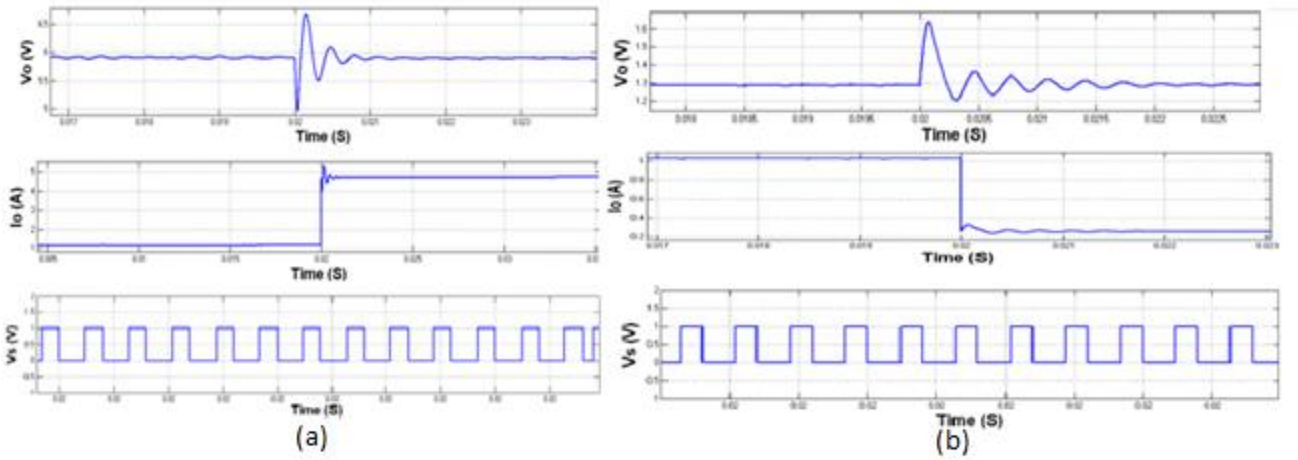


Fig. 9 Simulation results for change in load when E = 3.3V, r = 6mΩ

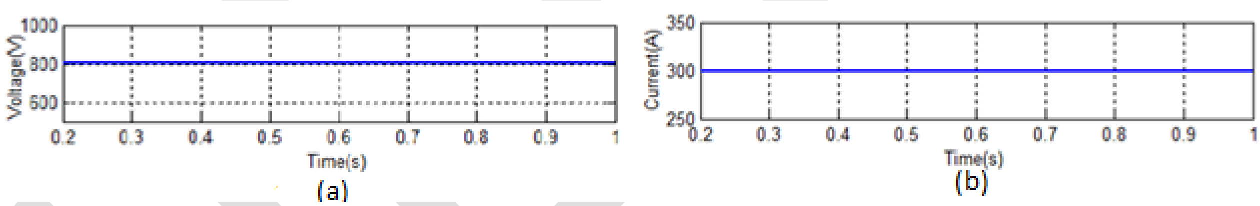


Fig. 10 Results for photovoltaic system (a) PV voltage (b) PV current

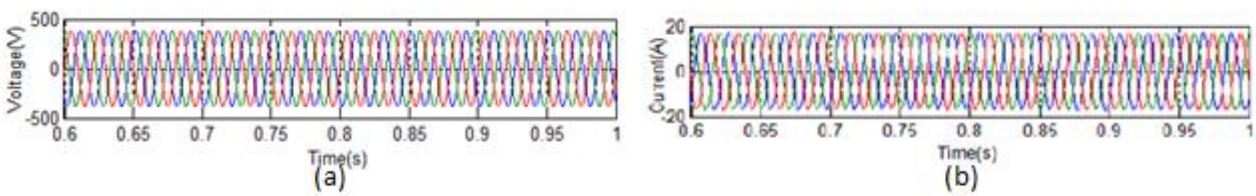


Fig. 11 (a) Three phase grid voltage (b) Three phase grid current

## IV.CONCLUSION

Here a variable frequency fixed off time controlled DC- DC buck converter is designed with five operating modes. By taking the ESR of the output capacitance into consideration the FOT controller is studied for different values of load resistance R, inductance L and effective series resistance ESR .Hence the fast transient response of the converter is obtained by choosing the appropriate value of the resistance which is used in series with the output capacitor. Therefore three phase grid connected system is implemented using this technique.

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