VARIABLE ON-TIME CONTROL SCHEME TO ACHIEVE HIGH EFFICIENCY FOR AC/DC BORDER LINE CURRENT MODE BUCK CONVERTER

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ABSTRACT

The Buck power factor improvement converter (BPFIC) is much better topology because of having advantages like less inrush current, less voltage gain ratio, gives less voltage output ripple and steps down the voltage even with high input voltage, protection from short circuit and its single active switch operation makes it attractive. However borderline current mode (BCM) operated with fixed on-time control technique (FOCT) results in its low efficiency. The main reason of low efficiency is due to high conduction and switching losses which occur due to high peak and rms inductor current. In this paper, varying on-time control technique (VOCT) has been implemented that reduces the peak value of current which results in improved efficiency. In the proposed research, work is related to BPFIC operating in BCM because BCM has many advantages like no reverse recovery of diode, and zero current turning off the switch. To verify the effectiveness of proposed control technique, comparative analysis is obtained between both the two control techniques using SABER SIMULATOR. It is found that VOCT improves the converter's efficiency compared to FOCT.

KEYWORDS

Buck Power Factor Improvement Converter (BPFIC), Borderline Current Mode (BCM), Fixed On-Time Control Technique (FOCT), Varying On-Time Control Technique (VOCT), Saber Simulation.

1. INTRODUCTION

The increasing need of electronic devices (requires AC to DC conversion) have resulted in harmonic content produced by non-linear elements (diodes and thyristors) of electronic devices connected to AC supply system should be in such limit that it meets regulatory standard. This requirement is fulfilled by using active power factor improvement (PFI) circuits that shape the input phase current to be sinusoidal in nature and in phase with input phase voltages. The combined effect of non-linear loads results in problem of serious harmonic distortion in electrical distribution system and its result is poor Power Factor (PF) and power quality, voltage distortion and low efficiency (Azazi *et al*., 2010). PFI can be categorized into active and passive types. Compared with a Passive Power Factor Improvement Converters (PFIC), an active PFIC can achieve a high PF (Nagaraju & Krishnaveni, 2017). The PFIC are being widely used in ac–dc power conversions to get power factor near to unity and to reduce harmonic distortion so as to meet the standards like IEC61000-3-2 and IEEE 519 (Yao *et al*., 2011).

Amongst PFIC, buck Power Factor Improvement Converter (BPFIC) is much better topology because of having advantages like less inrush current, less voltage gain ratio, gives less voltage output ripple and steps down the voltage even with high input voltage, protection from short circuit and its single active switch operation makes it attractive. However, because of dead zone in the input current of (BPFIC) has resulted in poor PF and other power quality issues

For enhancing the performance of BPFIC, different authors have proposed several control techniques (Endo, Yamashita, & Sugiura, 1992; Memon *et al*., 2021).

In this paper, Variable On-Time Technique (VOCT) is implemented to reduce the conduction and switching losses occurred in borderline current mode BPFIC caused by peak and rms value of inductor current.

This paper is divided into six sections. First section gives detailed analysis of traditional BPFIC. In, second section VOCT is implemented to improve converter's efficiency. Third section represents loss analysis caused by conduction and switching losses. Fourth section

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shows simulation verification to confirm the effectiveness of proposed control technique. In last section conclusion is discussed.

2. METHODOLOGY

The research methodology is based on:

1. Mathematical analysis of the operating principle of the control schemes for Borderline Current Mode (BCM) Buck Power Factor Improvement Converter (BPFIC) for FOCT with the help of MATHCAD converter.
2. Introducing the Varying On-Time Control Technique (VOCT) to obtain high efficiency.
3. Comparative analysis of the converter for FOCT and VOCT strategy.
4. Developing the simulation model of BCM Buck converter with the help of SABER software.
5. Confirming the results.

2.1. WORKING ANALYSIS OF TRADITIONALLY USED BCM BPFIC

Figure 1 shows the circuit of Buck Power Factor Improvement Converter (BPFIC) that can be operated in borderline current mode (BCM). The working of the BPFIC will be analyzed in detail with the help of equations in order to find out the expression of fixed on-time technique (FOCT).

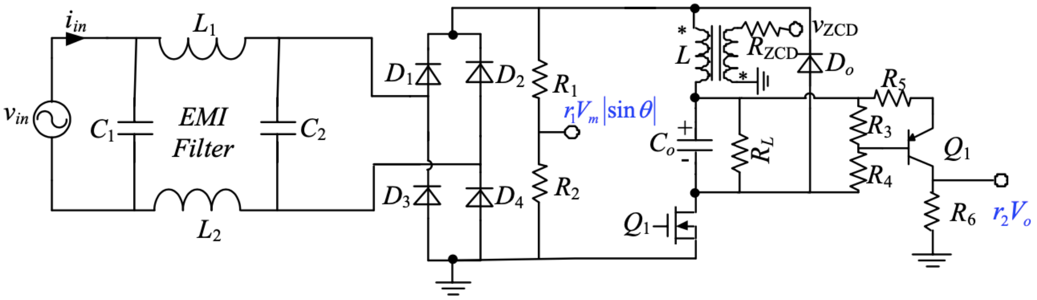

Figure 1. Circuit Diagram of BPFIC.
Source: (Memon *et al.*, 2021).

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The instantaneous value of source voltage at the input and output of bridge is expressed as

$$v_{in\_bpfic} = v_g = V_m \sin\theta \tag{1}$$

BPFIC operated with BCM has two switching cycles.

The inductor is charged from supply voltage when the buck switch is ON, as indicated in Figure 2 (First switching cycle).

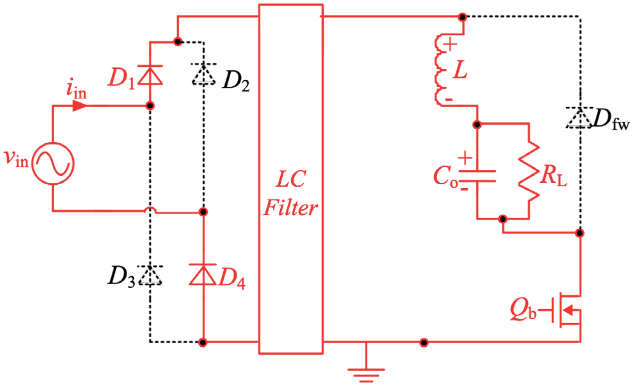

Figure 2. BPFIC when switch is on.
Source: (Memon *et al.*, 2018).

The maximum current flowing through inductor for BPFIC with FOCT is

$$i_{m\_foct} = t_{on\_foct} \frac{V_m |\sin\theta| - V_{o\_bpfic}}{L} \tag{2}$$

The inductor is discharged through load when the buck switch is OFF, as showed in Figure 3 and the expression is given in (3) (Second switching cycle).

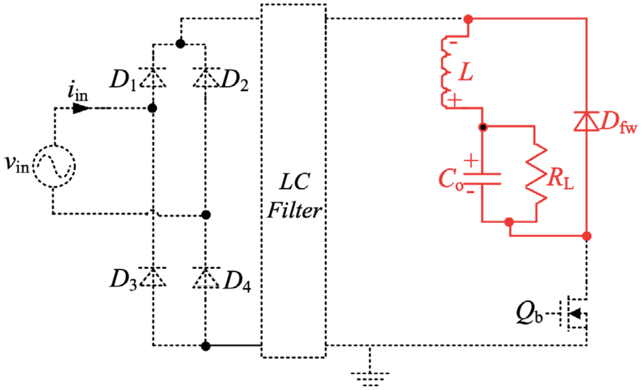

Figure 3. BPFIC when switch is off.
Source: own elaboration.

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$$i_{m\_foct} = -\frac{V_o}{L} T_{off} \tag{3}$$

The maximum current for charging and discharging is same as per energy conservation. So, following relation is got

$$t_{off} = t_{on\_foct} \frac{V_m |\sin\theta| - V_{o\_bpfic}}{V_{o\_bpfic}} \tag{4}$$

Similarly

$$t_{s\_bpfic} = t_{on\_foct} + t_{off} \tag{5}$$

By substituting (3) into (5) yields

$$t_{s\_bpfic} = \left(\frac{V_m |\sin\theta|}{V_{o\_bpfic}} \right) t_{on\_foct} \tag{6}$$

The average input current for BPFIC with FOCT is calculated as

$$i_{avg\_bpfic} = i_{avg\_bpfic(foct)} = \frac{i_{m\_foct} t_{on\_foct}}{2 t_{s\_bpfic}} = \frac{t_{on\_foct} V_{o\_bpfic}}{2L} \left(\frac{V_m |\sin\theta| - V_{o\_bpfic}}{V_m |\sin\theta|} \right) \tag{7}$$

From (1) and (7), the input power of the BPFIC with FOCT is given

$$P_{in\_foct} = \frac{t_{on\_foct} V_{o\_bpfic}}{2\pi L} \int_{\theta_0}^{\pi-\theta_0} \left(V_m |\sin\theta| - V_{o\_bpfic} \right) d\theta \tag{8}$$

The value of t_{on_foct} is expressed after supposing 100% efficiency as

$$t_{on\_foct} = \frac{2\pi P_o L}{\int_{\theta_0}^{\pi-\theta_0} V_{o\_bpfic} \left(V_m |\sin\theta| - V_{o\_bpfic} \right) d\theta} \tag{9}$$

2.2. PROPOSED VOCT FOR BPFIC FOR ENHANCING EFFICIENCY

For improving the efficiency for the BPFIC, the on-time of buck CMOS in (9) has to change as

$$t_{on\_voct} = M_{on} \frac{\left(V_m |\sin\theta| \right)^2}{V_{o\_bpfic} \left(V_m |\sin\theta| - V_{o\_bpfic} \right)} \tag{10}$$

where M_{on} is a constant

Replacing (10) into (7), the input current of the BPFIC is

$$i_{in\_voct\_bfpic} = \frac{V_m \left|\sin\theta\right|}{2L} M_{on} \quad (\theta_0 \le \theta \le \pi - \theta_0) \tag{11}$$

The input power for BPFIC with VOCT is got as

$$P_{in\_bpfic\_voct} = \frac{1}{\pi} \int_{\theta_0}^{\pi-\theta_0} \frac{M_{on} \left(V_m \sin\theta\right)^2}{2L} d\theta = P_o \tag{12}$$

Rearranging (12), we get

$$M_{on} = \frac{2\pi L P_o}{\int_{\theta_0}^{\pi-\theta_0} \left(V_m \sin\theta\right)^2 d\theta} \tag{13}$$

2.3. EFFICIENCY COMPARISON

2.3.1. POWER LOSS DUE TO BRIDGE RECTIFIER

The power loss due to bridge rectifier in BPFIC with FOCT and VOCT is estimated as

$$P_{con\_bpfic\_bridge(fotc)} = 2V_{FD}\, i_{avg\_bpfic(foct)} \tag{14(a)}$$

$$P_{con\_bpfic\_bridge(voct)} = 2V_{FD}\, i_{avg\_bpfic(voct)} \tag{14(b)}$$

The value of VFD for GBU 406 is 0.89.

2.3.2. CONDUCTED LOSSES BY CMOS (SWITCH)

The rms current flowing through switch, when it is on is given as

$$I_{rms\_bpfic\_Q\_on} = \sqrt{\frac{\int_{\theta_0}^{\pi-\theta_0} i^2_{m\_bpfic} D_{on}\, d\theta}{3\pi}} \tag{15}$$

The rms current of the off time period can be determined as

$$I_{rms\_bpfic\_Q\_off} = \sqrt{\frac{\int_{\theta_0}^{\pi-\theta_0} i^2_{m\_bpfic} D_{off}\, d\theta}{3\pi}} \tag{16}$$

The rms current due to switch on and off is calculated as

$$I_{rms\_bpfic\_foct} = \sqrt{I^2_{rms\_bpfic\_Q\_on} + I^2_{rms(Qb\_off\_cdccs)}} \tag{17(a)}$$

$$I_{rms\_bpfic\_voct} = \sqrt{I^2_{rms\_bpfic\_Q\_on} + I^2_{rms(Qb\_off\_voct)}} \tag{17(b)}$$

The losses due to conduction of switches can be got as

$$P_{con\_cmos\_bpfic\_foct} = I^2_{rms\_bpfic\_foct} R_{DS(on)\_S} \tag{18(a)}$$

$$P_{con\_cmos\_bpfic\_voct} = I^2_{rms\_bpfic\_voct} R_{DS(on)\_S} \tag{18(b)}$$

The resistance from drain to source is 0.188, which is from data sheet of 8N60.

2.3.3. SWITCH OFF LOSSES BY CMOS (SWITCH)

When the switch is off, the loss of BPFC with FOCT and VOCT is expressed as

$$P_{off\_cmos\_foct} = \frac{t_{s\_bpfic} t_f}{2\pi} \int_0^{\pi} i_{m\_foct} \left(V_m \sin\theta\right) d\theta \tag{19(a)}$$

$$P_{off\_cmos\_voct} = \frac{t_{s\_bpfic} t_f}{2\pi} \int_0^{\pi} i_{m\_voct} \left(V_m \sin\theta\right) d\theta \tag{19(b)}$$

T_f for 8N60 is 12ns.

2.3.4. COPPER LOSS OF THE BPFIC’ S INDUCTOR

The inductor’s copper loss of BPFIC with FOCT and VOCT is given as

$$P_{cu\_foct} = I^2_{rms\_bpfic\_foct} R_{cu} \tag{20(a)}$$

$$P_{cu\_voct} = I^2_{rms\_bpfic\_foct} R_{cu} \tag{20(b)}$$

2.3.5. CORE LOSS OF BPFIC’ S THE INDUCTOR

The inductor’s core loss of BPFIC with FOCT and VOCT is given as

$$P_{bpfic\_core\_foct} = \left[\int_0^{\pi} C_m f_{s\_bpfic\_foct}{}^{x} B_{ac\_bpfic\_foct}{}^{y} \left(ct_0 - ct_1 T_a - ct_2 T_a^2\right) d\theta\right] \frac{10^3 V_e}{\pi} \tag{21(a)}$$

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$$B_{ac\_bpfic\_foct} = \frac{i_{m\_foct} L}{2NA_e} \tag{21(b)}$$

$$P_{bpfic\_core\_voct} = \left[\int_0^{\pi} C_m f_{s\_bpfic\_foct}{}^{x} B_{ac\_bpfic\_voct}{}^{y} \left(ct_0 - ct_1 T_a - ct_2 T_a^2 \right) d\theta \right] \frac{10^3 V_e}{\pi} \tag{21(c)}$$

$$B_{ac\_bpfic\_voct} = \frac{i_{m\_foct} L}{2NA_e} \tag{21(d)}$$

The value of core parameters can be found from Memon *et al.* (2018).

2.3.6. CONDUCTED LOSS BY FREEWHEELING DIODE

The conducted losses by freewheeling diode of BPFIC with FOCT and VOCT is got as

$$P_{bpfic\_con\_freewhdiode\_foct} = \frac{V_{FD_{fw}}}{\pi} \int_0^{\pi} \frac{i_{m\_foct}}{2} D_{off}\, d\theta \tag{22(a)}$$

$$P_{bpfic\_con\_freewhdiode\_voct} = \frac{V_{FD_{fw}}}{\pi} \int_0^{\pi} \frac{i_{m\_voct}}{2} D_{off}\, d\theta \tag{22(b)}$$

The forward voltage drop is 0.669 for MUR 860.

2.3.7. THE EFFICIENCY COMPARISON

The efficiency of BCM BPFIC with FOCT and VOCT can be estimated as

$$\eta_{bpfic\_foct} = \frac{P_o}{\begin{bmatrix} P_o + P_{con\_bpfic\_bridge(fotc)} + P_{con\_cmos\_bpfic\_foct} + P_{off\_cmos\_foct} \\ + P_{cu\_foct} + P_{bpfic\_core\_foct} + P_{bpfic\_con\_freewhdiode\_foct} \end{bmatrix}} \tag{23(a)}$$

$$\eta_{bpfic\_voct} = \frac{P_o}{\begin{bmatrix} P_o + P_{con\_bpfic\_bridge(votc)} + P_{con\_cmos\_bpfic\_foct} + P_{off\_cmos\_voct} \\ + P_{cu\_voct} + P_{bpfic\_core\_voct} + P_{bpfic\_con\_freewhdiode\_voct} \end{bmatrix}} \tag{23(b)}$$

The calculated efficiency of BCM BPFIC with FOCT and VOCT from (14-23) and specification is depicted in Figure 4. It can be observed the efficiency of BPFIC with VOCT is more than FOCT.

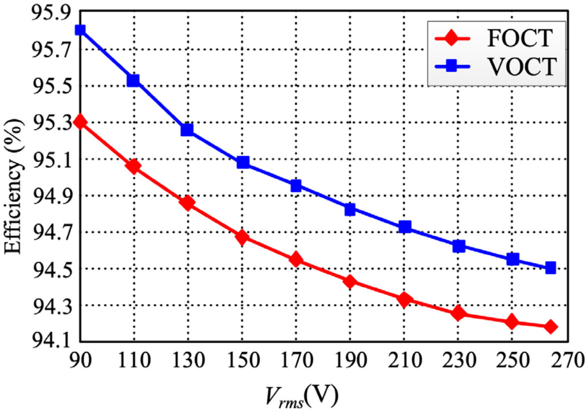

Figure 4. Efficiency at universal input voltage (Mathcad Graph from Eq. (14-23)).
Source: own elaboration.

3. SIMULATION RESULTS

In order to verify the effectiveness of VDCT, simulation verification is obtained using MATLAB. The input voltage range is 90-264VAC, and the output is 80V. For ensuring the current to be in CRM, L6561 IC is used. All the components in the circuit are selected as idea.

In Figure 5, the peak of input current obtained in case of FOCT is more. The current having more peak results in losses that degrades converter's efficiency whereas in Figure 6, the peak of input current obtained in case of VOCT is less which reduces conduction and switching losses hence converter's performance is improved.

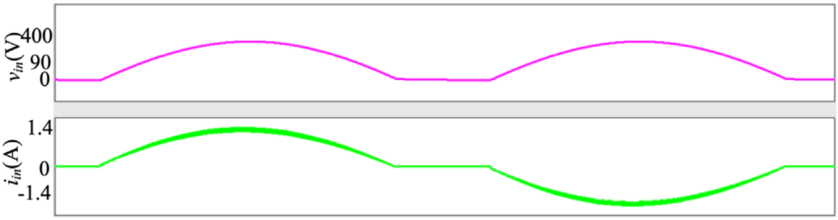

Figure 5. v_{in}, and i_{in} with FOCT (Simulation waveform).
Source: own elaboration.

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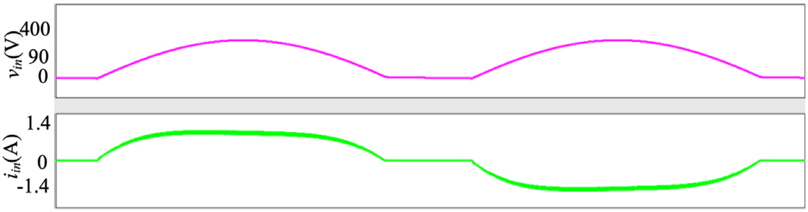

Figure 6. v_{in}, and i_{in} with VOCT (Simulation waveform).
Source: own elaboration.

4. CONCLUSIONS

The Buck Power Factor Improvement Converter (BPFIC) is much better topology because of having many advantages. However Borderline Current Mode (BCM) operated with Fixed On-Time Technique (FOCT) results in its low efficiency. The main reason of low efficiency is due to high conduction and switching losses which occur due to high peak and rms inductor current. In this paper, Varying On-Time Technique (VOCT) has been implemented that reduces the peak value of current which results in improved efficiency.

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